frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 24 March 2020
doi: 10.3389/fsufs.2020.00027

Constraints and Perspectives for Sustainable Wheat Production in Tajikistan

Bahromiddin Husenov[1,2]*, Munira Otambekova[2], Hafiz Muminjanov[3], Alexey Morgounov[4], Siham Asaad[5], Larisa Garkava-Gustavsson[1] and Eva Johansson[1]

[1] Department of Plant Breeding, The Swedish University of Agricultural Sciences, Alnarp, Sweden, [2] Agronomy Faculty, Tajik Agrarian University, Dushanbe, Tajikistan, [3] Food and Agriculture Organization of the United Nations, Rome, Italy, [4] Omsk State Agrarian University, Omsk, Russia, [5] International Centre for Agricultural Research in the Dry Areas (ICARDA), Beirut, Lebanon

Wheat is a major crop with a key role for food security in Tajikistan, contributing 60% of daily calorie intake for the Tajik population. A clear understanding of the major constraints and opportunities relating to wheat production and sustainability in farmers' fields is therefore required. A survey of 210 different wheat fields of different sizes, located in different agricultural zones in Tajikistan and at different altitudes, was conducted during three consecutive years (2012–2014). A questionnaire on wheat production and sustainability, seeking overall information about farms and specific data on crop management practices, was applied. It was accompanied by surveillance of field status concerning diseases, pests, weeds, and influence of abiotic stresses. In addition, a screening was carried out on major Tajik wheat varieties and advanced breeding lines, to assess their resistance to important diseases. The results showed that the agronomic knowledge of Tajik farmers was generally poor and that wheat yield was low, affecting social, economic, and environmental sustainability. The farms surveyed were generally small, growing winter wheat for human consumption year after year. Seeds were hand-broadcast at the optimal sowing time, without chemical treatments and either wheat or technical crops were used as preceding crops. Most farmers used nitrogen fertilizer and irrigation but no weed treatment. The low knowledge status of wheat farmers influenced crop performance and were correlated with lack of crop rotation, while the lack of pest management resulted in high levels of weeds and severe insect damage. While some similarities were shared by most wheat fields surveyed, there was also some variation in wheat crop performance among farms in relation to their size, year of study, agricultural zone, and altitude. Wheat production on small farms still relied heavily on manual labor, while larger farms used more machinery. However, larger farms were not more successful wheat producers than small farms. Most of the Tajik wheat varieties and lines screened were found to be susceptible to at least one of the diseases screened for, i.e., stripe rust, leaf rust, and common bunt. Our findings demonstrate a need for concerted action to overcome wheat yield constraints and achieve sustainability in crop production in Tajikistan. Education of farmers appears key to improving social,

OPEN ACCESS

Edited by:
Patrick Meyfroidt, Catholic University of Louvain, Belgium

Reviewed by:
Zvi Lerman, The Hebrew University of Jerusalem, Israel
L. Jamila Haider, Stockholm University, Sweden

***Correspondence:**
Bahromiddin Husenov
bahromiddin@gmail.com

Specialty section:
This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems

Received: *18 June 2019*
Accepted: *24 February 2020*
Published: *24 March 2020*

Citation:
Husenov B, Otambekova M, Muminjanov H, Morgounov A, Asaad S, Garkava-Gustavsson L and Johansson E (2020) Constraints and Perspectives for Sustainable Wheat Production in Tajikistan. Front. Sustain. Food Syst. 4:27. doi: 10.3389/fsufs.2020.00027

economic, and environmental sustainability. Use of certified seed of suitable wheat varieties and appropriate crop management practices, including weed control while also taking biodiversity into consideration, are other important measures for increasing wheat yield and improving sustainability.

Keywords: crop management, farming practices, food security, survey, sustainability, *Triticum aestivum* L

INTRODUCTION

Sustainability is commonly described as resting upon three pillars, i.e., social, economic, and environmental concepts (Purvis et al., 2019). Thus, equal consideration should be given to social equity, livability, community development, etc. (social sustainability) as to long-term economic growth and development (economic sustainability), and carbon footprint and biodiversity (environmental sustainability). However, this approach has been criticized for dividing sustainability into separate realms, and the necessity to find an integrated way forward has been highlighted (Boyer et al., 2016). In an agricultural context, sustainable crop production systems involve enhanced biodiversity and living soils, use of integrated pest management, and low greenhouse gas emissions, while simultaneously producing high-quality food and sustaining food security (Imadi et al., 2016). Sustainable and successful crop production should thus comprise: (i) development of farming and stable livelihoods for farmers, together with (ii) high biodiversity and low carbon footprint, and (iii) high, secure, and safe yield of high quality and stability in provision of food for end-users. Various factors can negatively impact the security, safety, and quality of crop production, with diseases, pests, weeds, animal pests, and abiotic factors being the most important factors (Oerke, 2006; Savary et al., 2012). Strategies to combat these biotic and abiotic stresses, without affecting biodiversity, soil micro-environments, and carbon footprint, are essential. Continuous monitoring and strategy development is required for managing different agricultural crops at national and international levels (Park et al., 2011; Sikharulidze et al., 2015; Bouwmeester et al., 2016).

Tajikistan is amongst the poorest countries in the world, with high levels of hunger and undernourishment (FAO, 2015; WFP, 2017). Wheat is the major staple food crop in Tajikistan, contributing 60% of the daily calorie intake of the Tajik people (Braun, 2003). The crop is widely grown throughout Tajikistan, from 300 m above sea level (masl) in Tajik Delvarzin in the north-west, near the border with Uzbekistan, to 3,000 masl in Western Pamirs (Muminjanov et al., 2016). According to the latest official figures from the State Agency of Statistics of Tajikistan, wheat was grown on 276 000 ha in 2018, representing 70% of all areas under cereals and pulses. Overall wheat production in 2018 was 779 000 tons, with an average yield of about 2.8 t/ha (TajStat, 2018). Despite the clear dominance of wheat over other crops in Tajikistan, domestic production cannot meet domestic demand, so imports, primarily from Kazakhstan, are required. Price fluctuations and instability on the world market led to increased domestic wheat production being set as a major strategic goal by the Tajik government. However, the current wheat yield in Tajikistan is low in comparison with that in neighboring countries, e.g., in Uzbekistan the average yield is 4.7 t/ha (FAO-REU, 2016).

Tajikistan is known as a hotspot of biodiversity due to its varied mountainous landscape, with habitats ranging from deserts to glaciers and frozen mountains (Fauna Flora International, 2019). The Pamir regions are known as a rich habitat for local tree species and varieties of e.g., apple, apricot, mulberry etc. (Giuliani et al., 2011). Tajikistan is also the home of many unique wheat types, including dwarf wheat and sphere grain wheat, and of most legumes (peas, lentil, chickpea, common bean, golden bean, horse bean), and is the center of diversity for rye, mustard, flax, safflower, cotton-guza, etc. (Muminjanov, 2008). However, Tajikistan is also known as a "cradle" of weed flora, i.e., as the center of origin, and is thereby rich in endemic plants (Nowak et al., 2011, 2013). This widespread presence of weeds is a serious issue for wheat production in Tajikistan, hampering safe and secure food production for the population through decreased yield and through the harvested grain comprising a mixture of wheat and weed seeds. Weed management is currently completely lacking in many wheat fields and, when carried out at all, it involves either hand weeding or hoeing (Nowak et al., 2013).

Another issue for crop production in Tajikistan is the negative impact of pests and diseases on yields. Wheat rusts, especially stripe rust (*Puccinia striiformis* f.sp. *tritici*) and leaf rust (*P. recondite* f.sp. *tritici*), are the major diseases negatively affecting the wheat crop in Tajikistan, followed by powdery mildew (*Blumeria graminis* f. sp. *tritici*), tan spot (*Pyrenophora tritici-repentis* as a complete stage), and seed-borne diseases such as common bunt (*Tilletia laevis*; *T.tritici*) and loose smut (*Ustilago tritici*) (Pett and Muminjanov, 2006a; Pett et al., 2006). Significant yield losses due to stripe rust outbreaks have been reported during epidemic years (Rahmatov et al., 2010). Further, yield and quality reductions in wheat grain are caused by attacks of the major insect pests, i.e., cereal leaf beetle (*Oulema melanopus*), sunny pest (*Eurygaster integriceps*), and aphids (*Schizaphis graminum*, *Diuraphis noxia*) (Pett and Muminjanov, 2006a).

Previous studies have identified increased effectiveness of seed production for cereal crops (Muminov, 2009) and improved wheat management technologies (Rashidov, 2009) as key measures for increasing the security of wheat production in Tajikistan. However, yield still remains low, calling for further concerted actions to increase yield simultaneously with securing environmental sustainability. This requires multi-faceted research to identify the major constraints within wheat production and sustainable ways forward to secure yield, and thereby food production in Tajikistan, without affecting the environment. No previous study has sought to provide insights into crop production in farmers' fields in Tajikistan.

The aim of the present study was thus to evaluate and define the major constraints affecting wheat yield and the sustainability (economic, social, and environmental) of wheat production in Tajikistan. Specific objectives were: (1) to gain knowledge about farming practices; (2) to assess the impact of biotic and abiotic factors on wheat yield; (3) to understand sustainability issues, including impacts on the economy, society, and the environment, of the Tajik wheat production system; and (4) to identify actions necessary to increase the yield and sustainability (economic, social, and environmental) of Tajik wheat production. The intention was to provide a multi-faceted understanding of the major constraints to increasing the yield of wheat in Tajikistan and of the concerted actions needed for achieving sustainability (high yield, and thereby good economic and social development, without hampering biodiversity and the environment) of wheat production, and securing high yield of good quality. Due to the importance of wheat as a staple crop world-wide, the findings of the study can also be applicable in actions to achieve a sustainable increase in production of staple crops in other developing countries. To enhance the opportunities for higher wheat yield, without increasing chemical inputs and decreasing biodiversity, and thereby hampering sustainability in the production system, farmers need better access to resistant, and high-yielding varieties. Therefore, in this study the major wheat varieties and advanced breeding lines in Tajikistan were screened for resistance to the most important diseases (common bunt, stripe rust, and leaf rust) and their potential as parents within the national breeding program was assessed.

MATERIALS AND METHODS

A survey of farmers' fields under wheat production in Tajikistan was conducted in the period 2012–2014, in order to identify major constraints affecting production and sustainability. All the major small-grain cereals (i.e., wheat, barley, rye, and oats) were recorded in the survey, but the focus of the present analysis is on wheat, which is by far the most dominant crop in Tajikistan, occupying the significantly largest production area. In total, 210 fields were surveyed over the 3-years study period, with 53 wheat fields surveyed in 2012, 77 fields in 2013, and 80 fields in 2014. The surveyed fields included both irrigated and rainfed wheat fields, which were randomly chosen during each of the years, and therefore differed between years, to cover as many different farmers' fields as possible. The surveyed fields were divided according to district and agro-climate zone, as shown in **Figure 1** and further defined in **Table 1**. Previous studies have also divided the country into agro-climatic zones, e.g., a system of 11 agro-climate zones devised by Babushkin (1964) is still widely used by local scientists (Saidmuradov and Stanyukovich, 1982). Later, simpler zone divisions have been suggested, e.g., the following four agro-climatic zones (Muminjanov et al., 2016): (i) Hot, dry, comparatively fertile valleys in the south; (ii) hot, dry, comparatively less fertile valleys in the north; (iii) cool and in some places humid zones in the foothills; and (iv) cold, dry, less fertile highlands in the east. The present survey was designed to cover the main areas where cereals are grown in Tajikistan, and therefore fields were classified based on their geographical and administrative location into seven zones (ZI-ZVII) (**Figure 1** and **Table 1**).

Survey Form

Plants in the surveyed fields were mostly at anthesis and early maturation stage (growth stage 55–75 on the Zadoks scale) (Zadoks et al., 1974). The timing of the field survey was chosen to ensure that questions in the questionnaire were covered and to gain as much information as possible from the observations, especially regarding the occurrence of major diseases and possible effect of abiotic stresses.

The questionnaire (in Tajik) defined classifications for different variables (**Table 2**), and consisted of three main parts:

(i) General farm information, included the address, ownership, and contacts for a farm and information on cereals grown on the farm.
(ii) Overall information about the fields, including field size, previous crop, variety grown, and the purpose of cultivation (food—to be used for home consumption of sold to mill/bakery, seed—to be used for resowing either at farm or sold for seed purpose), and crop management information, such as planting time, seed rate, irrigation type and rate, disease and pest control, and weed management. Field locations were identified using global positioning system (GPS) with a Garmin eTrex 20 device.
(iii) Main constraints in the field, including an overview of the crop, evaluation of drought effects and nutrient deficiency, assessment of the spread of weeds, identification of the dominant weed species, and assessment of the main foliar and seed-borne diseases, insect pests, and other constraints affecting growth and yield of the wheat crop.

The 23 variables included in the survey are listed in **Table 2**, which also shows the coding number and the coding levels for each variable. Interviews were carried out orally, by authors BH and MO, who applied the questionnaire to a total of 210 farmers.

Assessment of the Fields

Each surveyed field was assessed for crop performance, including the effects of drought and nutrient deficiency, deploying the 23 numbered variables according to their classification (**Table 2**). Drought effect (variable 15) was assessed visually by looking at plant leaves and constituents, as well as overall field and ground view. Nutrient deficiency (variable 16) was also assessed visually in the plants.

Weed density (variable 14) was recorded as low when <20% per m^2; moderate on ranging from 20 to 40 %, and high when the density was above 40%. Common weeds were identified by morphological characteristics of the plants, following previous descriptions (Pett and Muminjanov, 2006b).

Incidence of major foliar diseases, such as stripe rust (variable 19), leaf rust (variable 20), and stem rust (variable 21), was assessed and classified into different levels (**Table 2**). When a

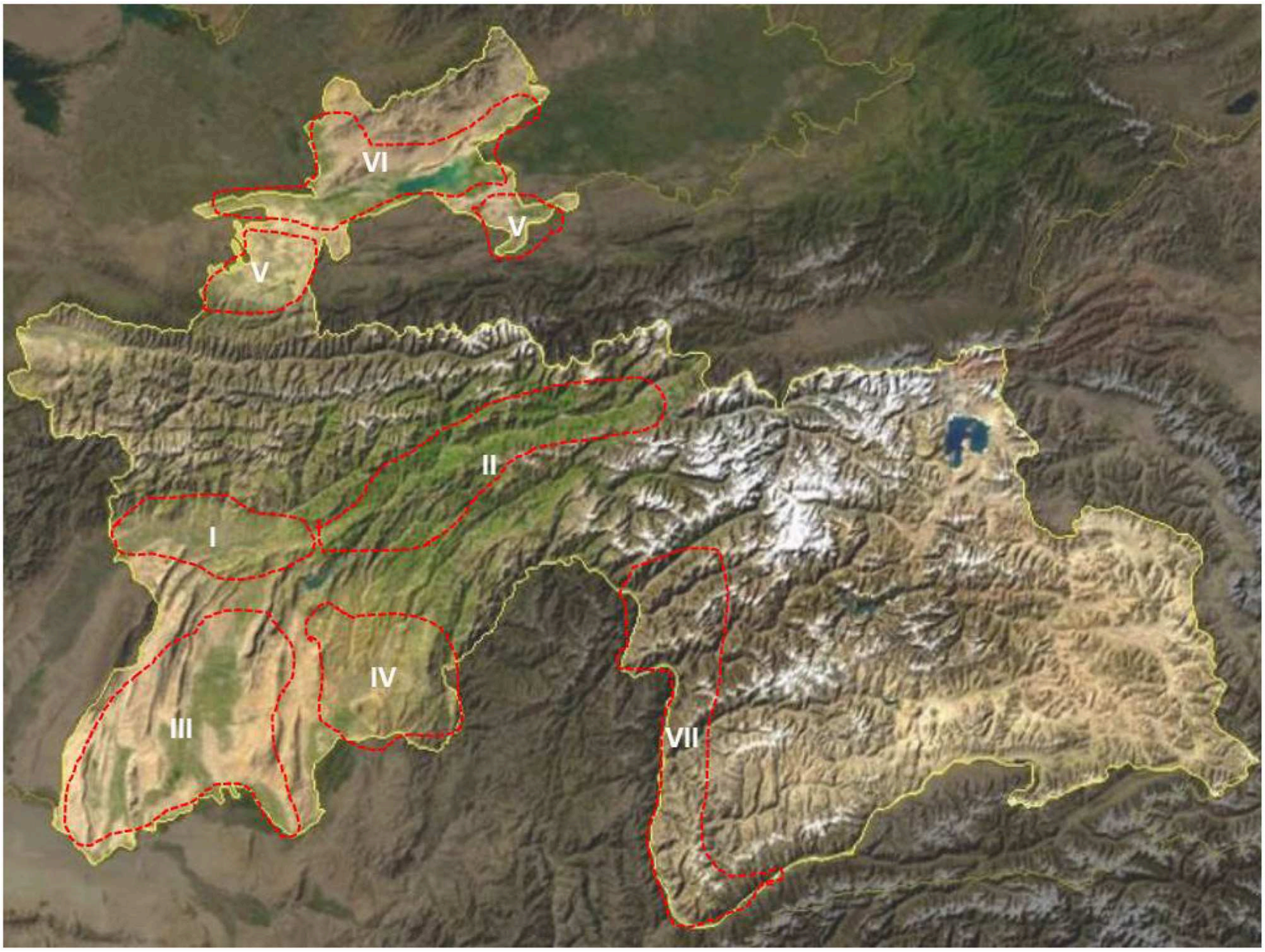

FIGURE 1 | Surveyed agriculture zones, where numbers correspond to zones (ZI-ZVII) listed in **Table 1** (Map source: https://landofmaps.com/2013/12/24/satellite-map-of-tajikistan-borders-overlaid/).

seed-borne disease, loose smut (variable 17), or common bunt (variable 18) was recorded in any of the fields, detection of <1 infected plant per ∼1,000 m^2 was rated as a low incidence. In cases of obviously higher incidences, several sampling areas of 1 m^2 were randomly inspected and percentage infection was calculated as the proportion of infected plants in all inspected plants. For loose smut, fields with no infection were classified as "not observed," infection observed on <1% of the plants was recorded as low incidence, and infection on more than 1% of the plants was recorded as considerable incidence. Common bunt incidence was recorded as not observed, low (<5%), and considerable (>5%). Percentage infection in the field was calculated as:

$$\text{Disease, \%} = \frac{\textit{Number of Infected Plants}}{(\textit{All Plants per Selected m2 Area})} \times 100$$

Insect damage (variable 23) was assessed, the major insect pests damaging the crops were recorded, and dominant species were identified and listed. The insect damage level was rated as low (<20% damage), moderate (20–40%), and high (more than 40% damage).

Screening of Major Wheat Varieties for Resistance to Major Wheat Diseases

To gain an understanding of wheat breeding efforts needed to secure sustainable, high-yielding wheat production in Tajikistan with a low need for chemical inputs, presence of resistance was evaluated by screening the major wheat varieties for major wheat diseases. A total of 38 varieties were identified and selected for screening, based on available reports and articles (e.g., National variety Catalog - SCVT, 2011), recently bred varieties (Rahmatov et al., 2010), and varieties widely grown in the country (Muminjanov et al., 2016). Grain samples were collected at harvest in 2012 and 2013 and sent to Turkey for screening in controlled experiments during the 2013–2014 growing season for the major diseases (stripe rust, leaf rust, and common bunt).

The grain samples were grown at several locations in Turkey, with the main site at Trakya Agricultural Institute in Edirne. At this site, tests for leaf rust resistance were performed in plots of 5 m^2 with no replicates. Checks were planted after every 20 entries, and days to heading, height, and grain yield were recorded, in addition to leaf rust symptoms. Another nursery was established at the Central Field Crop Research Institute in Haymana (40 km from Ankara), for evaluation of stripe rust resistance under artificial inoculations. At this site, readings were taken twice, at grain formation and full maturity. A third nursery was established at the Maize Research Station in Adapazari, a hotspot for leaf rust, and readings were taken once during the season. The final trial on stripe rust was carried out on 16 June 2014 in Haymana, and the final trial on leaf rust on 27 May 2014 in Adapazari.

Statistical Analyses/Calculations

The 23 variables evaluated were divided into different classes (**Table 2**), based on the criteria described above for different variables. To compare the relationships between factors such as year, zone, altitude of cultivation, and farm size with the evaluated variables, a generalized linear model (GLM) followed by means separated with Tukey *post hoc* test was used.

The statistical software SAS 9.3 (SAS, 2011) was used for all statistical calculations. The evaluated variables were used as dependent variables and the factors (year, zone, altitude, and farm size) as independent variables, using the following model:

$$\text{Response} = \text{Year} + \text{Zone} + \text{Altitude} + \text{Farm size} + \text{Crop rotation}$$

Spearman rank correlation analysis was applied to evaluate the significance of correlations between farmers' practices and crop performance. In order to understand and visualize the distribution and relationship between variables and factors evaluated, principal component analysis (PCA) was applied to orthogonally represent the variables in a data matrix vector. PCA is known to show the distribution of dependent variables and independent factors, in a loading and score plot, respectively (Wold et al., 1987). Here, we used PCA to evaluate the relationships between all variables for all factors in a loading plot and the relationships between each of the factors separately, presented in a joint score plot.

RESULTS

Respondent Information

The total number of surveyed farms was a reasonable 210, spread over different agricultural zones, altitudes, districts, and fields (**Table 1**). All the wheat farmers whose fields were surveyed agreed to be interviewed. Of the 210 interviewees, a total of 199 (95%) answered all questions of relevance for this study. The similar numbers of farmers' fields surveyed during each of the years (53 in 2012, 77 in 2013, 80 in 2014) made it possible to compare the situation in farmers' fields across different years, despite different farms being surveyed in different years. A reasonable number of farms (23–45) was also surveyed in most of the seven zones, making them suitable for comparisons. The only exception was ZVII (Western Pamir), which has a limited number of wheat growers and was difficult to investigate due to security and cost constraints, but was included in 2014 due to its specific climate conditions for growing wheat at high altitude (cool temperature, low precipitation, and low soil fertility). Furthermore, similar number of farms (30–35) were surveyed at different altitudes (<400, 400–700, 700–1,000, 1,000–1,500, 1,500–2,000, >2,000 masl), except for very high altitudes (>2,000 masl), where only 12 farms were surveyed, again due to security and cost constraints. Farm size is generally small in Tajikistan, as reflected in the majority (>50%) of the farms surveyed growing <1 ha of wheat and only 9% growing more than 5 ha of wheat (**Table 2**).

General Findings From the Survey

Two types of preceding crop (variable 2), i.e., wheat and technical crops (cotton, potatoes, and maize), were found to dominate in the wheat-growing fields evaluated in this study, emphasizing that wheat is the major crop and reflecting a culture of growing wheat after wheat in the Tajik production system (**Table 2**). Only about half of the farmers interviewed (47%) knew which wheat variety (variable 3) they were growing, indicating traditional use of saved seed (**Table 2**). The farmers who knew which wheat variety they were growing mentioned a total of 26 wheat varieties (**Table 3**). The majority of the wheat crop produced was of winter type (83%) and for human consumption (77%), reflecting that wheat is the major food staple of the Tajik people. Planting (variable 5, "Planting time") was mostly carried out at the optimal time (67%) for the specific zone (**Table 2**). Optimal planting time, defined for each agro-climate zone depending on the season, was based on previous research (Mahmadyorov, 2007) and practical work. This information is also included in the guidelines and recommendations compiled by the Ministry of Agriculture and regional authorities (Litvinov et al., 1964). Regarding planting method (variable 6) and seed chemical treatment (variable 7), wheat seed was mainly hand broadcast (78%) with chemically untreated seeds (94%), showing the low mechanization of Tajik farming systems. General observation of the crop (variable 12, "Crop general view") revealed that 74% fields had satisfactory or better performance according to the classification used (**Table 2**). Lodging (variable 13) was low (1% of the fields showed lodging >30%), no drought effects (variable 15) were seen in most fields (82%), and no nutrient deficiency (variable 16) was recorded (97%), all factors contributing to the good general view of the crop. Concerning fertilizer (variable 9), the majority of the farmers surveyed used nitrogen fertilizer (58%) and irrigation (variable 11) (73%), but no weed control (variable 10) (87%). With regard to weed density (variable 14), low amounts of weeds (<20%) were found in around 30% of the fields, but the amount of weeds was high (>40%) in another 30% of the fields surveyed, indicating that farmers grow a mixture of wheat and weeds. Visual recording of the seed-borne diseases loose smut (variable 17) and common bunt (variable 18) indicated that 5 and 11% of the surveyed fields, respectively, were infected. Wheat crop evaluations revealed that the crop was mostly healthy, i.e., most fields showed no symptoms of stripe rust (variable 19) (66%), leaf rust (variable 20) (78%), or stem rust (variable 21) (99%). However, 30% of the fields showed low symptoms (<20%) of stripe rust, 18% showed low levels of leaf rust, and 87% showed

TABLE 1 | Agricultural zones (based on geographical and administrative divisions), altitude, and total number of districts and fields surveyed in this study.

Agriculture zone					Altitude range of surveyed fields, masl	No. of total surveys						
						2012		2013		2014		2012–2014 (total)
Zone	Name	Administrative region	Surveyed districts	Zone characteristics		Districts	Fields	Districts	Fields	Districts	Fields	Fields
ZI	Hisor valley	DRS*	Dushanbe, Hisor, Tursunzoda, Vahdat, Varzob,	Hot days and cool nights, fertile soils, partially sufficient to sufficient precipitation	732–1,180	5	6	2	3	2	14	23
ZII	Rasht valley	DRS	Fayzobod, Lakhsh, Nurobod, Rasht, Roghun, Tojikobod	Cool, relatively fertile soils, sufficient precipitation	1,116–2,035	1	3	5	17	5	19	39
ZIII	Vakhsh valley	Khatlon	Bokhtar, J.Balkhi, N.Khisrav, Panj, Qubodiyon, Qumsangir, Shahritus, Vakhsh, Yovon	Hot, dry, relatively fertile soils, partially sufficient precipitation	338–631	5	9	-	-	6	20	29
ZIV	Kulob zone of Khatlon region	Khatlon	Baljuvon, Danghara, Kulob, Khovaling, Muminobod, Sh.Shohin, Vose	Hot on plains, cool at piedmont sites, relatively fertile soils, partially sufficient to sufficient precipitation	578–2,060	7	19	4	12	3	10	41
ZV	Piedmont zones of Sughd region	Sughd	Ghonchi, Isfara, Istaravshan, Shahriston	Hot days and cool nights, less fertile to relatively fertile soils, insufficient precipitation	566–1,603	3	8	3	27	3	10	45
ZVI	Plains zones of Sughd Region	Sughd	Asht, B.Ghafurov, J.Rasulov, Konibodom, Mastchoh, Spitamen	Hot, dry, relatively less fertile soils, insufficient precipitation	326–538	4	8	5	18	2	2	28
ZVII	Western Pamir	GBAO**	Ishkoshim, Rushon	Cool, less fertile, insufficient precipitation	2,261–2,581	-	-	-	-	2	5	5
				Total		25	53	19	77	23	80	210

DRS, Districts of Republican Subordination; GBAO, Gorno Badakhshan Autonomous Oblast.

TABLE 2 | Characteristics and frequency of observations per year.

Variables	Classification	No. of classes	Coding	2012		2013		2014		Overall for 3 years	
				No. of fields	Percentage	No. of fields	Percentage	No. of fields	Percentage	No. of fields	Percentage
1. Wheat field area, ha	Small ≤1	3	1	25	47.2	38	49.4	58	72.5	121	57.6
	Medium 1–5		2	19	35.8	32	41.6	19	23.8	70	33.3
	Big >5		3	9	17.0	7	9.1	3	3.8	19	9.0
2. Preceding crop	Wheat	6	1	20	37.7	15	19.5	19	23.8	54	25.7
	Other small-grain cereals (barley, rye, oats, rice)		2	3	5.7	6	7.8	3	3.8	12	5.7
	Fabaceae (peas, lucerne)		3	2	3.8	3	3.9	8	10.0	13	6.2
	Technical crops (cotton, potato, maize)		4	16	30.2	32	41.6	36	45.0	84	40.0
	Vegetables and Cucurbitaceae (tomato, watermelon, onion)		5	7	13.2	21	27.3	11	13.8	39	18.6
	Other (fallow, sorghum, sunflower)		6	5	9.4	0	0.0	3	3.8	8	3.8
3. Wheat variety knowledge	Known	2	1	21	39.6	32	41.6	45	56.3	98	46.7
	Unknown		2	32	60.4	45	58.4	35	43.8	112	53.3
4. Crop season type	Winter	2	1	35	66.0	68	88.3	73	91.3	176	83.8
	Spring		2	18	34.0	9	11.7	7	8.8	34	16.2
5. Planting time	Earlier than optimal	3	1	0	0.0	0	0.0	0	0.0	0	0.0
	Optimal		2	31	58.5	63	81.8	46	57.5	140	66.7
	Later than optimal		3	22	41.5	14	18.2	34	42.5	70	33.3
6. Planting method	Hand broadcast	2	1	47	88.7	48	62.3	68	85.0	163	77.6
	Planter		2	6	11.3	29	37.7	12	15.0	47	22.4
7. Seed chemical treatment	Yes	2	1	4	7.5	4	5.2	4	5.0	12	5.7
	No		2	49	92.5	73	94.8	76	95.0	198	94.3
8. Crop purpose	For seed	2	1	6	11.3	15	19.5	27	33.8	48	22.9
	For food		2	47	88.7	62	80.5	53	66.3	162	77.1
9. Fertilizer	Yes (complex, NPK)	3	1	1	1.9	0	0.0	0	0.0	1	0.5
	Yes (Nitrogen only)		2	33	62.3	38	49.4	50	62.5	121	57.6
	No		3	19	35.8	39	50.6	30	37.5	88	41.9
10. Weed control	Yes (hand weeding)	3	1	10	18.9	6	7.8	2	2.5	18	8.6
	Yes (by herbicide)		2	2	3.8	2	2.6	5	6.3	9	4.3
	No		3	41	77.4	69	89.6	73	91.3	183	87.1
11. Irrigation	Irrigated	2	1	30	56.6	62	80.5	61	76.3	153	72.9
	Rainfed		2	23	43.4	15	19.5	19	23.8	57	27.1
12. Crop general view	Very good (optimal)	3	1	9	17.0	5	6.5	12	15.0	26	12.4
	Good (satisfactory)		2	19	35.8	59	76.6	51	63.8	129	61.4
	Poor		3	25	47.2	13	16.9	17	21.3	55	26.2
13. Lodging	No	3	1	47	88.7	75	97.4	75	93.8	197	93.8

(Continued)

TABLE 2 | Continued

Variables	Classification	No. of classes	Coding	2012		2013		2014		Overall for 3 years	
				No. of fields	Percentage	No. of fields	Percentage	No. of fields	Percentage	No. of fields	Percentage
	Low <30%		2	6	11.3	1	1.3	4	5.0	11	5.2
	High >30%		3	0	0.0	1	1.3	1	1.3	2	1.0
14. Weed density	Low <20%	3	1	10	18.9	38	49.4	21	26.3	69	32.9
	Medium 20–40%		2	14	26.4	21	27.3	39	48.8	74	35.2
	High >40%		3	29	54.7	18	23.4	20	25.0	67	31.9
15. Drought effect	No	2	1	39	73.6	71	92.2	62	77.5	172	81.9
	Visible effect		2	14	26.4	6	7.8	18	22.5	38	18.1
16. Nutrient deficiency	No	2	1	52	98.1	76	98.7	76	95.0	204	97.1
	Visible effect		2	1	1.9	1	1.3	4	5.0	6	2.9
17. Loose smut	Not observed	3	1	46	86.8	74	96.1	79	98.8	199	94.8
	Observed <1%		2	3	5.7	2	2.6	1	1.3	5	2.4
	Observed >1%		3	4	7.5	1	1.3	0	0.0	6	2.9
18. Common bunt	Not observed	3	1	44	83.0	67	87.0	76	95.0	187	89.0
	Observed <5%		2	8	15.1	7	9.1	3	3.8	18	8.6
	Observed >5%		3	1	1.9	3	3.9	1	1.3	5	2.4
19. Stripe rust	Not observed	4	1	46	86.8	40	51.9	53	66.3	139	66.2
	Low <20%		2	6	11.3	34	44.2	24	30.0	64	30.5
	Medium 20-40%		3	1	1.9	2	2.6	1	1.3	4	1.9
	High >40%		4	0	0.0	1	1.3	2	2.5	3	1.4
20. Leaf rust	Not observed	4	1	42	79.2	61	79.2	61	76.3	164	78.1
	Low <20%		2	7	13.2	13	16.9	18	22.5	38	18.1
	Medium 20–40%		3	4	7.5	2	2.6	1	1.3	7	3.3
	High >40%		4	0	0.0	1	1.3	0	0.0	1	0.5
21. Stem rust	Not observed	4	1	52	98.1	75	97.4	80	100.0	207	98.6
	Low <20%		2	1	1.9	2	2.6	0	0.0	3	1.4
	Medium 20–40%		3	0	0.0	0	0.0	0	0.0	0	0.0
	High >40%		4	0	0.0	0	0.0	0	0.0	0	0.0
22. Other diseases	Not observed	4	1	14	26.4	6	7.8	3	3.8	23	11.0
	Low <20%		2	39	73.6	68	88.3	76	95.0	183	87.1
	Medium 20–40%		3	0	0.0	3	3.9	1	1.3	4	1.9
	High >40%		4	0	0.0	0	0.0	0	0.0	0	0.0
23. Insect damage	Low <20%	3	1	45	84.9	69	89.6	77	96.3	191	91.0
	Medium 20–40%		2	4	7.5	7	9.1	1	1.3	12	5.7
	High >40%		3	4	7.5	1	1.3	2	2.5	7	3.3

TABLE 3 | Reported knowledge of varieties grown on the farm.

	Variety knowledge								
Zone	**2012**			**2013**			**2014**		
	Total surveyed fields	**Fields with known varieties**	**Varieties (fields reported)**	**Total surveyed fields**	**Fields with known varieties**	**Varieties (fields reported)**	**Total surveyed fields**	**Fields with known varieties**	**Varieties (fields reported)**
ZI	6	3	Irishka (1); Krasnodar 99 (1); Breeding trials (1)	3	2	Ekiz (1); Krasnodar 99 (1)	14	7	Besribey (1); Najibey (1); Yusufi (2); Sarvar (3)
ZII	3	1	Jayhun (1)	17	7	Irodi (1); Irishka (4); Lastochka (1); Safedak (1)	19	19	Sarvar (13); Yusufi (2); Sadokat (2); Navruz (1); Safedak (1)
ZIII	9	3	Atai (1); Multiple varieties (1); Jayhun (1)	-	-	-	20	2	Krasnodar 99 (1); Irishka (1)
ZIV	19	4	Jayhun (1); Norman (1); Surkhak (1); Steklovidnaya 24 (1)	12	-	-	10	8	Sadokat (2); Sarvar (3); Krasnodar 99 (3)
ZV	8	8	Starshina (2); Umanka (1); Multiple varieties (1); Sarvar (1); Siete-Cerros 66 (1); Lastochka (1); Krasnodar 99 (1)	27	20	Irishka (3); Starshina (6); Ziroat 70 (1); Yusufi (1); Sila (1); Multiple varieties (1); Krasnodar 99 (6); Lastochka (1)	10	5	Steklovidnaya 24 (1); Vassa (1); Sila (1); Starshina (2)
ZVI	8	2	Krasnodar 99 (1); Starshina (1)	18	3	Krasnodar 99 (1); Breeding trials (1); Kazakhstan (1)	2	2	Krasnodar 99 (2)
ZVII	-	-	-	-	-	-	5	2	Safedaki Ishkoshimi (1); Kilaki Bartang (1)
Total	53	21	1. Jayhun (3); 2. Krasnodar 99 (3); 3. Starshina (3); 4. Irishka (1); 5. Atai (1); 6. Norman (1); 7. Surkhak (1); 8. Steklovidnaya 24 (1); 9. Umanka (1); 10. Sarvar (1); 11. Siete-Cerros 66 (1); 12. Lastochka (1); Field with multiple varieties (2); Breeding trials (1)	77	32	1. Krasnodar 99 (8); 2. Irishka (7); 3. Starshina (6); 4. Lastochka (2); 5. Ekiz (1); 6. Irodi (1); 7. Safedak (1); 8. Ziroat 70 (1); 9. Yusufi (1); 10. Sila (1); 11. Kazakhstan (1); 12. Field with multiple varieties (1); Breeding trials (1)	80	45	1. Sarvar (19); 2. Krasnodar 99 (6); 3. Yusufi (4); 4. Sadokat (4); 5. Starshina (2); 6. Besribey (1); 7. Najibey (1); 8. Navruz (1); 9. Safedak (1); 10. Irishka (1); 11. Steklovidnaya 24 (1); 12. Vassa (1); 13. Sila (1); 14. Safedaki Ishkoshimi (1); 15. Kilaki Bartang (1)

low levels of other diseases. Insect damage (variable 23) at low levels (<20%) was recorded in 91% of the fields, with a high level (>40%) only in 3% of the fields (**Table 2**).

Differences in Crop Performance Between Different Years

The random selection of farms for the survey resulted in a significantly higher number of small wheat fields being surveyed in 2014 than in 2012 and 2013 (**Table 2**). On selected farms, the purpose of wheat production was to a significantly higher extent for seed on farms surveyed in 2012 than on those surveyed in 2014 (**Tables 2**, **4**, **Table S3a**). Planting was carried out significantly more often at the optimal time and less often by hand broadcasting on farms surveyed in 2013 than on those surveyed in 2012 and 2014 (**Tables 2**, **4**, **Table S3a**). Irrigation was less common on the farms visited in 2012 than on those visited in 2013 and 2014 (**Tables 2**, **4**, **Table S3a**). The general view of the crop was less satisfactory on the farms surveyed in 2012 than on the farms surveyed in the other 2 years (**Tables 2**, **4**), mainly due to a significantly higher amount of weeds in the fields in 2012, which also resulted in a significantly higher degree of hand weeding (**Tables 2**, **4**, **Table S3a**). The major weed species recorded during all 3 years were: *Convolvulus arvensis* L., *Avena fatua*, *Lolium multiflorum*, *Gallium apparena*, *Sinapis arvensis*, *Chenopodium album*, *Vicia* spp., *Cynodon dactylon*, *Sorghum hallepense*, *Cirsium arvensis*, *Xanthium*, and *Capsella bursa pastoris*. The following species were recorded less frequently: *Medicago*, *Alhagi*, *Rumex*, *Setaria*, *Papaver*, and *Equisetum arvensis* (**Table S1**). Drought effects were significantly more commonly observed on the farms surveyed in 2013 than in 2012 and 2014, while loose smut was recorded significantly more frequently, and stripe rust and other diseases significantly less frequently, in 2012 than in the other 2 years (**Tables 2**, **4**, **Table S3a**). Drought effects were also observed relatively more frequently in irrigated compared with rainfed areas. Differences recorded between the study years might be the result of different farms being selected in different years, but also of general environmental (weather-related) events and pest outbreaks influencing cultivation environments.

Impact of Zone on Crop Performance

The size of the fields surveyed differed between the seven zones evaluated, with smaller fields in ZI-ZIII and larger fields in ZVI (**Table S2**). Wheat was the significantly most frequent preceding crop in ZIV, while the most common preceding crop in ZIII and ZVI was a technical crop (**Table 4**, **Tables S2**, **S3b**), indicating less crop rotation in ZIV. Farmers in ZV showed greater knowledge about what wheat variety they were growing than farmers in ZIII (**Table 4**, **Tables S2**, **S3b**), which might indicate more educated farmers in ZV. The main purpose reported for growing wheat was to use it as food, although a significantly higher proportion of farmers in ZI, ZII, and ZV reported growing wheat for seed than the farmers in ZIII and ZVI (**Table 4**, **Tables S2**, **S3b**). The use of wheat grain for food might indicate that a higher proportion of the grain is used for direct home consumption. A higher proportion of spring wheat was recorded in ZIV than in all other zones except ZVII, where only spring wheat was grown (**Table 4**, **Tables S2**, **S3b**), due to severe winters. Most fields were sown by hand broadcasting, at an optimal time in all zones, although a significantly higher proportion of fields were sown late in ZI and ZIII than in ZVI, and a higher proportion of fields in ZV were machine-sown than in the other zones (**Table 4**, **Tables S2**, **S3b**), indicating a higher technological level on farms in ZV. No use of fertilizer was reported by farmers in ZVII. A higher level of nitrogen fertilizer use was reported by farms in ZV compared with ZIV, where the latter was the zone with the significantly highest proportion of rainfed fields, i.e., irrigation was less common than in the other zones (**Table 4**, **Tables S2**, **S3b**). A significantly higher incidence of weeds was found in fields in ZI and ZIV than in ZV, and drought effects were noted more commonly in fields in ZIII and ZVI than in the other zones (**Table 4**, **Tables S2**, **S3b**). Insect damage was more commonly noted in fields in ZV than in fields in ZII. Low incidence of insect damage and a high degree of lodging and stripe rust were seen in ZVII (**Table 4**, **Tables S2**, **S3b**), most likely due to the severe winters and short growing season in that zone. Generally, farmers from ZV seemed to be more technologically advanced, using seed drills, nitrogen fertilizer, having better knowledge of what wheat variety they were growing, and using crop rotation to a higher degree than farmers in other zones.

Impact of Altitude and Farm Size on Crop Performance

Most factors evaluated were not affected by altitude (**Table 4**). However, significantly larger fields were found on farms at altitude 400–700 masl than on farms at 1,500–2,000 masl, and technical crops were more common as the preceding crop at lower altitude levels (<400 masl) than at higher altitudes (>1,000 masl) (**Table 4**, **Table S2**), indicating farming for household use at higher altitudes. Spring wheat was more commonly found at higher altitudes (>1,500 masl) than at altitudes <1,500 masl (**Table 4**, **Tables S2**, **S3c**), due to severe cultivation conditions at high altitudes. Farms at altitude 700–1,000 masl showed more technological cultivation, as they grew wheat for seed production and used seed drills, fertilizers, and irrigation more commonly than farms at other altitudes, although drought effects were more commonly seen (**Table 2**, **Tables S2**, **S3c**). Most factors were also not affected by farm size. However, large farms (>5 ha) used seed drills significantly more commonly, irrigated less commonly, had a higher weed density, and more seldomly had recorded incidences of loose smut than small farms (<1 ha) (**Table 4**, **Tables S2**, **S3d**).

Impact of Crop Rotation on Crop Performance

The crop reported to be grown before the wheat evaluated in the present investigation was taken as an indication of whether crop rotation was applied, or whether wheat was grown after wheat. Generally, the effect of the previous crop was significantly low for most of the factors evaluated (**Table 4**, **Table S3e**). Farmers' knowledge about the wheat variety grown was more significant when wheat was grown after a Fabaceae crop than when grown after wheat or other crops (**Table 3**,

TABLE 4 | Mean square values from generalized linear model (GLM) analyses comparing relationships between year, agricultural zone, altitude, farm size, and crop rotation and various variables.

Variable	Year (DF = 2)	Zone (DF = 6)	Altitude (DF = 5)	Farm size (DF = 2)	Crop rotation (DF = 5)	Error (DF = 184)
Previous crop	3.36	30.3***	0.98	7.42**		1.57
Wheat variety knowledge	0.26	1.57***	0.20	0.14	0.53*	0.20
Crop season type	1.04***	1.56***	0.51***	0.26	0.12	0.07
Planting time	1.00**	0.42	0.24	0.03	0.19	0.20
Planting method	1.31***	0.87***	0.23	4.25***	0.16	0.10
Seed chemical treatment	0.01	0.10	0.17**	0.02	0.05	0.05
Crop purpose	0.64*	0.97***	0.25	0.02	0.06	0.14
Fertilizer	0.54	1.41***	0.36	0.03	0.55*	0.20
Weed control	1.35*	1.21***	0.36	0.22	0.23	0.32
Irrigation	1.16***	2.05***	0.22	0.42*	0.75***	0.10
Crop general view	0.84*	0.83*	0.25	0.24	0.28	0.37
Lodging	0.09	0.36***	0.01	0.00	0.07	0.08
Weed spread	6.05***	0.99*	0.36	0.88*	0.26	0.59
Drought effect	0.79***	1.28***	0.25	0.04	0.29*	0.10
Nutrient deficiency	0.04	0.02	0.01	0.04	0.02	0.03
Loose smut	0.55*	0.08	0.39**	0.99***	0.25	0.12
Common bunt	0.26	0.42*	0.02	0.25	0.38*	0.16
Stripe rust	2.43***	1.09***	0.19	0.23	0.23	0.34
Leaf rust	0.01	0.86***	0.10	0.00	0.30	0.29
Stem rust	0.01	0.00	0.02	0.00	0.02	0.01
Other diseases	1.03***	0.06	0.21	0.11	0.08	0.12
Insect damage	0.37	0.57***	0.05	0.34	0.08	0.17

*Spearman rank correlation: *,**,***Significant at $P < 0.05$, 0.01, 0.005.*

Table S3e). Thus, there seemed to be a relationship between farmers' knowledge and use of crop rotation. Fertilizer was significantly more commonly used on wheat grown after a Fabaceae crops than on wheat grown after wheat or other crops (**Table 4**, **Table S3e**). Wheat grown after wheat, a Fabaceae crop, or another crop was significantly more commonly rainfed than wheat grown after another cereal, a technical crop, or vegetable crop, which were more commonly irrigated, while drought effects were significantly more commonly seen on wheat grown after technical crops than after other crops (**Table 4**, **Table S3e**).

Correlations Between Farmers' Practices and Crop Performance

Spearman rank correlation analysis relating farmers' crop cultivation practices to crop performance revealed a highly significant and positive correlation between farmers' knowledge of variety cultivated and the general view of the crop, as well as low drought effects and low levels of weed, loose smut, common bunt, and leaf rust (**Table 5**). Thus, farmers' knowledge was related to more successful crop cultivation than lack of knowledge. Cultivation of spring wheat led to a significantly higher incidence of loose smut and common bunt than cultivation of winter wheat, presumably due to cultivar differences and soil conditions. The use of machinery for sowing contributed to a higher incidence of stripe rust and insect damage in the crop, possibly due to higher density of wheat cultivation. Growing wheat for food resulted in a less good general view of the crop, with more weeds and drought symptoms, and higher incidence of common bunt and insect damage than growing wheat for seed. Small farmers depending on producing their own daily food using saved seeds might be the reason for this negative relationship. The use of fertilizers and weed control improved the general performance of the crop and reduced insect damage. Weed control also resulted in lower weed density and thereby higher security of production. Irrigation resulted in reduced levels of loose smut in the crop (**Table 5**).

Resistance of Screened Wheat Varieties to Major Diseases

Resistance to common bunt, stripe rust, and leaf rust was found to be limited in the wheat material screened (**Table 6**). For common bunt, none of the varieties screened showed full resistance, four varieties showed moderate resistance (MR), and the remaining 34 varieties were found to be susceptible (S). For stripe rust, five varieties were found to be fully resistant, showing no symptoms of the disease, one variety (Vahdat) was classified as having MR toward the disease, and the remaining varieties showed high susceptibility. A higher level of resistance to leaf rust than to stripe rust was seen in the screened material, with 16 of the investigated varieties showing no symptoms of this disease.

Only two varieties, Lalmikor 1 and Starshina, showed no symptoms of both stripe rust and leaf rust, but both these varieties were highly susceptible to common bunt.

TABLE 5 | Spearman rank correlation coefficient for relationships between crop cultivation variables and crop performance.

	View	Lodging	Weed	Drought	Nutrient	Smut	Bunt	Stripe	Leaf	Stem	Other	Insect
Wheat variety knowledge	0.46***	−0.07	0.28***	0.29***	0.16*	0.21***	0.24***	0.04	0.17*	0.11	0	−0.15*
Crop season type	0.16*	0.05	0.11	−0.03	−0.07	0.19***	0.14*	0.06	0.02	0.06	−0.04	−0.13
Planting time	−0.02	0.05	0.02	0	0.05	0.04	0.08	0.08	−0.17**	−0.03	−0.01	0.14*
Planting method	−0.13	−0.08	−0.14*	−0.15*	−0.02	0.03	−0.07	0.17**	0.02	−0.06	0.16*	0.27***
Seed chemical treatment	0.11	0.06	0.05	0	0.04	0.06	0.08	−0.14	0.15*	0.07	0.07	−0.28***
Growing purpose	0.36***	0.1	0.24***	0.26***	0.1	0.13	0.19***	0.04	0.15*	0.07	0.07	−0.23***
Fertilizer	0.34***	0.02	0.14*	0.03	0.14*	0.19**	0.13	0.04	0.07	0.14*	0.08	−0.19***
Weed control	0.29***	−0.02	0.26***	0.06	0.06	0.09	0.08	0.04	0.02	0.04	0.15*	−0.27***
Irrigation	0.11	−0.07	0.1	−0.1	0.02	0.27***	0.08	−0.18**	−0.12	0.01	−0.02	−0.12

*Spearman rank correlation: *,**,***Significant at $P < 0.05, 0.01, 0.005$.*

DISCUSSION

Constraints and perspectives on sustainable wheat production in Tajikistan were identified in this survey. Farmers' knowledge, here measured as knowing which wheat variety they were growing (variable 3), was the outstanding factor influencing the performance of the crop, thereby affecting economic sustainability (**Table 5**). Lack of knowledge in this regard resulted in less good general performance of the crop, increased signs of drought effects, and increased levels of weed and diseases (variables 12, 14, 15, 17, 18, 20), all factors known to be correlated with decreased yield (Waddington et al., 2010; Amelework et al., 2016). Lack of knowledge was also related to low levels of crop rotation, indicating that farmers with little knowledge of the variety they were growing also lacked knowledge about the benefits of increased and secure yield through crop rotation. This lack of crop rotation might also have a negative environmental impact (Wienhold et al., 2006), thereby negatively affecting the environmental sustainability of wheat production. The low level of crop rotation and high degree of "wheat followed by wheat" cultivation in the Tajik system may be because wheat is a critical staple food for the Tajik people (Braun, 2003), but the wheat crop is relatively low-yielding in the country (FAO-REU, 2016). This low economic sustainability (low yield in the staple crop for food security) negatively affects the environmental sustainability (crop monoculture, as farmers need to grow wheat continuously in order to feed the population), and probably also the social sustainability (as communities get locked into trying to produce enough food to avoid hunger/starvation). Social sustainability is well-known to be connected to poverty and low educational status (UNESCO, 2019; UNICEF, 2019).

Lack of knowledge of the variety grown was most likely a result of farmers using farmer saved seeds, a behavior known to be common among farmers in Tajikistan (Husenov, 2018). Use of farmer saved seeds may be an indication of use of traditional landraces, but also of lack of income to buy seeds. Traditional landraces are known for their local adaptation and that some of them contribute specific characters e.g., they may be high in minerals, nutrient dense, tasty and often have a higher capacity to withstand weed pressure (Murphy et al., 2008; Hussain et al., 2010, 2012; Moreira-Ascarrunz et al., 2016). Appropriate use of farmer saved seeds with a careful cleaning of the seeds to get rid of e.g., weed seeds, can thereby contribute positively to sustainability, by local adaptation of the seeds, resulting in crop mixtures contributing to abiotic and biotic stress tolerance and also to securing agrobiodiversity in the crop, helping to counter future constraints (Constanzo and Bàrberi, 2014). However, farmer saved seeds can also spread seed-borne diseases and weed seeds from the previous harvest (Husenov et al., 2017). Previous studies have shown presence of spores of seed-borne diseases in practically all wheat material in Tajikistan (Husenov, 2018). In the present study, we found that in one-third of the fields surveyed, farmers are co-cultivating wheat with weed (variable 8), with weeds comprising more than 40% of the production (**Table 2**). One possible reason for that could be, e.g., negative impact of modern agricultural practices, like use of fungicides and herbicides, on landraces' performance. However, as only 5% of the farmers are using such chemical inputs, according to our study, this is not a likely explanation. Thus, the use of farmer saved seeds because of poverty, lack of resources to buy proper seeds, and lack of locally adapted landraces (Schmidt et al., 2019), are the most likely reasons for the high amount of weed on the fields, which can be a direct cause of inferior crop performance and yield, thereby contributing negatively to sustainability in crop production. However, without solving the weed issue, the use of modern wheat varieties might not be a better solution, except from such seed being free from weed, than the use of landraces, as modern wheat often is less weed competitive than lanraces (Murphy et al., 2008). Use of suitable wheat material to achieve high yield of desired quality can be seen as the second most important factor to increase yield, and thereby economic sustainability, in Tajik wheat production. The present survey revealed the negative impact of lack of knowledge of the variety grown on crop production (**Tables 2**, **3**, **5**) and lack of resistance in the Tajik wheat material (**Table 6**). The use of resistant and weed-competitive wheat material, obtained either from local landraces of traditional varieties (Rahmatov et al., 2019) or from novel varieties developed through modern breeding, could also contribute to continued low use of chemicals in the Tajik agricultural system, thereby contributing to environmental sustainability. However, the currently grown wheat varieties, and also the breeding lines screened in this study, showed limited levels of resistance, with most of the

TABLE 6 | Resistance and susceptibility levels of Tajik wheat varieties, evaluated in Turkey in the 2013–2014 growing season, to stripe rust (SR), leaf rust (LR), and common bunt (CBUNT).

			Haymana	Adapazari	Eskisehir
#	Variety	Variety origin	SR	LR	CBUNT
1	Navruz	Tajikistan	80S	30MSS	S
2	Surkhak-5688	Tajikistan	80S	70S	S
3	Farhodi	Tajikistan	30MS	30MSS	S
4	Aikt	Tajikistan	20MS	20MSS	S
5	Iz-80	Tajikistan	60S	0	S
6	Shumon	Tajikistan	30MS	10MSS	S
7	Lalmikor 1	Tajikistan	0	0	S
8	Lalmikor 2	Tajikistan	10MS	0	S
9	Zafar	Tajikistan	60S	20MSS	S
10	Alex	Tajikistan	0	20MSS	S
11	Norman	Tajikistan	0-60S	40MSS	S
12	Ormon	Tajikistan	0	30MSS	S
13	Somoni	Tajikistan	80S	40S	S
14	Sadokat	Tajikistan	50S	30S	S
15	Ziroat 70	Tajikistan	70S	5MR	MR
16	Oriyon	Tajikistan	50S	5MS	S
17	Sarvar	Tajikistan	50S	0	MR
18	Yusufi	Tajikistan	20MS	0	S
19	Vahdat	Tajikistan	10MR	0	S
20	Isfara	Tajikistan	30MS	0	S
21	Iqbol	Tajikistan	40MS	30MSS	S
22	Shokiri	Tajikistan	30MS	20MSS	S
23	Fayzbakhsh	Tajikistan	30MS	70S	S
24	Krasnodar 99	Russia	40MS	60S	S
25	Starshina	Russia	0	0	S
26	Lastochka	Russia	50S	0	S
27	Irishka	Russia	30MS	0	S
28	Yesaul	Russia	40MS	10MS	MR
29	Kralya	Russia	10MR-MS	0	S
30	Sila	Russia	10MS	0	S
31	Grom	Russia	40MS	0	S
32	Afina	Russia	20MS	0	S
33	Krassar	Russia	50S	0	S
34	Nota	Russia	40S	0	MR
35	Steklovidnaya 24	Kazakhstan	100S	40MSS	S
36	Tr. Khatti	Turkey	60S	30MSS	S
37	Basribey	Turkey	0	40S	S
38	Jagger 9	USA	20MS	40MSS	S

Reaction to diseases: S, Susceptible; MS, Moderately susceptible; MSS, Moderately susceptible to susceptible; MR-MS, moderately resistant to moderately susceptible; MR, moderately resistant; R, resistant.

widely grown varieties showing no resistance to seed-borne diseases and all showing susceptibility to the three major diseases (**Table 6**), creating a higher risk of severe losses in the event of epidemics. Previous studies have found that home-grown wheat seed in Tajikistan contains high levels of seed-borne disease pathogens and has low protein quality, indicating both low level of resistance and low bread-making quality in the majority of the wheat produced in the country (Husenov, 2018).

Bread is the major staple food in Tajikistan, as confirmed by our finding that most wheat was produced for food purposes (variable 8) (**Table 2**). Wheat material from the national plant breeding program in Tajikistan has better quality properties than home-grown material (Husenov, 2018), although a comparison of current wheat varieties with novel advanced breeding lines found limited signs of improved baking quality (Husenov et al., 2015). Increased wheat yield is essential if bread continues to be the staple food in the Tajik diet. To achieve this, monoculture of wheat should be avoided, and the economic and social sustainability of wheat production should be raised. At present, wheat contributes 60% of the daily calorie intake of the Tajik population, but the country is not self-sufficient in wheat, resulting in Tajikistan ranking highly on the hunger map, while crop monoculture is known to be negative for agricultural sustainability (Braun, 2003; FAO, 2015; WFP, 2017). To increase wheat yield in Tajikistan, the total amount of weeds in wheat fields needs to be decreased. Relatively low amounts of weeds were found in one-third of the wheat fields surveyed here, but in another one-third of fields the weed density was >40%, meaning that the farmer grew almost as much weeds as wheat (variable 14) (**Table 2**). As mentioned above, farmer saved seeds might be one reason for this high weed density. The other reason might be the almost total absence of weed control (variable 10) (**Table 2**). In weed control strategies, the biodiversity of the flora always has to be taken into consideration. Tajikistan is known as one of the "cradles" of weed flora, as it is rich in endemic plants (Nowak et al., 2011, 2013). A high level of biodiversity is a sign of environmental sustainability of the Tajik agricultural system, despite monoculture of wheat. Moreover, the wheat varieties grown has been found to consist largely of variety mixtures of unknown origin (Husenov et al., 2015), thereby contributing to biodiversity in the field. To maintain biodiversity and environmental sustainability in wheat production, while simultaneously reducing weed density for economic and social sustainability reasons, education of farmers is crucial. Farmers need to be educated on coping strategies for maintaining high biodiversity, combined with weed control strategies to reduce weed pressure in production fields and thus sustainably increase yield in Tajik wheat production. Weed management techniques, such as mechanical control and crop rotation, combined with cultivation of allelopathic varieties able to compete with weeds for growing space, may contribute to higher yield, as may use of certified seed or clean seed. Seed breeding programs need to take into consideration novel varieties with specific resistance genes and combine them with locally adapted varieties with certain qualities and possibly also with variety mixtures, to sustain resistance and quality (Husenov, 2018).

A high percentage of the wheat fields surveyed contained >40% weeds (variable 14), of more than 18 different types (**Table S1**), so weed biodiversity is high in these wheat fields, which can be taken as a sign of sustainable wheat production. However, such a heavy weed density is known to reduce wheat yield drastically (e.g., Rasmussen, 2004), which is not socially or economically sustainable from a food security perspective (Smith and Gregory, 2013). Recent studies have shown that landsharing (combining fields for high-yielding crop production

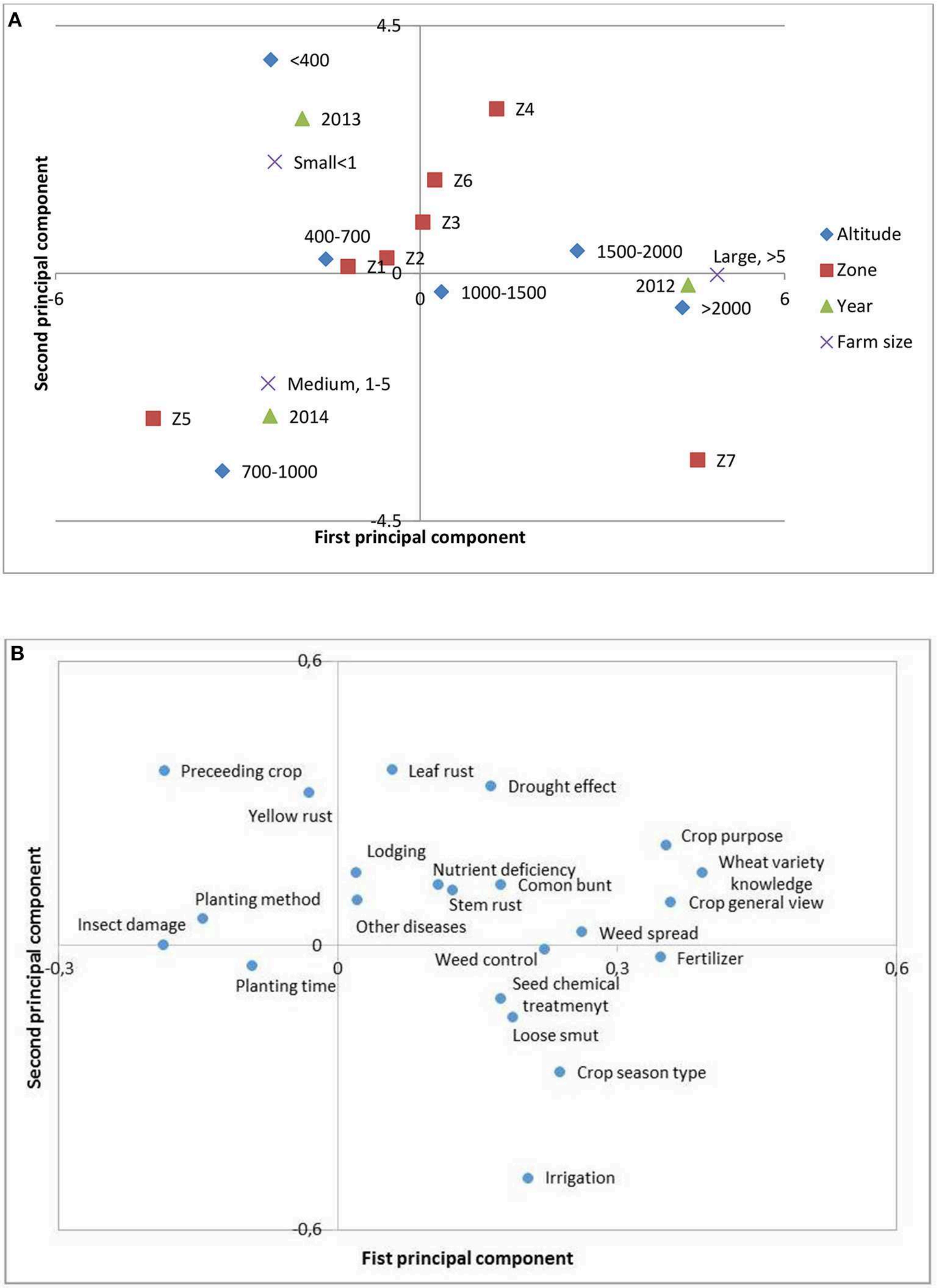

FIGURE 2 | (A) Joint score plot from separate principal component analysis (PCA) of factors evaluated in wheat fields in different years (2012–2014), agricultural zones (ZI-ZVII), altitudes (<400–>2,000 masl), and of different sizes (small<1 ha to large >5 ha), and **(B)** loading plot of variables from PCA of all variables for all factors. The first principal component explained 81% of the variation, while the second principal component explained 18%.

with fields for high biodiversity) can be the most beneficial solution, resulting in high crop production and good biodiversity (Colbach et al., 2018). Lack of crop rotation is another issue hampering sustainability in the Tajik cropping system (Wienhold et al., 2006), despite high biodiversity in the wheat varieties grown (Husenov et al., 2015). Due to lack of land and high demand for wheat from consumers, with wheat contributing 60% of daily calories (Braun, 2003), wheat is often grown in monoculture in Tajikistan, often also using farmer saved, home-grown seeds. Having wheat as the pre-crop for wheat (variable 2) was taken as an indicator of lack of crop rotation in the present study, but these systems were not found to be less sustainable (higher weed density, more diseases, etc.) than those with other pre-crops. Instead, a vague correlation between lack of farmer knowledge and lack of crop rotation was found (**Table 4**). However, the high reliance on wheat for food security might be an increasing risk factor under climate change with an increasing frequency of extreme weather events (Mukamuhirwa et al., 2019) and emergence of novel, highly devastating wheat diseases for which resistance genes are lacking (Rahmatov et al., 2016, 2019). Therefore, a more diversified crop cultivation would be beneficial for increased sustainability and food security in Tajikistan.

Several of the farmers interviewed reported drought problems in their fields and drought effects were observed in 18% of fields (variable 15), despite 73% of the farmers using irrigation (variable 11). Drought effects were observed in both irrigated and rainfed fields, and the reason reported by the farmers was lack of water access, especially in early spring.

The results showed variations in wheat crop performance between years, agricultural zones, altitudes, and farm sizes (**Table 4**). Previous studies have found larger farms to be more business-driven, with more commercial production and a more positive attitude to use of machinery, inputs such as pesticides, and high-tech solutions, e.g., genetically modified crops (Ahmed et al., 2011; Azadi et al., 2016). In the present study, larger farms were found to use more machinery (**Tables 2**, **4**), but the farmers concerned did not have higher knowledge of e.g., what variety they were using and were not more successful in wheat production (**Tables 2**, **4**), confirming earlier findings (Calviño and Sadras, 2002). Variations in crop production with agricultural zone and altitude are well-known from previous studies (Clay and Dejaegher, 1987; Hailu et al., 2010) and were confirmed in the present study. **Figure 2** summarizes differences in measured variables by year of study, agricultural zone, altitude, and farm size, applying a PCA. As seen, the studied farms in ZI-ZII seemed to share some characteristics; they were generally small and situated <700 masl (**Figure 2A**), but similarities in cultivation issues were more difficult to find. Instead, altitude of the farm seemed more relevant, with common features for farms situated <700 masl being more common use of technical crops as preceding crops, low knowledge among farmers, production of wheat for food purposes, visible effects of drought despite use of irrigation, and low levels of loose smut and stripe rust in wheat fields (**Figure 2B**). Zones ZV and ZVII were found to have the most deviating features. In ZV, farms were in general of medium size and situated at 700-1000 masl (**Figure 2A**), and were characterized by the highest amount of knowledge among farmers, the lowest weed density in fields, and the greatest area of winter wheat, sown using machinery and for seed purposes (**Figure 2B**). In ZVII, the farms were situated at >2,000 masl (**Figure 2A**) and farmers used hand broadcasting for sowing spring wheat at the optimal time (**Figure 2B**). The wheat was grown for food, irrigation was used, and lodging was a problem (**Figure 2B**). Variations between years found in this study could be partly explained by the farmers' fields being selected independently for survey in each year, i.e., they were not the same over the years. However, other studies (e.g., Calviño and Sadras, 2002; Verón et al., 2004) have shown an impact of various constraints on yearly variations in yield. The variation over years for the different variables evaluated in this study might be the result of weather variations or outbreak of diseases etc., apart from the effect of farm selection.

As shown in previous studies (Sadras et al., 2002; Pretty et al., 2003), we found that improved farming practices, including knowledge of the farmer, use of a suitable variety, use of fertilizer, weed control, and irrigation, contributed to a healthier crop (**Table 2**), which is known to correlate with increased yield. Resistance genes to the major diseases were in principle lacking in the Tajik wheat material screened here (**Table 6**). Among the five most widely grown wheat varieties in 2011 (Krasnodar 99, Basribey, Starshina, Lastochka, and Steklovidnaya 24) (see **Table 3**), together representing about 57% of the area under wheat (Muminjanov et al., 2016), two varieties (Krasnodar 99 and Steklovidnaya 24) showed high susceptibility to all three diseases tested, while the others were susceptible to one or more of these diseases. Breeding tolerant varieties that are also competitive to weeds has not even started. Strategies to secure biodiversity and simultaneously increase yield with continuous low chemical input are in place to a limited extent. Thus, our results clearly show that, to increase sustainable wheat production in developing countries, where Tajikistan can be seen as an example, concerted action is urgently needed, with education of farmers and suitable incentives for steering the development of farming systems in a sustainable direction being of critical importance.

CONCLUSIONS

Three key major constraints to sustainable high-yielding wheat production in Tajikistan were identified: (i) lack of knowledge among farmers (lack of knowledge about variety grown, correlating with lack of crop rotation and poor crop performance); (ii) lack of use of certified seed and resistant varieties in production (lack of crop knowledge, related to use of saved seeds and lack of resistance in wheat varieties grown); and (iii) lack of suitable management systems, in particular for weeds (co-production of wheat and weeds, and no weed management). Differences in wheat production also arose from variations in cropping practices between regions (zones), altitudes, and farms of different sizes, and from selection of different farms for survey in different years, but these variations were lower than those caused by the three key factors.

A combination of greater knowledge among farmers, use of certified seed and resistant varieties, and suitable weed management could contribute to higher yield and increased social and economic sustainability (higher yield of the main staple, contributing to less hunger). Increased wheat yield would improve the chances of Tajikistan becoming self-sufficient in wheat, the staple food of the country, reduce hunger among local people, and provide opportunities to grow other crops to support the household with food, which might lead to a change from wheat monoculture to a more diverse system. Higher yield might also create economic opportunities for actions to secure high biodiversity in e.g., weed species in the country. Sustainable weed management techniques, such as crop rotation, tolerant wheat varieties, and e.g., landsharing, need to be developed for the country to secure the current high biodiversity and limit chemical solutions.

Thus, to secure sustainability (environmental, economic, and social), the Agriculture Authority of Tajikistan needs to educate farmers in wheat production, make certified seed widely available, and develop suitable weed management systems, while also maintaining high biodiversity.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

BH, EJ, and HM planned the study, the hypothesis, and the objectives. BH and SA developed the questionnaire. BH and MO conducted the survey, with guidelines by AM and SA. AM assisted in screening of varieties in Turkey. BH, EJ, and LG-G evaluated the results. EJ and HM provided overall coordination for the project. BH drafted the manuscript, together with LG-G. All authors contributed to manuscript improvement, read, and approved the final manuscript.

FUNDING

This study was part of Ph.D. work of BH, with major contribution received from Swedish International Development and Cooperation Agency (Sida). MO participation in the surveillance was supported by the FAO.

ACKNOWLEDGMENTS

The authors would like to thank all the farmers surveyed for opening up their farms to this investigation and for their time for answering the questions, colleagues in Turkey for helping with screening for major diseases, and Mary McAfee for a thorough language editing of the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2020.00027/full#supplementary-material

REFERENCES

Ahmed, N., Englund, J. -E., Åhman, I., Lieberg, M., and Johansson, E. (2011). Perception of pesticide use by farmers and neighbors in two periurban areas. *Sci. Total Environ*. 412, 77–86. doi: 10.1016/j.scitotenv.2011.10.022

Amelework, A., Shimelis, H., Laing, M. D., Ayele, D. G., Tongoona, P., and Mengistu, F. (2016). Sorghum production systems and constraints, and coping strategies under drought-prone agro-ecologies of Ethiopia. *S. Afr. J. Plant Soil*. 33, 207–217. doi: 10.1080/02571862.2016.1143043

Azadi, H., Samiee, A., Mahmoudi, H., Jouzi, Z., Rafiaani Khachak, P., de Maeyer, P., et al. (2016). Genetically modified crops and small-scale farmers: main opportunities and challenges. *Crit. Rev. Biotechnol.* 36, 434–446. doi: 10.3109/07388551.2014.990413

Babushkin, L. N. (1964). Agro-climatic description of Middle Asia (Agroclimaticheskoe opisanie Sredney Azii). *Scientific Works of Tashkent State University. Geogr. Sci.* 236.

Bouwmeester, H., Heuvelink, G., and Stoorvogel, J. (2016). Mapping crop diseases using survey data: the case of bacterial wilt in bananas in the East African highlands. *Eur. J. Agron.* 74, 173–184. doi: 10.1016/j.eja.2015.12.013

Boyer, R. H. W., Peterson, N. D., Arora, P., and Caldwell, K. (2016). Five approaches to social sustainability and an integrated way forward. *Sustainability* 8:878. doi: 10.3390/su8090878

Braun, H. J. (2003). *FAO-Database: Daily Calories Intake From Wheat in Different Countries and Regions*. CIMMYT.

Calviño, P., and Sadras, V. (2002). On-farm assessment of constraints to wheat yield in the south-eastern pampas. *Field Crops Res.* 74, 1–11. doi: 10.1016/S0378-4290(01)00193-9

Clay, D., and Dejaegher, Y. (1987). Agro-ecological zones: the development of a regional classification. *Tropicultura* 5, 153–159.

Colbach, N., Cordeau, S., Garrido, A., Granger, S., Laughlin, D., Ricci, B., et al. (2018). Lansharing vs landsparring: how to reconcile crop production and biodiversity? A simulation study focusing on weed impacts. *Agric. Ecosyst. Environ.* 251, 203–217. doi: 10.1016/j.agee.2017.09.005

Constanzo, A., and Bàrberi, P. (2014). Functional agrobiodiversity and agrosystem services in sustainable wheat production. a review. *Agron. Sustain. Dev.* 34, 327–348. doi: 10.1007/s,13593-013-0178-1

FAO (2015). *The State of Food Insecurity in the World*. Rome: FAO.

FAO-REU (2016). "Wheat production and regional food security in CIS: the case of Belarus, Turkeminstan and Uzbekistan," in *FAO Regional Office for Europe and Central Asia, Policy Studies on Rural Transition*, eds Z. Lerman, D. Sedik, Y. Yusupov, I. Stanchin, and I. Kazakevich (Budapest: FAO), 140.

Fauna and Flora International (2019). Available online at: https://www.fauna-flora.org/countries/tajikistan (accessed December 17, 2019).

Giuliani, A., van Oudenhoven, F., and Mubalieva, S. (2011). Agricultural biodiversity in the Tajik Pamirs. *Mt. Res. Dev.* 31, 16–26. doi: 10.1659/MRD-JOURNAL-D-10-00109.1

Hailu, F., Johansson, E., and Merker, A. (2010). Patterns of phenotypic diversity for phenologic and qualitative traits in Ethiopian tetraploid wheat germplasm. *Genet. Resour. Crop Evol.* 57, 781–790. doi: 10.1007/s10722-009-9518-z

Husenov, B. (2018). *Towards an Impact on Food Security for Tajikistan.* Alnarp: The Swedish University of Agricultural Sciences (SLU).

Husenov, B., Asaad, S., Muminjanov, H., Garkava-Gustavsson, L., Yorgancillar, A., and Johansson, E. (2017). Evaluation and managing wheat seed-borne diseases: options and suggestions from the case of Tajikistan. *Cereal Res. Commun.* 45, 124–138. doi: 10.1556/0806.44.2016.045

Husenov, B., Makhkamov, M., Garkava-Gustavsson, L., Muminjanov, H., and Johansson, E. (2015). Breeding for wheat quality to assure food security of a staple crop: the case study of Tajikistan. *Agri. Food Secur.* 4:8. doi: 10.1186/s40066-015-0029-1

Hussain, A., Larsson, H., Kuktaite, R., and Johansson, E. (2010). Mineral composition of organically grown wheat genotypes: contribution to daily minerals intake. *Int. J. Environ. Res. Public Health* 7, 3442–3456. doi: 10.3390/ijerph7093442

Hussain, A., Larsson, H., Kuktaite, R., and Johansson, E. (2012). Healthy food from organic wheat: choice of genotypes for production and breeding. *J. Sci. Food Agric.* 92, 2826–2832. doi: 10.1002/jsfa.5665

Imadi, S. R., Shazadi, K., and Gul, A. (2016). "Sustainable crop prduction system," in *Plant, Soil, and Microbes,* eds K. Hakeem, M. Akhtar, and S. Abdullah (Cham: Springer), 103–116. doi: 10.1007/978-3-319-274 55-3_6

Litvinov, V. N., Chugunnikov, N. I., Mazur, K. K., and Loshkareva, A. F. (1964). *Cultivation Recommendations of Cereals and Legume Crops in Tajik SSR (In Russian)*. Dushanbe: Irfon.

Mahmadyorov, U. M. (2007). *Scientific justification of growing cereals and legumes as a second crop in irrigated lands of Central Tajikistan (In Russian)* (Ph. D. dissertation). Dushanbe: Tajik Agrarian University.

Moreira-Ascarrunz, S. G., Larsson, H., Prieto-Linde, M. L., and Johansson, E. (2016). Mineral nutritional yield and nutrient density of locally adapted wheat genotypes under organic production. *Foods* 5:89. doi: 10.3390/foods5040089

Mukamuhirwa, A., Persson Hovmalm, H., Bolinsson, H., Ortiz, R., and Johansson, E. (2019). Concurrent drought and temperature stress in rice - a possible result of the predicted climate change: effects on yield attributes, eating characteristics, and health promoting compounds. *J. Environ. Res. Public Health* 16:1043. doi: 10.3390/ijerph16061043

Muminjanov, H. (2008). *State of Plant Genetic Resources for Food and Agriculture (PGRFA) in the Republic of Tajikistan*. Country Report. FAO. Available online at: http://www.fao.org/pgrfa-gpa-archive/tjk/Tajikistan2.pdf

Muminjanov, H., Otambekova, M., and Morgounov, A. (2016). "The history of wheat breeding in Tajikistan," in *The World Wheat Book,* eds A. Bonjean and W. Angus (Paris: Lavoisier), 283–309.

Muminov, M. M. (2009). *Organizational and economical aspects of increasing efficiency of cereal seed production: based on materials of Tajikistan seed farms (In* Russian) (Ph. D. thesis). Dushanbe: Tajik Agrarian University.

Murphy, K. M., Dawson, J. C., and Jones, S. S. (2008). Relationship among phenotypic growth traits, yield and weed suppression in spring wheat landraces and modern cultivars. *Field Crops Res.* 105, 107–115. doi: 10.1016/j.fcr.2007.08.004

Nowak, A., Nowak, S., and Nobis, M. (2011). Distribution patterns, ecological characteristic and conservation status of endemic plants of Tadzhikistan–a global hotspot of diversity. *J. Nat. Conserv.* 19, 296–305. doi: 10.1016/j.jnc.2011.05.003

Nowak, S., Nowak, A., Nobis, M., and Nobis, A. (2013). Weed vegetation of cereal crops in Tajikistan (Pamir Alai Mts., Middle Asia). *Phytocoenologia* 43, 225–253. doi: 10.1127/0340-269X/2013/0043-0557

Oerke, E.-C. (2006). Crop losses to pests. *J. Agri. Sci.* 144, 31–43. doi: 10.1017/S0021859605005708

Park, R., Fetch, T., Hodson, D., Jin, Y., Nazari, K., Prashar, M., et al. (2011). International surveillance of wheat rust pathogens: progress and challenges. *Euphytica* 179, 109–117. doi: 10.1007/s10681-011-0375-4

Pett, B., and Muminjanov, H. A. (2006a). *The Main Diseases and Insects of Wheat in Tajikistan and the Ways of Their Control (In Russian)*. Dushanbe: GTZ-CIMMYT.

Pett, B., and Muminjanov, H. A. (2006b). *Weeds of Tajikistan and they management (In Russian: Sornye rasteniya Tadzhikistana i mery borby s nimi)*. Dushanbe: MMK.

Pett, B., Muminjanov, H., and Morgounov, A. (2006). Monitoring of wheat diseases and pests in Tajikistan in 2004. *Agromeridian Theor. Appl. Agric. Res. J.* 1, 43–48.

Pretty, J. N., Morison, J. I., and Hine, R. E. (2003). Reducing food poverty by increasing agricultural sustainability in developing countries. *Agric. Ecosyst. Environ.* 95, 217–234. doi: 10.1016/S0167-8809(02)00087-7

Purvis, B., Mao, Y., and Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. *Sustain. Sci.* 14, 681–695. doi: 10.1007/s11625-018-0627-5

Rahmatov, M., Husenov, B., Otambekova, M., Makhkamov, M., Eshonova, Z., Soliev, B., et al. (2010). Results of investigations on wheat breeding in Tajikistan (in Russian). *News Acad. Sci. Republic of Tajikistan (Dep. Biol. Med. Sci.)* 3, 71–82.

Rahmatov, M., Otambekova, M., Muminjanov, H., Rouse, M. N., Hovmoller, M. S., Nazari, K., et al. (2019). Characterization of stem, stripe and leaf rust resistance in Tajik bread wheat accessions. *Euphytica* 215:55. doi: 10.1007/s10681-019-2377-6

Rahmatov, M., Rouse, M. N, Steffenson, B. J., Andersson, S. C., Wanyera, R., Pretorius, Z. A., et al. (2016). Sources of stem rust resistance in wheat-alien introgression lines. *Plant Dis.* 100, 1101–1109. doi: 10.1094/PDIS-12-15-1448-RE

Rashidov, K. A. (2009). *Productivity of advanced wheat varieties under the bed planting in Central Tajikistan (In Russian)* (Ph.D. thesis). Dushanbe: Tajik Agrarian University.

Rasmussen, I. A. (2004). The effect of sowing date, stale seedbed, row width and mechanical weed control on weeds and yields of organic winter wheat. *Weed Res.* 44, 12–20. doi: 10.1046/j.1365-3180.2003.00367.x

Sadras, V., Roget, D., and O'Leary, G. (2002). On-farm assessment of environmental and management constraints to wheat yield and efficiency in the use of rainfall in the Mallee. *Crop Pasture Sci.* 53, 587–598. doi: 10.1071/AR01150

Saidmuradov, H., and Stanyukovich, K. (1982). *Tajikistan: the Nature and Natural Resources.* Dushanbe: Tajikistan Publishing house "Donish."

SAS (2011). *"SAS Institute Inc 9.3"*. Cary, NC: SAS Institute Inc.

Savary, S., Ficke, A., Aubertot, J.-N., and Hollier, C. (2012). Crop losses due to diseases and their implications for global food production losses and food security. *Food Sec.* 4, 519–537. doi: 10.1007/s12571-012-0200-5

Schmidt, S. B., George, T. S., Brown, L. K., Booth, A., Wishart, J., Hedley, P.E., et al. (2019). Ancient barley landraces adapted to marginal soils demonstrate exceptional tolerance to manganese limitation. *Ann. Bot.* 20, 831–843. doi: 10.1093/aob/mcy215

SCVT (2011). *National Catalogue of Plant Varieties and Hybrids Accepted for Use in the Territory of Tajikistan (official issue)*. Dushanbe: Ministry of Agriculture of the Republic of Tajikistan, State Entity "State commission on plant variety testing and variety protection" (SCVT).

Sikharulidze, Z., Natsarishvili, K., Dumbadze, R., Mgeladze, L., and Tsetskhladze, T. (2015). Monitoring of Cereal rusts in Georgia in 2009–2013. *Biol. Forum* 7, 721–725.

Smith, P., Gregory, P. J. (2013). Climate change and sustainable food production. *Proc. Nutr. Soc.* 72, 21–28. doi: 10.1017/S0029665112002832

TajStat (2018). *Agriculture of the Republic of Tajikistan.* Statistical Yearbook. Dushanbe: Agency on Statistics under the President of the Republic of Tajikistan.

UNESCO (2019). Available online at: https://unesdoc.unesco.org/ark:/48223/pf0000230508 (accessed December 20, 2019).

UNICEF (2019). Available online at: https://www.unicef-irc.org/article/945-end-extreme-poverty-increase-environmental-sustainability.html (accessed December 20, 2019).

Verón, S. R., Paruelo, J. M., and Slafer, G. A. (2004). Interannual variability of wheat yield in the Argentine pampas during the 20th century. *Agric. Ecosyst. Environ.* 103, 177–190. doi: 10.1016/j.agee.2003.10.001

Waddington, S. R., Li, X., Dixon, J., Hyman, G., and de Vicente, M. C. (2010). Getting the focus right: production constraints for six major food crops in Asian and African farming systems. *Food secur.* 2, 27–48. doi: 10.1007/s12571-010-0053-8

WFP (2017). *World Food Programme (WFP) Hunger Map 2017*. Available online at: https://www.wfp.org/publications/2017-hunger-map (accessed December 12, 2018).

Wienhold, B. J., Pikul, J. L., Liebig, M. A., Mikha, M. M., Varvel, G. E., and Doran, J.W. (2006). Cropping system effects on soil quality in the Great Plains: synthesis from a regional project. *Renew. Agr. Food Syst.* 21, 49–59. doi: 10.1079/RAF2005125

Wold, S., Esbensen, K., and Geladi, P. (1987). Principal component analysis. *Chemom. Intell. Lab. Syst.* 2, 37–52. doi: 10.1016/0169-7439(87)80084-9

Zadoks, J., Chang, T., and Konzak, C. (1974). A decimal code for the growth stages of cereals. *Weed Res.* 14, 415–421. doi: 10.1111/j.1365-3180.1974.tb01084.x

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.