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Regional variability in leaf rust infestation across the Hindukush region of Pakistan as revealed through a four years surveillance effort made during 2019 to 2022

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Abstract

Despite the importance of leaf rust disease across Pakistan, limited information is available regarding its status in the Hindukush region of Pakistan. This study was designed to investigate the disease status in the region through the surveillance effort made during 2019 to 2022. The surveillance was comprised of 25 districts across four different regions viz: Peshawar Valley (5 districts), Southern Hindukush (7 districts), Western Hindukush (7 districts), and Northern Hindukush (6 districts). Although the disease observed was very low, it varied over years and across the different geographical locations. The incidence of the disease was high in Southern Hindukush (8% fields infected) and Peshawar Valley (4% fields), while the disease was observed with low frequency in Western Hindukush (1% fields) and Northern Hindukush (0% fields). The disease was observed in the maximum fields during 2022 (5%), followed by 2020 and 2021 (each with only 3% infected fields), while the disease was not observed during 2019. The average co-efficient of leaf rust infection was recorded the maximum for local land races (7.3), while it was found the minimum for most of the surveyed varieties (0.0). Although most of the recently developed varieties were observed with no leaf rust, sporadic appearance was observed on some host varieties like Pirsabak-2005, Pirsabak-2013 and Shahkar-2013. The overall low co-efficient of infection for the surveyed varieties could be either due to resistance in these varieties or the lack of favorable environmental conditions for the disease development. The information provided in the study could help breeders in identifying desirable wheat lines while considering the prevalence of the disease in the region.

Introduction

Wheat is a staple food crop cultivated on more than 220 million hectares of the cultivable land around the world with the total production of 781.31 million metric tonnes per annum (Petrescu-Mag and Burny, 2023). Though wheat is grown on large areas in Pakistan, it has low overall yield. The production is sufficient to feed the present populations but might not be sufficient to fulfill the demands of the future generations. The population of the world could be projected to 7.9 billion by 2025 and will touch 9.7 billion by 2050 (Siegel, 2021). To feed such huge population the production should reach 140 million tonnes by 2050 (Singh et al., 2023). Several environmental factors are responsible for limiting wheat production and productivity like drought stress, heat stress, insect pests and diseases etc. Among the diseases, rusts prevail in most wheat growing areas thereby threatening wheat production (Aslam et al., 2026; Ali et al., 2014a; Singh et al., 2016). Wheat production can be enhanced either through management of wheat diseases or the use of appropriate cultural practices to reduce the losses (Ali et al., 2023). Wheat is host to different diseases caused by fungi, viruses and bacteria; however, the three rusts are of significant interests among the diseases (Ali et al., 2023). In early 20th century the widespread epidemics of wheat rusts provided insights to the advancement in understanding pathogen epidemiology, disease resistance and plant pathogen interactions. But still the sustainable wheat production is highly threatened by rusts causing huge losses worldwide (Kashyap et al., 2021)).

Among the three rusts, leaf rust that is caused by *Puccinia triticina* Erikss. (Huerta-Espino et al., 2011; Wang *et al*., 2016) that prevails in the mild to warm climatic conditions, therefore distributed extensively in the wheat basket of Asia. *Puccinia triticina* Erikss. is adapted to a wide range of environments (McCallum et al., 2016). The favorable condition for leaf rust to infect wheat plants must possess high relative humidity with a temperature range of 15-22^{0}C with optimum temperature for spore's development is 20^{0}C for only 6–8 h for the development of the disease. It threatens wheat production causing huge losses in regions where environmental conditions are favorable (Carpenter, 2018). It has the potential to threaten the yield of wheat up to 10% as compared to black rust and yellow rust. The severity of the disease depends upon the developmental stage of the plant and susceptibility of the plant (Duplessis, et al., 2021).

Puccinia triticina Erikss. is a heteroecious fungus with macrocyclic life cycle. Its sexual and asexual stages of life cycle are completed in two separate hosts. Its life cycle consists of five different spore stages. The fungi form dark brown, diploid teliospores on the surface of a leaf, which undergo meiosis upon germination to produce haploid basidiospores under the correct conditions. Because the wind transports these basidiospores to distant areas, they require a different host to produce haploid pycnials during germination (Bolton et al., 2008). Alternate hosts of *Puccinia triticina* Erikss. include clematis, thalictrum, isopyrum, anchusa, and barberry. In contrast to cells that develop plasmogamy, the pathogen produces pycniospores that are transported by insects and sexually propagate into two after infection with a different host. The wind transport aeciospores, which are formed in aecia. When aeciospores mature into asexual urediniospores and cause obvious symptoms on the host plant, the life cycle is completed. External symptoms include circular or slightly oval pustules that do not mix in and are smaller than stem rust. These pustules are filled with urediniospores ranging in color from brown to orange that appears on the upper leaf surface. All five spore types are produced during sexual or asexual reproduction. Urediospores are responsible for asexual reproduction. They go through numerous stages and grow haustoria, which they use to take nutrients from the host plant. It also aids in the growth and germination of fungi and inhibits the plant defense mechanism (Ramachandran et al., 2017). The ideal temperature range for the disease to develop is 10 to 25°C, and prolonged exposure to free moisture on the leaf surface aids in the spread of disease. If suitable conditions are present, the uredinial cycle repeats every 8 to 14 days. While pycniospores and aeciospores are formed on the alternate host, urediniospores, teliospores, and basidiospores are produced on wheat. Teliospores are formed near the end of the season that aids in overwintering of the pathogen and serve as a source of inoculum for the next season. The spores germinate on wheat by themselves and infect the plant. *Puccinia triticina* Erikss. produces 1.5 mm-diameter pustules with about 20,000 spores during the mature phases of development.

Epidemics have been observed in many parts of the world, causing yield losses of up to 50% (Marasas et al., 2004), however, higher yield losses have been reported associated with early infection of leaf rust (Huerta-Espino et al., 2011). The losses estimated in the United Kingdom due to leaf rust and yellow rust were £83 million in some years (Bouvet et al., 2022). In Tunisia and Egypt, the estimated yield losses of 30% to 50% have been reported (Anriquez et al., 2021). In USA losses of $350 million have been reported from 2000 to 2004 (Haque et al., 2021). Singh et al., (2004a) reported yield losses worth $32 million in Mexico during 2000–2003. In Argentina, losses of US$74 million have been reported associated with epidemics that occurred between1999 and 2003 (Abebe, 2021). In Russia, 18 to 25% of yield losses occurred in 2009 (Volkova et al., 2009). Germa´n et al., 2004 reported $172 million losses from 1996 to 2003 in South America. The yield loss of 75% have been reported in the hot spot areas of Ethiopia (Gadisa, 2019; Habtamu et al., 2020). The disease affects more than half of China's wheat production and commercial wheat fields often lose 10% to 30% of their crop yield (Huerta-Espino et al. 2011). The 1980 leaf

rust epidemics in India were believed to have resulted in a loss of one million metric tons (Joshi et al., 1986). In Pakistan, the national financial loss reported for leaf rust was US$ 86 million in 1978 (Hussein et al., 1980). Punjab's wheat harvest is being threatened by leaf rust and it is also becoming alarming in the northern areas of KP due to the changing climatic conditions (Khan et al., 2021). At a severe level, it can cause up to 50% yield losses (Ahmad et al. 2010).

Considering the impact of leaf rust on wheat production, it is important to control the disease which can be accomplished either by the application of fungicides or by the development of resistant varieties to the disease (Kashyap et al., 2025). However, chemical control has limitations of its own, including high cost and environmental issues; so, developing resistant cultivars could be the most suitable option (Ali et al., 2009a; Paillard et al., 2012; de Vallavieille-Pope et al., 2012; Singh et al., 2016; Chen, 2020). The development and deployment of resistant varieties could be done on continuous basis while considering the potential invasion of the pathogen (Bhardwaj et al., 2021). More than 80 leaf rust resistant (Lr) genes have been discovered distributed on all the 21 wheat chromosomes (Kumar et al., 2022). Deployment of these resistant genes into wheat genotypes requires the knowledge of distribution of the disease in different geographical areas.

Although several studies have documented the distribution of leaf rust at the national level in Pakistan, information on the disease status in the Pakistan-Afghanistan bordering Hindukush region remains limited (Ali et al., 2012). The Hindukush region is mostly inhabited by the tribal population and remained an inaccessible area due to its security situation. During the period of 2018 to 2022, the situation ameliorated due to changes in government policies, which enabled to make a comprehensive survey in the region to assess the status of leaf rust in the Hindukush region. Previous nationwide surveillance efforts primarily focused on identifying broad regional disease patterns and did not provide a detailed epidemiological assessment of the diverse agroecological conditions characteristics of the Hindukush region. Consequently, the current distribution, intensity and spatial variability of the disease in this strategically important wheat production region remain insufficiently understood.

The present study addresses this knowledge gap by conducting a comprehensive field-based surveillance to assess the relative distribution of wheat leaf rust in different geographical areas in the Hindukush region of Pakistan during the four cropping seasons (2019–2022). By generating region specific baseline data on disease incidence, severity and spatial distribution, this study provides valuable information for strengthening regional disease surveillance, guiding the deployment of resistant cultivars and supporting the development of disease management strategies under the changing environmental conditions. The primary purpose of the study was to assess the relative importance of wheat leaf rust in major wheat growing regions of Hindukush region with specific objectives: i). to evaluate the status of leaf rust across different locations in the Hindukush region of Pakistan. ii). to assess the status of the disease on different host varieties in farmers' fields in the study area.

MATERIALS AND METHODS

Study Area

Afghanistan

This study was conducted in the different wheat growing regions of the Hindukush Pakistan, characterized by semi-arid climate and fertile soils. The region was selected for the study due to its significant contribution to national wheat production and has recently experienced an alarming increase in leaf rust incidence. In the current study, a total of 25 districts were surveyed in the Hindukush regions of KP over the four years surveillance made during 2019–2022. The districts covered in Peshawar Valley included Nowshera, Charsadda, Mardan, Peshawar and Swabi (34.00^0 N, 71.51^0 E to 34.19^0 N, 72.04^0 E). The districts of Bajaur, Mohmand, Khyber, Lower Kurrum, Upper Kurrum, North Waziristan and South Waziristan were surveyed in the Western Hindukush region (32.32^0 N, 69.85^0 E to 34.73^0 N, 71.51^0 E). The districts of Lower Dir, Upper Dir, Malakand, Swat, Buner and Shangla were covered from Northern Hindukush region (34.39^0 N, 72.61^0 E to 35.33^0 N, 72.04^0 E). In the Southern Hindukush, Bannu, DI Khan, Karak, Kohat, Lakki Marwat, Hangu, Dara Adam Khel and Tank (31.74^0 N, 70.62^0 E to 33.58^0 N, 71.44^0 E) were covered during the study (Z.-U. Rehman et al., 2025). Further details of the studied districts are given in Fig. 1 & the Supplementary Table S1.

Figure 1. Map of Khyber Pakhtunkhwa showing the districts surveyed in the Hindukush regions of Pakistan over the four years surveillance made in 2019-22.

Surveillance of wheat leaf rust and the disease scoring:

Surveillance for leaf rust scoring was carried out in Farmers fields and experimental plots in different geographical districts in the Hindukush region of Khyber Pakhtunkhwa (KP) Pakistan during the peak of leaf rust infection (March-April) over the four years surveillance made during 2019–2022. A total of 25 districts were covered over the four years disease scoring in four distinct regions viz Peshawar Valley, Western Hindukush, Northern Hindukush and Southern Hindukush of Pakistan. Within each district, farmers' wheat fields were randomly selected and successive sampling sites were maintained at approximately 10–20 km intervals, depending on the presence of wheat fields to ensure broad geographical coverage and minimize spatial sampling bias (Rehman et al., 2025). This sampling strategy was adopted to obtain a representative assessment of leaf rust distribution across the surveyed region. During field surveys, information on wheat varieties cultivated in each studied location was recorded in order to describe varietal distribution and assess its relationship with the occurrence of leaf rust. The major varieties surveyed were the commercial wheat varieties including some local land races and triticale (Fig. 2). However, some introduced wheat varieties were also observed particularly in experimental wheat trials conducted in Peshawar, Nowshera and Swabi.

Disease assessments were performed using a standardized protocol. In each selected field, wheat plants were inspected for leaf rust symptoms and disease scores were made visually using two parameters i.e., disease severity and host reaction following the standard protocol of Ali and Hodson (2017) and Ali et al. (2025). The severity of the disease (percentage leaf area infected) was recorded using Modified Cobb (0-100) scale (Peterson et al., 1948).

Simultaneously the host response was recorded according to the standard infection response categories. Host reaction types recorded were in the type S (susceptible), MS (moderately susceptible), MRMS (moderately resistant-moderately susceptible), MR (moderately resistant) and R (resistant; Table 1). Disease severity and host reaction were evaluated together for each field and the same assessment procedure was consistently applied across all the surveyed locations and years to ensure reliable and comparable disease estimates (Iqbal et al., 2023).

Table 1
Modified Cobb's scale used for data recording during the wheat seasons of 2019–2022

Reaction	Code	Field response
susceptible	S	Large uredia and little or no chlorosis present.
Moderately Susceptible- Susceptible	MSS	Medium uredia with no necrosis but possible some distinct chlorosis as well as large uredia with little or chlorosis present
Moderately Susceptible	MS	The medium uredia with no necrosis but possible some distinct chlorosis
Moderately resistant, moderately susceptible	MRMS	The minute uredia present surrounded by necrotic areas as well as medium uredia with no necrosis but possible some distinct chlorosis
Moderately Resistant	MR	Small uredia present surrounded by necrotic area
Resistant	R	Necrotic areas with or without minute uredia
Immune	0	No visible infection

Calculation of the average coefficient of infection (ACI)

The surveillance data collected was put in MS Excel file for further analysis. The data was analyzed in MS Excel program. The coefficient of infection was determined by using the formula

Coefficient of infection = disease severity * incremental value

Remember each infection type has its own incremental value proposed by Pathan and Park, (2007) and Saari and Wilcoxson, (1974). The average coefficient of infection was determined by taking average of the CI values.

Fields surveyed in the Hindukush region of KP, Pakistan

During wheat disease surveillance a total of 1145 fields were surveyed covering 25 districts in different regions of KP over the four wheat growing years in 2019–2022. Among the total 1145 fields, 66 fields were surveyed in Peshawar, Swabi (69), Nowshera (64), Mardan (15), while only 10 fields were covered in Charsadda. In the Western Hindukush, a total of 132 fields were surveyed in Bajaur, Khyber (24), Lower Kurrum (34), Mohmand (63), South Waziristan (10), North Waziristan (56) and Upper Kurrum (53). In Northern Hindukush, 66 fields were surveyed in Buner, Lower Dir (68), Malakand (18), Swat (51), Upper Dir (74) and Shangla (21). In Southern Hindukush a total of 41 fields were surveyed in Bannu, Hangu (37), Kohat (57) and Tank (33) DI Khan (37), Karak (21) and Lakki Marwat (25; Supplementary Table S2).

RESULTS

Status of leaf rust in the Hindukush region of Pakistan

Wheat leaf rust varied across locations and over years. Considering the disease status in all the four years, the leaf rust incidence was found the maximum in 8% fields in Southern Hindukush followed by Peshawar Valley (3.0% fields), while the minimum (0.0%) fields in Northern Hindukush followed by Western Hindukush (1.0% fields).

Considering the within year variations, leaf rust incidence was low in the studied regions as maximum observed was only in 5.0% fields during 2022 in which only 2% fields were found with high disease (> 50% severity), while the disease was absent during 2019 followed by 2020 and 2021 (each with only 3.0% infected fields). However, the disease was observed with high severity in 1.0% fields during 2020 only. The disease was found the maximum in 2.0% fields during 2019 in Northern Hindukush only. During 2020, the disease was found the maximum in 9.0% fields at Southern Hindukush where 5.0% fields were detected with high disease, while the disease was observed in only 1.0% fields in Western Hindukush, however none of the fields were found infected in Peshawar Valley and Northern Hindukush regions. The disease was detected in 11.0% and 1.0% fields in Peshawar Valley and Western Hindukush respectively during 2021, while in 2022, the disease was found the maximum in 17% fields in Southern Hindukush where 6.0% fields were found with high disease (Table 2 & Fig. 3).

Mean leaf rust severity (%) across different regions of KP

The results were further confirmed by the mean leaf rust severity (%) and co-efficient of infection. Considering the overall mean leaf rust severity over the four years, the mean leaf rust severity was found the maximum for Southern Hindukush (2.1%) followed by Peshawar Valley (0.2%), while it was found the minimum for Northern Hindukush and Western Hindukush (0.0% each).

Considering the within year variations, the mean leaf rust severity was found the maximum (1.0%) during 2022 followed by 2020 (0.8%), while the minimum (0.0%) during 2019 followed by 2021 (0.2%). The region wise distribution of leaf rust showed the maximum mean severity of 0.2% for Northern Hindukush during 2019, while it was found the minimum (0.0%) for the other three regions. During 2020, the severity was found the maximum (3.3%) for Southern Hindukush only. During 2021, the severity was observed the maximum for Peshawar Valley (0.7%), while the minimum for Northern Hindukush and Southern Hindukush (0.0% each) followed by Western Hindukush (0.1%). The mean leaf rust severity was observed the maximum at Southern Hindukush (4.0%), while the minimum (0.0%) for the other three regions during 2022 (Fig. 4 & Table 3).

Leaf rust co-efficient of infection

The co-efficient of infection for leaf rust was also determined using disease severity and host response values. Considering the all four years, the co-efficient of infection for leaf rust was found the maximum for Southern Hindukush (2.0) followed by Peshawar Valley (0.1), while it was found the minimum of 0.0 for Western Hindukush and Northern Hindukush regions.

Considering the within years variations, the maximum co-efficient of infection was observed during 2022 (0.9) followed by 2020 (0.7), while it was found the minimum (0.0) during 2019 followed by 2021 (0.1). Considering the region wise distribution each year, the co-efficient of infection for leaf rust during 2019 was found the maximum for Northern Hindukush (0.1), while the minimum for the other three regions (0.0 each). During 2020, it was found the maximum for Southern Hindukush (2.8), while the minimum for the rest of the regions (0.0). The co-efficient of infection recorded during 2021 was found the maximum for Peshawar Valley (0.5), while the minimum of 0.0 for Northern Hindukush and Southern Hindukush followed by Western Hindukush (0.1). During 2022, the co-efficient of leaf rust infection was recorded the maximum for Southern Hindukush (3.8), while the minimum for the other three other regions (0.0; Table 2).

Table 3
Mean leaf rust severity (%) and co-efficient of infection as observed across the Hindukush region of Khyber Pakhtunkhwa, surveyed during the disease seasons of 2019 to 2022.

Leaf rust severity (%)					
Region	**2019**	**2020**	**2021**	**2022**	**Overall period**
Peshawar Valley	0.0	0.0	0.7	0.0	0.2
Western Hindukush	0.0	0.0	0.1	0.0	0.0
Northern Hindukush	0.2	0.0	0.0	0.0	0.0
Southern Hindukush	0.0	3.3	0.0	4.0	2.1
Total	0.0	0.8	0.2	1.0	0.6
Leaf rust co-efficient of infection					
Region	**2019**	**2020**	**2021**	**2022**	**Overall period**
Peshawar Valley	0.0	0.0	0.5	0.0	0.1
Western Hindukush	0.0	0.0	0.1	0.0	0.0
Northern Hindukush	0.1	0.0	0.0	0.0	0.0
Southern Hindukush	0.0	2.8	0.0	3.8	2.0
Total	0.0	0.7	0.1	0.9	0.5

Leaf rust status in different districts of KP

Leaf rust varied across locations and over years, however, it was found with relatively low prevalence in different districts of KP. Considering the overall period, the disease was found in 3% fields with only 1% fields infected with high disease (> 50%). The disease was reported in the maximum fields in Tank (33%; with 24% fields infected with high disease) followed by DI Khan (16%) and Lakki Marwat (8.0%) of Southern Hindukush, while it was found absent in Charsadda, Mardan and Nowshera of Peshawar Valley and most of the surveyed districts (except Khyber and Lower Kurrum) of Western Hindukush, while detected in only 1% fields in Lower Dir of Northern Hindukush.

Considering the within year variation, the disease was found in the maximum (5.0%) fields with 2% fields infected with high disease during 2022, while the minimum (0.0%) fields during 2019 except for Lower Dir (8% fields). In 2020, the disease was detected in the maximum fields in Tank and Lakki Marwat (100% each), however, the disease was found with high severity in 100% fields in Tank only (Fig. 4), while the disease was absent in other districts except Bannu (11% infected fields) and Khyber (9.0% fields). During 2021, the disease was found in the maximum (25%) fields in Peshawar followed by Swabi (19%) and Lower Kurrum (8%), while it was absent in the rest of the surveyed districts. In2022, leaf rust was detected in the maximum fields in DI khan and Tank (67% each) with 42% fields exhibiting high disease in Tank only, while the disease was not detected in any of the other districts surveyed (Table 4).

Table 4

Number of fields surveyed, percent of fields infected with leaf rust disease and percent of fields severely (> 50%) leaf rust infected across different district surveyed during the disease seasons of 2019 to 2022.

Region	District	2019			2020			2021			2022
		Fields sampled	Fields infected (%)	Fields severely (> 50%) infected (%)	Fields sampled	Fields infected (%)	Fields severely (> 50%) infected (%)	Fields sampled	Fields infected (%)	Fields severely (> 50%) infected (%)	Fields sampled
Peshawar Valley	Charsadda	-	-	-	-	-	-	-	-	-	10
	Mardan	-	-	-	-	-	-	6	0	0	9
	Nowshera	36	0	0	-	-	-	21	0	0	7
	Peshawar	38	0	0	11	0	0	8	25	0	9
	Swabi	36	0	0	8	0	0	21	19	0	4
Western Hindukush	Bajaur	22	0	0	46	0	0	33	0	0	31
	Khyber	5	0	0	11	9	0	-	-	-	8
	Lower Kurrum	5	0	0	5	0	0	13	8	0	11
	Mohmand	17	0	0	17	0	0	18	0	0	11
	North Waziristan	17	0	0	12	0	0	11	0	0	16
	South Waziristan	10	0	0	-	-	-	-	-	-	-
	Upper Kurrum	6	0	0	15	0	0	10	0	0	22
Northern Hindukush	Buner	20	0	0	12	0	0	10	0	0	24
	Lower Dir	13	8	0	22	0	0	17	0	0	16
	Malakand	2	0	0	8	0	0	3	0	0	5
	Shangla	10	0	0	11	0	0	-	-	-	-
	Swat	11	0	0	17	0	0	10	0	0	13
	Upper Dir	10	0	0	18	0	0	26	0	0	20
Southern Hindukush	Bannu	7	0	0	9	11	0	14	0	0	11
	DI Khan	5	0	0	11	0	0	12	0	0	9
	Hangu	6	0	0	14	0	0	9	0	0	8
	Karak	-	-	0	7	0	0	5	0	0	9
	Kohat	6	0	0	19	0	0	12	0	0	20
	Lakki Marwat	2	0	0	2	0	0	9	0	0	12
	Tank	7	0	0	3	0	100	11	0	0	12
Total		291	0	0	278	3	1	279	3	0	297

The "-" sign in the table shows the districts not observed in the corresponding years.

Mean leaf rust severity (%) across different districts of KP

Considering the overall four years, the mean leaf rust severity was found the maximum for Tank (20.5%), followed by Lakki Marwat (1.9%) and DI Khan (1.5%) of Southern Hindukush, while the minimum (0.0%) was observed for Charsadda, Mardan and Nowshera of Peshawar Valley and most of the surveyed districts of Western Hindukush (except Khyber (0.1%) and Lower Kurrum (0.2%)) and Northern Hindukush (except Lower Dir (0.2%).

Considering the within year variation, the mean leaf rust severity was found the maximum during 2022 (1.1%) followed by 2020 (0.8%), while it was observed the minimum during 2019 (0.0%) followed by 2021 (0.2%). During 2019, the mean leaf rust severity was observed the maximum for Lower Dir (0.8%), while the minimum (0.0%) for the rest of the surveyed districts. In 2020, the mean leaf rust severity was observed the maximum for Tank (60%) followed by Lakki Marwat (7.5%) and Bannu (2.2%), while the minimum (0.0%) was recorded for most districts except Khyber (0.5%). During 2021, the mean leaf rust severity was observed the maximum for Peshawar (1.9%) followed by Swabi (1.0%) and Lower Kurrum (0.8%), while the minimum (0.0%) for the rest of the surveyed

districts. In 2022, the maximum mean leaf rust severity was found for Tank (22.2%) followed by DI Khan (6.1%), while the minimum (0.0%) for other districts (Table 5).

Table 5
Mean leaf rust severity (%) as observed across different districts representing the Hindukush region of Khyber Pakhtunkhwa, surveyed during the disease seasons of 2019 to 2022.

Region	District	2019	2020	2021	2022	Overall period
Peshawar Valley	Charsadda	-	-	-	0	0
	Mardan	-	-	0	0	0
	Nowshera	0	-	0	0	0
	Peshawar	0	0	1.9	0	0.5
	Swabi	0	0	1	0	0.2
Western Hindukush	Bajaur	0	0	0	0	0
	Khyber	0	0	-	0	0.1
	Lower Kurram	0	0	0.8	0	0.2
	Mohmand	0	0	0	0	0
	North Waziristan	0	0	0	0	0
	South Waziristan	0	-	-	-	0
	Upper Kurram	0	0	0	0	0
Northern Hindukush	Buner	0	0	0	0	0
	Lower Dir	0.8	0	0	0	0.2
	Malakand	0	0	0	0	0
	Shangla	0	0	-	-	0
	Swat	0	0	0	0	0
	Upper Dir	0	0	0	0	0
Southern Hindukush	Bannu	0	2.2	0	0	0.5
	DI Khan	0	0	0	6.1	1.5
	Hangu	0	0	0	0	0
	Karak	-	0	0	0	0
	Kohat	0	0	0	0	0
	Lakki Marwat	0	7.5	0	0	1.9
	Tank	0	60	0	22.2	20.5
Total		**0**	**0.8**	**0.2**	**1.1**	**0.5**

Co-efficient of leaf rust infection recorded for different crop varieties

The average co-efficient of leaf rust infection was recorded the maximum for local land races (7.3) followed by Sumai 3 (1.9) and Ghaneemat-e-IBGE (1.1) while it was found the minimum (0.0) for most of the surveyed varieties. The maximum average co-efficient of infection for some local land races reveals the deployment of these varieties in regions with favorable environment for disease development particularly in the Southern Hindukush. However, the leaf rust was absent on most of the studied varieties but still the disease was detected with sporadic appearance on some host varieties like Pirsabak-2005, Pirsabak-2013 and Shahkar-2013. The overall low co-efficient of infection for the surveyed varieties shows the deployment of these varieties in regions where the disease is present with low prevalence (Supplementary Table S3).

DISCUSSION

This is the first ever study to assess the existence of leaf rust in the Hindukush region of Khyber Pakhtunkhwa, Pakistan, which lies in the bordering regions of Afghanistan. Leaf rust was found at a low prevalence throughout the four-year study period, with variability observed across years and geographical regions. Although, the disease has been a potential threat to wheat production in major wheat growing areas of Pakistan, it is also associated with socio-economic instability in wheat-growing regions around the world (Ali et al., 2017; Rehman et al., 2013). However, in the studied Hindukush region, it appears to be less frequent. Considering the response of many of the observed varieties in other parts of Pakistan (Khan et al., 2021; Ismail et al., 2021), the observed low prevalence could be most probably linked with climatic factors. Indeed, optimal environmental conditions play critical role in the development of fungal infections (Noor et al., 2025).

Across the geographical regions, the incidence of leaf rust was highest in Southern Hindukush followed by Peshawar Valley, while the lowest percentage of diseased fields were observed in Western Hindukush and Northern Hindukush. The high incidence and severity of leaf rust in Southern Hindukush and Peshawar Valley could be attributed to the relatively warmer climatic conditions of the region, while the low incidence in Western Hindukush and Northern Hindukush could be due to the relatively colder weather conditions in the regions (Supplementary Table S4). The variability observed across different regions could be due to variability in the prevailing climatic conditions at these regions (Ali et al. 2023), which impact the development of the pathogen (Te Beest et al. 2008). Our findings were consistent with the previous study of Khan et al. (2021), who found that leaf rust was more widespread in the warmer regions of Pakistan particularly in Sindh and Punjab provinces, while present with sporadic appearance in northern colder climatic conditions. Temperature, humidity, wind speed and rainfall all have an impact on leaf rust development because all these factors influence the landing of urediniospores, disease development and the severity of the disease (Schnurbusch, 2019; Hassan et al., 2022). Leaf rust thrives well in favorable environmental conditions with high humidity and a 10–30°C temperature range (El-Orabey and Elkot, 2020). Huerta-Espino et al., 2011 also proposed that temperature above 80% and rainfall between 10 mm more strongly encourages the development of the disease.

Although the Southern Hindukush exhibited the highest overall leaf rust prevalence during the survey period, disease distribution was not uniform across the entire region. Elevated disease severity was primarily confined to a limited number of districts where environmental conditions, wheat cultivar composition and local agronomic practices were likely more conducive to disease development (Khan et al., 2021). Therefore, the observed pattern should be interpreted as evidence of localized disease hotspots rather than indicating uniformly high vulnerability throughout the region.

Over the years, the disease was found with the maximum frequency during 2022, while with least frequency during 2020 and 2021, however, the disease was not observed during 2019. In 2022, there was a considerable increase in the severity and incidence of leaf rust in the Southern Hindukush. Prior to the cultivation of the most susceptible cultivars and the effects of climate change, the disease was not a significant issue in the Hindukush region, but it is now posing a damaging threat to wheat production in the main wheat growing regions of Pakistan (Khan et al., 2019b), which advocated the use of resistant varieties.

Sporadic appearance of leaf rust was observed on some varieties like, Ghaneemat-e-IBGE, Pirsabak-2005, Pirsabak-2013, Shahkar-2013, Sumai 3 and local landraces. These varieties were uniformly distributed across the Hindukush region of Pakistan, however, Sumai 3 was only found in research plots in Nowshera and Swabi, while the local land races, barley and triticale were mostly grown in rural areas particularly for fodder purposes. Sumai 3 is a Chinese spring wheat cultivar first released in 1970, was used as an important source of Fhb1 and other quantitative trait loci for high resistance to Fusarium head blight (FHB) in wheat breeding programs around the world (Ghimire et al., 2020). The observed disease on the varieties is consistent with previous research that found significant variation in leaf rust response of Pakistani wheat germplasm, reflecting variations in the durability and effectiveness of the deployed Lr genes against changing pathogen populations (Channa et al., 2022; Ali et al., 2024). Considering the low disease pressure, the low leaf rust severity could be attributed to disease escape in the Hindukush region and future studies could further elucidate the resistance status in controlled inoculation experiments or replicated field evaluations under adequate and comparable disease pressure conditions.

Several leaf rust resistance genes have been deployed in Pakistani wheat germplasm, including the cultivars surveyed in this study. The leaf rust resistant genes Lr1, Lr3, Lr9, Lr10, Lr13, Lr14a, Lr16, Lr17, Lr23, 255 Lr26, and Lr27 + Lr31 are the genes that have been hypothesized to be present in Pakistani wheat varieties and breeding lines (Rattu et al., 2010). Another study proposed that recent Pakistani wheat varieties and breeding lines carry the genes Lr1, Lr10, Lr16, Lr14a, Lr17, Lr24, and Lr26. Nonetheless, reports of virulence for numerous of these genes have been identified (Ali et al., 2024; Kolmer et al., 2017). However, partial resistance can also offer a more durable resistance, hence affecting the rate at which the pathogen adapts (Ali et al., 2009a; de Vallavieille-Pope et al., 2012).

Findings of the current study on disease appearance on some of the varieties emphasize the importance of continued field surveillance and the incorporation of quantitatively expressed, adult-plant resistance in breeding programs. According to recent studies, gene pyramiding and QTL-based resistance are two more viable techniques to developing more resilient leaf-rust resistance in wheat (Ullah et al., 2026). Standard crop breeding typically takes 8–12 years to develop new varieties, is insufficient to keep up with the rate of environmental change. Accelerated Generation Technologies (AGT), such as speed breeding, rapid generation advance, doubled haploids, genomic selection, genome editing and nanotechnology give innovative solutions by shortening breeding cycles from over a decade to two to four years (Imtiaz, 2025).

The information generated on leaf rust prevalence in the Hindukush region should be valuable for wheat varietal testing and seed dissemination for ensuring low leaf rust burden. Similar studies should be continued on tracking the variability in disease over time, particularly during the years with more rainfall and thus favorable condition for the disease (Khan et al., 2021). This will lead to avoid the losses associated with leaf rust and thus contributing to the food security of this conflict vulnerable farming area of Pakistan. Future studies should incorporate environmental variables, including temperature, humidity, rainfall and host resistance to develop comprehensive predictive models of wheat rust epidemics (Chen et al., 2020). The applications of cutting-edge technologies including Remote Sensing, Machine Learning, Deep Learning and Internet of Things (IoT) should be employed in surveillance programs for early detection and management of wheat diseases (Shafi et al., 2022).

Conclusion

Despite a low overall regional prevalence of wheat leaf rust, this four-year surveillance study (2019–2022) found significant geographical and temporal variation in the disease distribution across the Hindukush region of Pakistan with a comparatively high disease prevalence in the Southern Hindukush and Peshawar Valley. These patterns of the disease help to inform development of region-specific breeding programs, management practices and surveillance strategies, as well as regional disease risks. While breeders should incorporate long-term resistance and frequently evaluate deployed germplasm against the current pathogen populations, farmers should prioritize locally adapted, leaf rust-resistant cultivars, frequent field scouting and risk-based fungicide

treatment. Because host deployment, farming practices and climate variability can alter pathogen distribution and increases disease risks in previously unaffected areas, therefore, continuous systematic surveillance of the disease is critical.

Declarations

Ethics approval:

Not applicable.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

Clinical trial

Not applicable.

Clinical Trial Number

Not applicable.

Authors Contribution: ZUR, AI, JK and SA conducted the field surveillance. ZUR and SA analyzed the data. ZUR, SU, JM and SA wrote the manuscript. ZUR and MA revised the manuscript. JM and SA provided funding resources for the study. ZUR, JM and SA designed the study.

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Conflict of interest: The authors declare that they have no competing interests

Data availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

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Table 2

Table 2 is available in the Supplementary Files section.

Figures

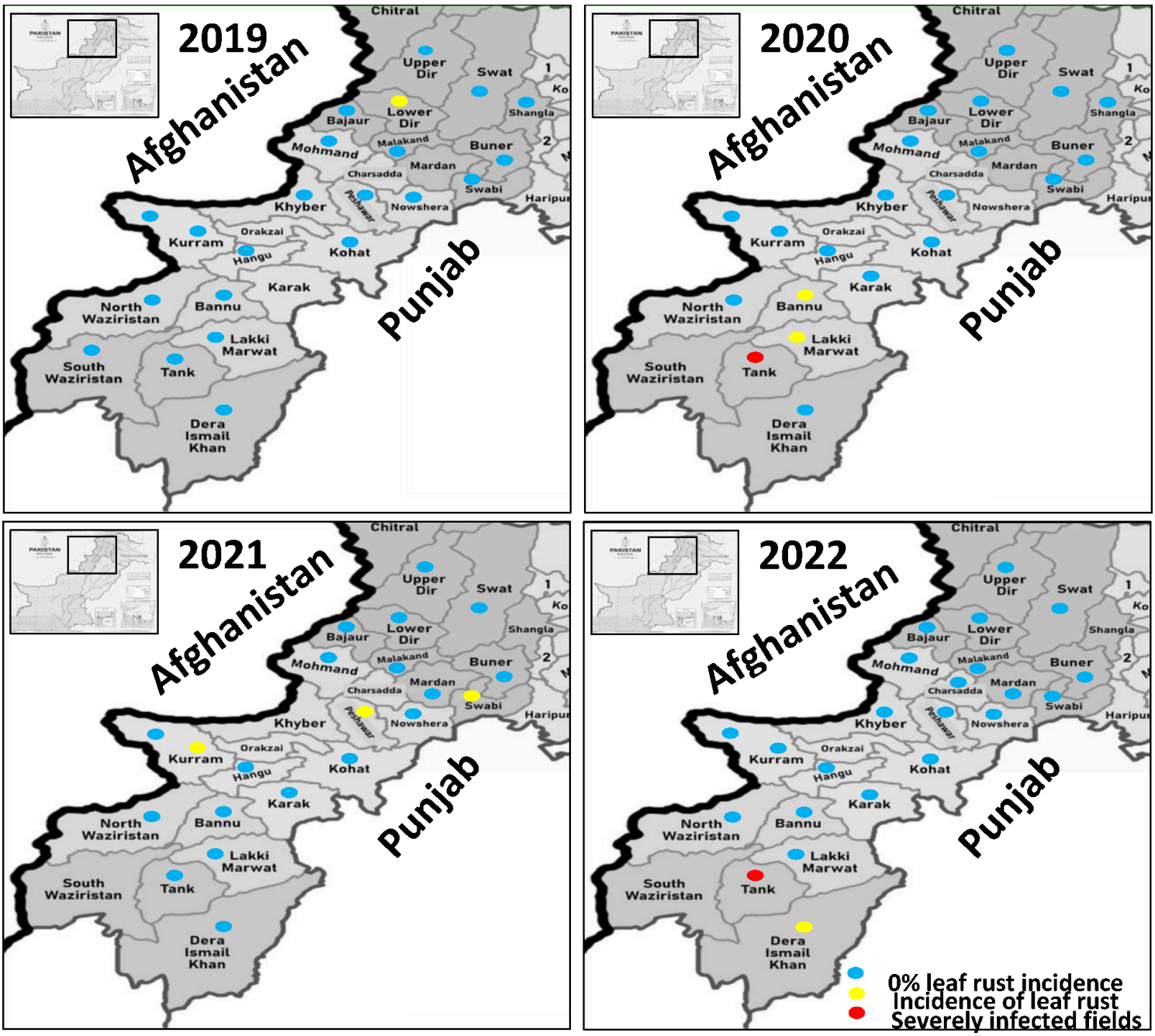


Figure 1

Map of Khyber Pakhtunkhwa showing the districts surveyed in the Hindukush regions of Pakistan over the four years surveillance made in 2019-22.

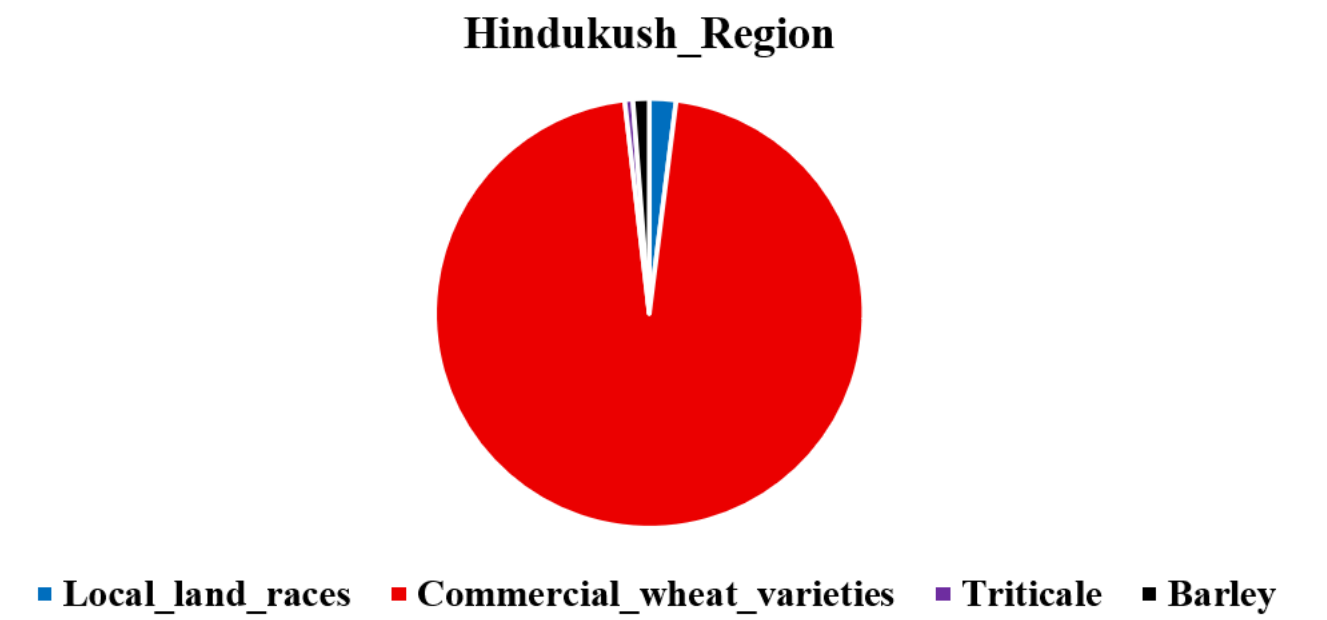


Figure 2

Distribution of host varieties across the geographical regions of the Hindukush Pakistan surveyed during the period of 2019-2022.

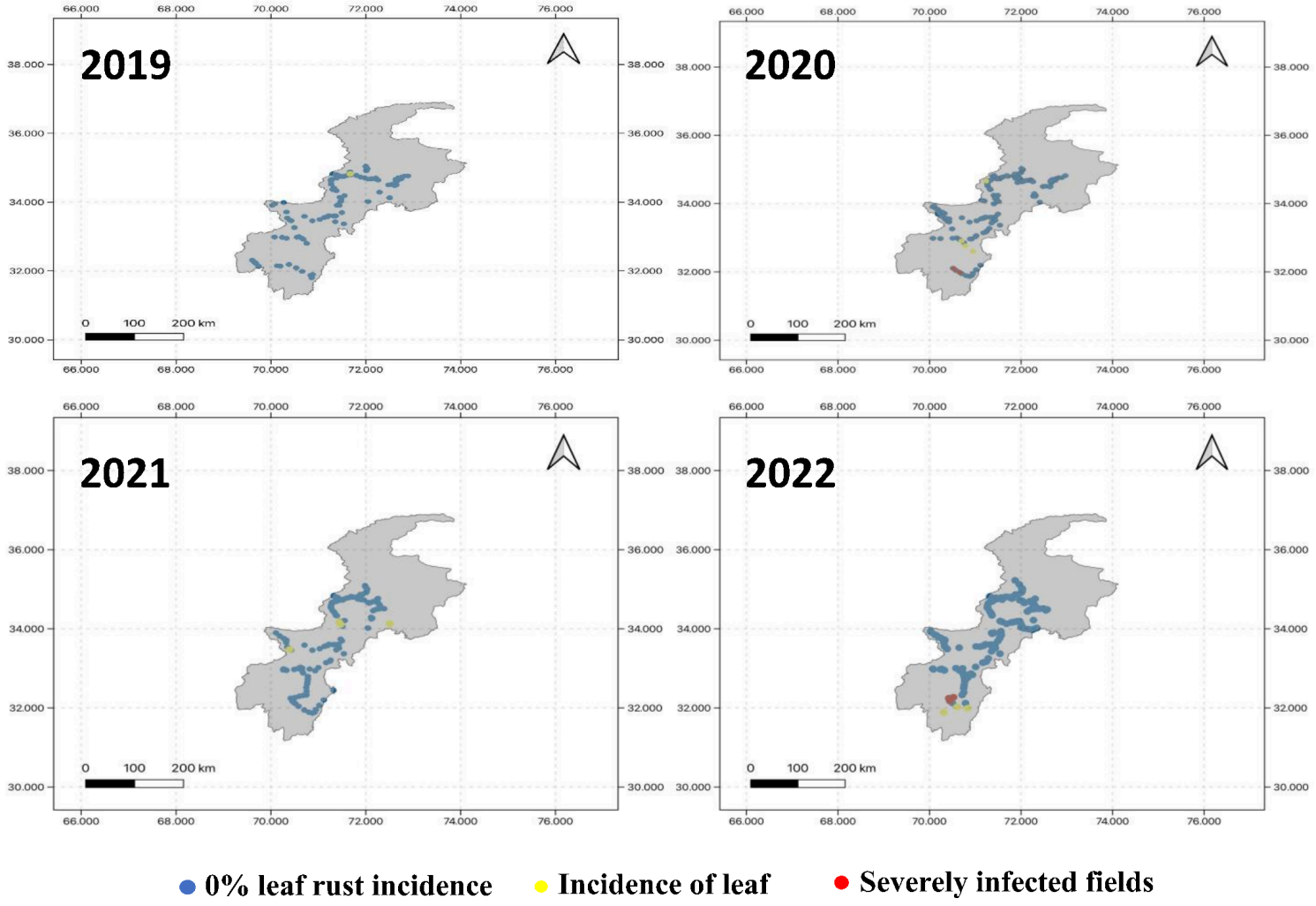


Figure 3

Spatial distribution of wheat leaf rust across the Hindukush region of Pakistan surveyed during the disease seasons of 2019-2022.

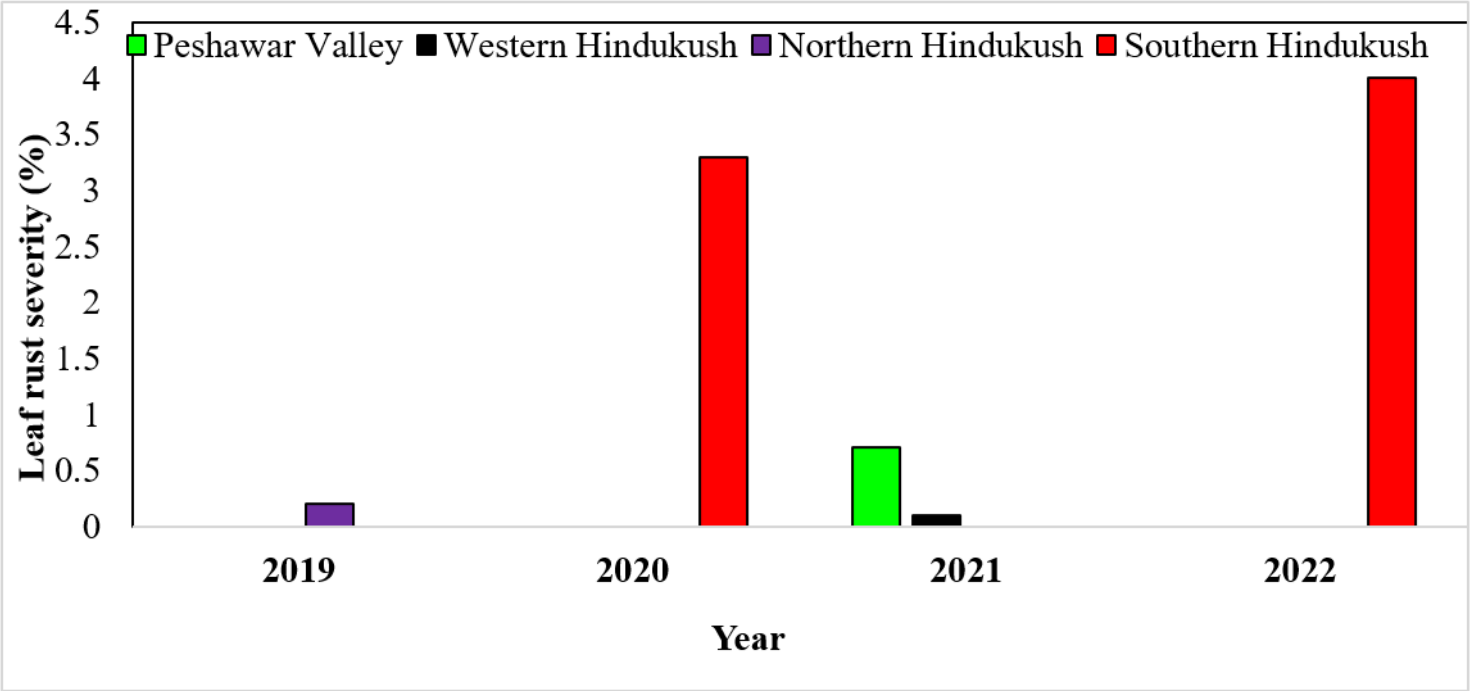


Figure 4

Mean leaf rust severity (%) observed across the Hindukush region of Khyber Pakhtunkhwa, surveyed during the disease seasons of 2019 to 2022.



Figure 5

Wheat leaf rust symptoms observed in different wheat fields during surveillance effort made during 2019-2022.

Supplementary Files

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