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Research Article

Unlocking Landrace Potential Through Race-specific Screening and Field-level Resistance Evaluation for Durum wheat (*Triticum turgidum* subsp. *durum* (Desf.) Stem Rust Resistance under Natural Epidemic

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Abstract

Durum wheat (Triticum turgidum subsp. durum [Desf.]) Husn is a significant global food cereal. The stem rust caused by P. graminis f.sp. tritici can result in a yield loss of up to 100%. This study aimed to identify seedling-stage resistance of durum wheat landrace accessions to prevailing races (TTKSK, TKTTF, TRTTF, and JRCQC) of the pathogen and evaluate their performance under field conditions. A total of 34 landrace accessions were tested under controlled greenhouse and field conditions. Seedlings were inoculated at the Ambo Agricultural Research Center and assessed using the 0–4 scale. Selected accessions were further evaluated in the field at a hotspot location during the main growing season. Seedling evaluation results showed variability in genotype responses for the prevailing races. Fourteen and landrace accessions (TD7226, TD7227, TD7365, TD8489, TD3750, TD3751, TD3762, TD3764, TD8217, TD8218, TD8777, TD6309, TD6984, and TD8507) exhibited resistance (IT of 2 or below) types of infections to all four races. Some accessions displayed a vulnerable response with a score of 3 to 3. A highly significant ($p < 0.001$) correlation was observed between disease, plant parameters, and yield. Based on the field FRS (<30s), CI (<20), and AUDPC (30%) of the check variety, accessions TD3750, TD751, TD5917, and TD8778 exhibited high partial resistance. Identifying and using these landrace accessions can be beneficial in the development of durable resistance breeding strategies for novel resistant wheat varieties. However, the effectiveness of this landrace requires further molecular investigation to identify the resistance source.

Introduction

Ethiopia is Africa's second-largest wheat producer after Egypt, and it holds the top position in SSA [1]. Wheat ranks as the second most significant cereal crop in Ethiopia after maize [2]. In 2022, global wheat productivity increased by 1.9% compared with that in 2021. Ethiopia has two economically significant wheat species: Hexaploid bread wheat (*Triticum aestivum*) and tetraploid durum (*Triticum durum*) [3,4]. Wheat, a vital industrial crop, is the primary raw material for feed mills and is integral to bread, cakes, biscuits, pasta, and macaroni. It plays a crucial role in the diets of many Ethiopians, contributing approximately 15% of calories consumed for a population exceeding 90 million [5,6].

Triticum turgidum subsp. *Durum* (Desf) Husn, also known as durum wheat, is a significant global food cereal, cultivated over approximately 17 million hectares with an average yield of 36 metric tons per hectare [7]. Ethiopia is the largest producer of durum wheat in Sub-Saharan Africa, utilizing about 0.6 million hectares for cultivation. Despite its substantial economic and dietary importance, Ethiopia's average wheat yield remains low compared with that of other countries. The average yield of durum wheat in Ethiopia is only 1.3 tons per hectare [8]. This low productivity can be attributed to a range of biotic and abiotic factors, including erratic rainfall patterns, inadequate agronomic practices, poor soil fertility, insect pests, and serious plant diseases such as rusts [9]. Wheat rust is a widespread disease in and around the United States [10].

In many regions of the country's wheat-growing area, stem rust, which is caused by **Puccinia graminis* f.sp. *Tritici* is a major limitation on production that can result in yield reductions of up to 100% during epidemic years [11-13]. Rust diseases, particularly black and yellow rusts, are recognized as the most serious risks to wheat production and have been a major focus of research since the beginning of wheat disease studies. Rust epidemics can spread across continents due to the extensive spread of urediospores [14]. Fungi that cause wheat rust are obligate host-specific parasites that can evolve into virulent races through mutation and sexual recombination. The three types of wheat rust—leaf, stripe (yellow), and stem—have significantly contributed to yield reductions and profoundly impacted global socio-economic stability worldwide [15].

Recent studies in the country have revealed that many previously identified races of wheat rust are virulent against most currently grown wheat varieties [16]. This indicates the potential risk of resistance breakdown in Ethiopian-released wheat varieties. Resistance can manifest as a decrease in the number of lesions, a reduction in pustule size, an extension of the latent period, and a shorter sporulation period [17]. The national durum wheat program in Ethiopia employs strategies such as selecting indigenous germplasm, introducing new varieties, hybridization, and evaluating selected lines to address these disease challenges and enhance yield [18].

The durum wheat landraces of Ethiopia are promising origins of resistance to stem rust and could be effectively utilized in the breeding schemes for wheat [19]. Resistance conditioned by utilizing genes has been the most widely emphasized strategy for mitigating rust threats and reducing losses incurred [20,21]. Pyramiding or cascading of several major genes into a single cultivar is also an attractive breeding strategy for increasing resistance durability by reducing stepwise accumulation of virulence by the pathogen against each gene [20,21]. The alternative is the development and employment of cultivars carrying durable or slow-rusting resistance based on quantitatively inherited, multiple genes referred to as adult plant resistance [20]. The use of gene pyramid in the management of *Pgt* was more efficient than the sole application of monogenic and polygenic resistance materials, probably due to the synergistic effect of gene combination in combating the pathogen [22]. Moreover, knowledge of the prevailing races is crucial as pathogens, like *Pgt,* are known to evolve their virulence frequently [23]. Currently, most of the released commercial wheat varieties by the national wheat research program are frequently defeated by new races of stem rust. There is a crucial need for farmers to use wheat genotypes possessing adequate resistance to emerging new physiological races of *Pgt*. Ethiopian farmers prioritize various traits in wheat varieties, including grain production, disease resistance, and other important social values. However, the genetic variability of pathogens complicates their management. Utilizing a wheat variety is essential for farmers to exhibit strong resistance. It is essential to create new wheat cultivars that integrate a variety of resistance mechanisms because of the quick evolution and spread of more virulent stem rust races, the frequent failures of recently created resistant varieties, and the scarcity of long-lasting resistance sources. This calls for the exploration of new resistance sources from landraces, through screening under seedlings and field conditions. Achieving long-lasting resistance against wheat stem rust requires ongoing identification and characterization of the pathogen, and deployment of new resistance genes capable of overcoming current virulent races. Landrace accessions present a promising source for discovering resistance to be utilized in breeding programs. The resistance observed in seedlings of these landrace accessions is characterized as complete and monogenic; it is governed by a single gene and provides full protection against the pathogen. This robust form of resistance is not only effective during the seedling stage but also persists throughout all growth stages of the wheat plant, ensuring ongoing protection against potential infections. The alternative is the development and employment of cultivars carrying durable or slow-rusting resistance based on quantitatively inherited, multiple genes referred to as adult plant resistance [24]. The use of gene pyramid in the management of *Pgt* was more efficient than the sole application of monogenic and polygenic as resistance materials, probably due to the synergistic effect of gene combination in combating the pathogen [22]. Landrace accessions could be a potential source of resistance to be exploited in breeding programs. Therefore, this research was proposed to investigate new sources of resistance in durum [*Triticum turgidum* subsp. *Durum* (Desf.) Husn.] landraces accessions to the prevailing races of *Pgt* in a greenhouse at the seedling stage and evaluate at natural epidemics.

Materials and methods

Study area

Field evaluations were conducted at the Bishoftu Agricultural Research Center, Ethiopia. Bishoftu is in the East Shewa Administrative Zone of the Oromia National Regional State, 47 km southeast of Addis Ababa, at 38°57' E longitude and 08°44' N latitude, with an elevation of 1900 m.a.s.l. [25]. It receives an average annual rainfall of 851 mm, with an average annual minimum and maximum temperatures of 8.9 °C and 28.3 °C , respectively, and a mean annual relative humidity of 61.3% [26]. It is an internationally known hotspot area of stem rust because of its suitability for the establishment and rapid epidemics of wheat stem rust. Seedling tests were conducted in a greenhouse at the Ambo Agricultural Research Center (AARC). It is located at an elevation of 2175 meters in west Shewa, with a latitude of 8°57'58''N and a longitude of 37°51'33''E. The average annual rainfall is 1265.7 mm, and the average annual temperature is 27.54 °C.

Planting materials

A total of 34 durum wheat accessions collected from parts of Tigray, Amhara, Oomiya, and South Nation Nationality Peoples of Ethiopia regions by the Ethiopian Biodiversity Institute were used for this study. The accessions were selected based on the passport data from different geographical locations conserved in the genebank (Table 1). As well as the susceptible reference variety (McNair, Morocco), were utilized as planting materials from Bishoftu Agricultural Research Center (DZARC) (Table 1).

Field evaluation of durum wheat landrace accessions

A field experiment was conducted at Bishoftu Agricultural Research Center (BARC) under natural infection in the 2019/2020 main cropping season, and the 34 planting materials were collected from EBI and checks (Morocco and McNair) from BARC (Table 1). The total experimental field was 13.2 m *14 m (184.8 m^2). Each plot consists of four rows (0.6 m wide) and 1.5 m long and with a spacing of 0.2 m between rows, 0.5 m between plots, and 1 m between blocks and replications. The treatment was arranged in a simple lattice design with two replications. Seeding rate, fertilization, hand weeding (three times), and other management practices were applied according to the recommendations for the area. The seeding rate of the variety was 150 kg ha^{-1} with the spacing of 20 cm between rows. The recommended fertilizer rate in the study area is DAP 150 kg ha^{-1} and Urea 100 kg ha^{-1}.

Agronomic and yield components data

Plant height (cm): the average value of ten plants was taken randomly from two central rows, and their heights were measured at maturity.

Spike Length (SPL) (cm): the average value was ten plants randomly selected from two central rows, and their spike length was measured at maturity.

Number of kernels per spike: average value. Ten plants were randomly taken from two central rows of a plot at maturity, and the number of kernels in each spike was counted after threshing.

Table 1: To each of four isolated races of Pgt, thirty-four durum Wheat lines and landrace accessions were tested, coupled with one susceptible check (McNair).

No	Accession	Region	Zone	District	Latitude	Longitude	Altitude (m.a.s.l)
1	TD5917	Oromiya	Misrak Shewa	Lome	08-42-00-N	39-11-00-E	2000
2	TD7226	SNNP	Gurage	Goro	08-25-00-N	37-55-00-E	2000
3	TD7227	SNNP	Gurage	Goro	08-25-00-N	37-55-00-E	2000
4	TD7364	Amara	Semen Wello	Guba Lafto	1 1-46-00-N	39-36-00-E	1900
5	TD7365	Amara	Semen Wello	Guba Lafto	11-44-00-N	39-35-00-E	1910
6	TD8063	Oromiya	Misrak Shewa	Ada'a Chukala	08-40-00-N	39-06-00-E	2000
7	TD8489	Unknown	Unknown	Unknown	15-09-00-N	38-52-00-E	2000
8	TD3750	Amhara	Mirab Gojam	Dembecha	10 -42-00-N	37-07-00-E	2050
9	TD3751	Amhara	Mirab Gojam	Dembecha	10-42-00-N	37-07-00-E	2050
10	TD3762	Amhara	Mirab Gojam	Dembecha	10-34-00-N	37-29-00-E	2050
11	TD3764	Amhara	Mirab Gojam	Dembecha	10-34-00-N	37-29-00-E	2050
12	TD8211	Amhara	Mirab Gojam	Jabi Tehnan	Unknown	unknown	2020
13	TD8217	Amhara	Mirab Gojam	Jabi Tehnan	Unknown	unknown	2020
14	TD8218	Amhara	Mirab Gojam	Jabi Tehnan	Unknown	unknown	2020
15	TD8746	Oromiya	Mirab Wellega	Sayo	Unknown	unknown	1900
16	TD8777	Oromiya	Misrak Shewa	Adea	Unknown	Unknown	1900
17	TD8778	Oromiya	Misrak Shewa	Ada'a Chukala	Unknown	Unknown	1900
18	TD8780	Oromiya	Misrak Shewa	Ada'a Chukala	Unknown	Unknown	1900
19	TD8781	Oromiya	Misrak Shewa	Ada'a Chukala	Unknown	Unknown	1900
20	TD3262	Tigray	Misrakawi	Wukro	14-16-00-N	39-28-00-E	1945
21	TD6309	Amhara	Mirab Gojam	Bure Wemberma	Unknown	Unknown	2020
22	TD6984	Oromiya	Arsi	Seru	07-40-00-N	40-12-00-E	1995
23	TD6985	Oromiya	Arsi	Seru	07-40-00-N	40-12-00-E	2000
24	TD8117	Tigray	Mehakelegnaw	Adwa	14-02-00-N	38-04-00-E	1920
25	TD8118	Tigray	Mehakelegnaw	Werie Lehe	13-04-00-N	38-04-00-E	1980
26	TD8119	Tigray	Mehakelegnaw	Werie Lehe	14-04-00-N	38-04-00-E	2000
27	TD8121	Tigray	Mehakelegnaw	Werie Lehe	13-04-00-N	39-35-00-E	1850
28	TD8123	Tigray	Mehakelegnaw	Werie Lehe	13-04-00-N	39-35-00-E	2000
29	TD8124	Tigray	Mehakelegnaw	Werie Lehe	14-02-00-N	38-04-00-E	2000
30	TD8504	Oromiya	Misrak Shewa	Ada'a Chukala	Unknown	Unknown	1900
31	TD8507	Oromiya	Misrak Shewa	Lome	Unknown	Unknown	1860
32	TD8519	Oromiya	Misrak Shewa	Ada'a Chukala	Unknown	Unknown	1980
33	TD8525	Oromiya	Misrak Shewa	Ada'a Chukala	Unknown	Unknown	1900
34	TD8528	Oromiya	Misrak Shewa	Ada'a Chukala	Unknown	Unknown	1950
35	Susceptible Check1 McNair Both for field and greenhouse						
36	Susceptible Check2 Morocco Only for the field						

Thousand Kernel Weight (TKW) (g): It was done by counting and weighing 250 seeds, and the final result was multiplied by 4 to get the thousand kernel weight.

Above-ground dry biomass (t ha^{-1}): The entire plants were harvested at maturity; their weight was measured and converted into t ha-1.

Grain yield data (t ha^{-1}): Clean grain yield from each plot was recorded and converted into tons per hectare (t ha^{-1}).

Harvest index (HI%): Harvest index was determined as the ratio of dry grain yield to the aboveground biological yield (biomass yield) and expressed as a percentage.

Days to 50% heading: The duration recorded when 50% or more of the plants on the plots produced heads from the date of sowing.

Days to physiological maturity: It was taken as the number of days elapsed from seedling emergence to the date when 90% of the crop stems, leaves, and floral bracts in a plot changed to light yellow color.

Disease parameters: Stem rust infection of the field evaluation were recorded at the time of disease appearance, based on a 0–4 scale as described in [27] where "0" = no visible symptoms; ";" = only necrotic/chlorotic flecks without any uredia; "1" = small uredinia surrounded by necrosis; "2" = small to medium uredia surrounded by chlorosis or necrosis; "3" = medium-sized uredia without chlorosis or necrosis; "4" = large-sized uredia without chlorosis or necrosis; "X" = random distribution of variable-sized uredia; and "+" and "_" was used when uredia were somewhat larger or smaller than normal for the infection types (ITs). Seedling ITs of 0, 1, 2, and X were generally considered resistant, whereas 3 and 4 were considered susceptible. Where, Immune (I) = 0.0, Resistance (R) = 0.2, Moderately Resistant (MR) = 0.4, Moderately Susceptible- Moderately Resistant (MRMS) = 0.6, Moderately Susceptible (MS) = 0.8, Moderately Susceptible-Susceptible (MS-S) = 0.9 and Susceptible (S) = 1.0-Cobb's scale (28)) was used only to record the stem rust severity data.

Disease incidence (DI): The number of infected plants per plot was recorded by counting infected plants per four rows and converted to disease incidence.

Disease severity (DS): A proportion of the plant affected by the disease [28].

$$DS(\%) = \frac{Area\ of\ plant\ tissue\ affected}{Total\ plant\ tissue\ area} * 100$$

Final Rust Severity (FRS): Terminal stem rust severity was scored at the maturity stage of the crop [28,29]

Average Coefficient of Infection (ACI): calculated by multiplying the percentage severity by a constant for host response [30]. The ACI for each accession was computed from four severity observations, and the ACI was used for calculating AUDPC for each accession.

$$ACI = \frac{DS(\%) * constant\ for\ responce}{Total\ number\ of\ observations\ recorded}$$

The percentage severity index (PSI) was calculated by using the formula [31]

$$PSI = \frac{\text{Sum of numerical ratings}}{\text{No. of plants scored x Maximum score on scale}} * 100$$

Area under disease progress curve (AUDPC): Calculated by the stem rust disease severity scores taken at different times [32] method.

$$AUDPC = \sum_{i=1}^{n} [0.5(xi + xi + 1)]\ [ti + 1 - ti]$$

Where, x_i is the cumulative disease severity proportion at the ith observation; t_i is the time after planting at the ith observation, and n is the total number of observations.

Disease progress rate (Inf-rate): The disease severity was assessed four times at seven days interval from 10 randomly pre-tagged plants in the central two rows of each plot were regressed over time and the apparent infection rates as the coefficient of the regression line, ln [X/(100-X)], where X was average coefficient infection plotted against time in days [33] was calculated for each accession as tabulated (Table 2). The disease progress rate (DPR) as a function of time was calculated from disease severity observation by using a logistic regression model [34].

Seedling evaluation of durum wheat landrace accessions

The seedling evaluation was done at greenhouse conditions by using a completely randomized design (CRD) with two replications. Based on their economic significance for Ethiopian wheat production [35], four prominent Pgt races, TTKSK (Ug99 race), TKTTF (Digalu race), TRTTF, and JRCQC, were used to assess seedling reaction. These races' virulence/avirulence formulae are shown in Table 3. To obtain an adequate inoculum, the spores were multiplied by inoculating susceptible McNair varieties. Five seeds of McNair and wheat landrace accessions were pre-germinated on filter paper in a petri dish, and after three days, the germinated seeds were raised in plastic pots measuring 7 cm by 7 cm by 6 cm and filled with sand, light soil, and compost in a 1:2:1 (v/v/v) ratio. The vitality of the spores injected into the landrace accessions was determined using McNair. Each race's spores were suspended in Soltrol 170, a light mineral oil, and diluted to 1 × 10^5 spores per milliliter. Then, seven-day-old seedlings (Figure 1a, Figure 2a,b), when the first leaf is completely spread out and the second leaf is emerging, inoculation of spores' suspensions of virulent races of TKTTF, TTKSK, TRTTF, and JRCQC was separately done using atomized inoculators.

To create ideal circumstances for infection, seedlings were

Table 2: Disease progress rate (units/day) and parameter estimate of stem rust of durum wheat genotypes evaluated under field conditions at DARC, Central Ethiopia, during the 2019/2020 main cropping season.

Treatment	Intercept	SE of intercept	D. progress rate log/day	SE of rate	R^2 (%)
TD8525	-5.531	0.473	0.1118	0.0109	92.10
TD8218	-5.521	0.160	0.09900	0.00368	98.77
TD8063	-5.625	0.182	0.10082	0.00420	98.46
TD8781	-5.228	0.323	0.09948	0.00743	95.19
TD8504	-4.355	0.262	0.06122	0.00603	91.89
TD7226	-5.291	0.295	0.08912	0.00677	95.03
TD8117	-4.842	0.398	0.08490	0.00914	90.45
Morocco	-5.771	0.435	0.1235	0.0100	94.39
TD6984	-5.423	0.256	0.10240	0.00589	97.10
TD7364	-4.743	0.265	0.07483	0.00609	94.34
TD8746	-4.257	0.325	0.05545	0.00748	85.72
TD8118	-5.134	0.329	0.09178	0.00756	94.21
TD5917	-4.478	0.185	0.04258	0.00425	91.70
TD6985	-5.589	0.229	0.10258	0.00527	97.68
TD8119	-5.594	0.386	0.11587	0.00888	94.95
TD3750	-3.899	0.197	0.03541	0.00453	86.98
TD7365	-4.415	0.217	0.06257	0.00500	94.53
TD8121	-6.286	0.439	0.1152	0.0101	93.50
TD7227	-4.569	0.312	0.07036	0.00717	91.38
TD3751	-4.150	0.236	0.05051	0.00543	90.47
McNair	-5.980	0.465	0.1312	0.0107	94.31
TD6309	-5.215	0.483	0.1015	0.0111	90.17
TD3262	-5.148	0.481	0.1006	0.0111	90.07
TD8124	-5.437	0.326	0.10010	0.00748	95.18
TD8211	-5.656	0.500	0.1087	0.0115	90.75
TD8123	-5.651	0.479	0.1112	0.0110	91.81
TD8528	-5.781	0.255	0.10820	0.00587	97.41
TD8780	-3.970	0.254	0.04828	0.00585	88.18
TD3764	-4.913	0.424	0.08272	0.00975	88.74
TD8507	-5.6068	0.0841	0.10122	0.00193	99.67
TD8778	-3.624	0.127	0.02315	0.00291	87.38
TD8519	-6.108	0.507	0.1067	0.0116	90.20
TD8217	-5.146	0.130	0.08675	0.00298	98.95
TD8777	-5.589	0.306	0.10720	0.00703	96.26
TD3762	-3.970	0.254	0.04828	0.00585	88.18
TD8498	-5.530	0.345	0.11212	0.00792	95.68

Disease progress rate obtained from the regression line of severity (%) against time of disease assessment (days); SE Standard error of rate and parameter estimates (intercept), and R^2 Coefficient of determination for the Logistic model.

Table 3: Virulence or a virulence formula of Puccinia graminis f. sp. tritici isolates [36]

Race	Origin	Avirulence	Virulence
TTKSK	Uganda	*Sr24, 36, Tmp*	*Sr5,6,7b, 8a, 9a, 9b, 9d, 9e, 9g,10, 11, 17, 21, 30, 31, 38, McN*
TKTTF	Ethiopia	*Sr 11, 24, 31*	*Sr5,6,7b, 8a, 9a, 9b, 9d, 9e, 9g,10,17,21,30,36,38, Tmp, McN*
TRTTF	Yemen	*Sr8a, 24, 31*	*Sr5, 6, 7b, 9a, 9b, 9d, 9e, 9g, 10, 11, 17, 21, 30, 36, 38, McN, Tmp*
JRCQC	Ethiopia	*Sr5,7b,8a, 36,9b,10,30, Tmp,24,31,38*	*Sr21, 9e, 11, 6, 9g, 17, 9a, 9d, McN*

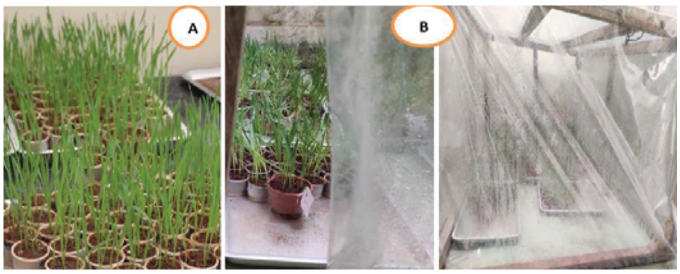

Figure 1: Schematic overview of the protocols for seedling evaluation of genotypes in the greenhouse at AARC, Ethiopia; (A) Seven-day-old seedling, (B) Seedling in the dew chamber for rust infection establishment.

moistened with tiny drops of distilled water 30 minutes after inoculation and placed in a dew chamber for 18 hours in the dark at 18 to 22 °C . They were then exposed to light for 4 hours [29,35] (Figure 1b).

Once the seedlings had dried for two hours, they were moved to glass containers in the greenhouse, where they were kept at a temperature of 18 to 25 °C and a relative humidity of 60% to 70% for a 12-hour photoperiod [37]. Infection types (IT) were recorded 14 days following inoculation using a 0-4 scale [29,35]. This is described in part 2.3.2 of this paper.

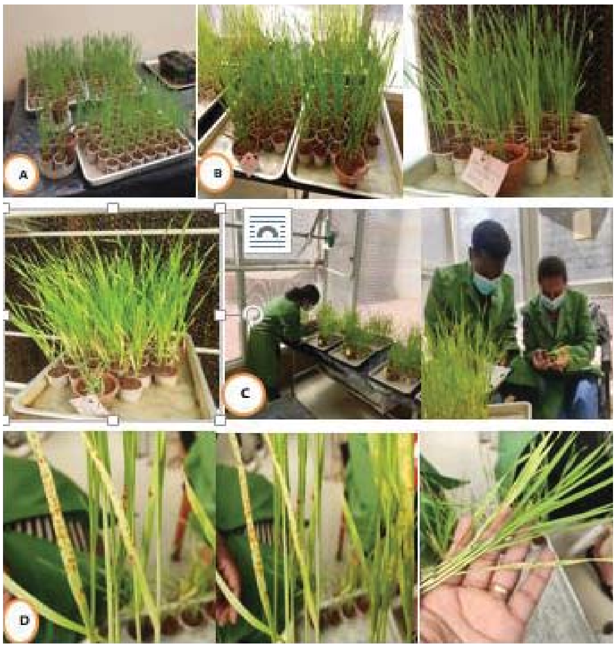

Figure 2: A. Germinated Durum wheat seeds on multi-pot trays filled with substrate; B. Inoculated against dominant *Puccinia graminis* f.sp. *tritici* after being ordered in the greenhouse at the side of Pads, and **C.** Recording the seedling reaction of inoculated samples, and D. Reaction of the wheat with different races, respectively.

Data analysis

Seedling resistance evaluation frequency of resistant and susceptible accessions data to each dominant race was analyzed by Microsoft Excel using descriptive statistics [38]. Field experimental data were analyzed by using analysis of variance (ANOVA), SAS version 9.4 statistical software, and mean comparison. Proc GLM procedure analyses of variance [39] and means computed using Least Significant Difference (LSD) tests at 5% significance level, to examine mean statistical differences among treatments.

Results

Seedling evaluation of durum wheat landrace accessions

A total of 34 durum wheat landrace accessions and McNair were tested and evaluated at the seedling stage in a greenhouse for their reactions to four distinct *Pgt* races. The McNair cultivar was a universally susceptible cultivar that was susceptible to all races found, used as a control reference to benchmark the responses observed in the landrace accessions. The accessions showed different reactions to stem rust races; TKTTF, TTKSK, TRTTF, and JRCQC, while a susceptible check, McNair, exhibited high ITs for all races between 3 to 3. It showed a high level of infection, effective inoculation, and it was possible to score ITs with accuracy [40]. The reaction of the durum wheat landrace accessions for the four races was categorized as resistant (to 2+), susceptible (3- to 3), and mixed (intermediate and susceptible) infection types in the seedling test (Table 4).

All accessions displayed a differential kind of reaction for the pathotype of stem rust that was employed. Most of the accessions displayed a resistant response to 2+; only some genotypes showed a vulnerable response with a score of 3- to 3. Fourteen accessions (TD7226, TD7227, TD7365, TD8489, TD3750, TD3751, TD3762, TD3764, TD8217, TD8218, TD8777, TD6309, TD6984 and TD8507) exhibited resistance infection or incompatible reaction (;1 to 2+) against to all the four races.

The scale described by [29,35] with IT readings of 3 (medium-size uredinia with/without chlorosis) and 4 (large uredinia without chlorosis or necrosis) considered as compatible (susceptible), while 0 (immune or fleck), 1 (small uredinia with necrosis), and 2 (small to medium uredinia with chlorosis or necrosis) as considered incompatible (resistant). Negative (-) = smaller uredinia than the normal size, and + larger than the normal uredinia.

The other nineteen accessions revealed that either susceptible or resistant kind of reaction (to 3) based on the examined pathotypes, although 1 durum wheat landrace accession and McNair (susceptible check) frequently displayed a compatible kind of reaction (3 or 3-) with all pathotypes. All of the stem rust races (TTKSK, TKTTF, TRTTF, and JRCQC) displayed some degree of variability, as demonstrated in Figure 3. This result was revealed with [36] because of the presence of different avirulent genes.

Five landrace accessions (TD7364, TD8117, TD8118, TD8519, and TD8528) revealed resilience responses for two race combinations. The landrace accession TD7364 was incompatible with TTKSK and JRCQC; hence, it implies that they possess the Sr36 and SrTmp resistance genes. Moreover, these accessions (TD7364) may also have more unidentified resistance genes, whereas wheat accessions TD8117, TD8118, TD8519, and TD8528 were resistant to TTKSK, and they might also have unidentified resistance genes.

The two accessions, TD8746 and TD8124, showed high ITs with every pathotype, except TKTTF, the only race that is avirulent to Sr11, suggesting that Sr11 is most likely present in these accessions. The three accessions TD8780, TD811.9, and TD8504 additionally showed low ITS (2 and 2+) in all pathotypes, except the race TRTTF, with high infection. Five accessions (TD8211, TD3262, TD8121, TD8123, and TD8525) demonstrated minimal ITs for every pathotype, except JRCQC, whereas four accessions TD8063, TD8778, TD8781, and TD6985 generated high ITs for all stem rust races, except TTKSK. At this stage, the resistance of these accessions cannot be explained; nevertheless, it may be caused by the presence of another resistance gene or genes.

Field evaluation of durum wheat landrace accessions

Slow-rusting characteristics of accessions described and

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Table 4: The reactions of durum wheat landrace accessions to four stem rust races at the seedling stage in the greenhouse.

Genotype code	Species	Selection history				Infection responses to *Pgt* races			
		Region	Zones	Woreda	Altitude(m)	TRTTF	TKTTF	TTKSK	JRCQC
TD5917	DW	Oromiya	Misrak Shewa	Lome	2000	3	3-	3-	3-
TD7226	DW	SNNP	Gurage	Goro	2000	2-	2-	2-	;1+
TD7227	DW	SNNP	Gurage	Goro	2000	;1	;1+	;1+	2-
TD7364	DW	Amhara	Semen Wello	Guba Lafto	1900	3-	3-	2+	;1+
TD7365	DW	Amhara	Semen Wello	Guba Lafto	1910	2-	2-	;1+	2-
TD8063	DW	Oromiya	Misrak Shewa	Ada'a Chukala	2000	3	3-	2+	3-
TD8489	DW	Unknown	Unknown	Unknown	2000	2+	2	2+	2+
TD3750	DW	Amhara	Mirab Gojam	Dembecha	2050	;1+	2-	2+	2+
TD3751	DW	Amhara	Mirab Gojam	Dembecha	2050	;1	2	;1	2-
TD3762	DW	Amhara	Mirab Gojam	Dembecha	2050	;1	2	;1	;1+
TD3764	DW	Amhara	Mirab Gojam	Dembecha	2050	;1	;1	;1	2-
TD8211	DW	Amhara	Mirab Gojam	Jabi Tehnan	2020	;	;1	;1	3-
TD8217	DW	Amhara	Mirab Gojam	Jabi Tehnan	2020	;1+	;1	;1+	2+
TD8218	DW	Amhara	Mirab Gojam	Jabi Tehnan	2020	;1	;1	;	;1
TD8746	DW	Oromiya	Mirab Wellega	Sayo	1900	3-	2+	3-	3-
TD8777	DW	Oromiya	Misrak Shewa	Adea	1900	;1	2+	;1	;1
TD8778	DW	Oromiya	Misrak Shewa	Ada'a Chukala	1900	3-	3-	2+	3-
TD8780	DW	Oromiya	Misrak Shewa	Ada'a Chukala	1900	3-	2+	2+	2+
TD8781	DW	Oromiya	Misrak Shewa	Ada'a Chukala	1900	3-	3-	2+	3-
TD3262	DW	Tigray	Misrakawi	Wukro	1945	2+	2+	;1+	3-
TD6309	DW	Amhara	Mirab Gojam	BureWemberma	2020	;1	;1+	2	;1
TD6984	DW	Oromiya	Arssi	Seru	1995	;1+	2	;1+	;1
TD6985	DW	Oromiya	Arssi	Seru	2000	3-	3-	2+	3-
TD8117	DW	Tigray	Mehakelegnaw	Adwa	1920	3-	2+	2+	3-
TD8118	DW	Tigray	Mehakelegnaw	Werie Lehe	1980	3-	2+	2+	3-
TD8119	DW	Tigray	Mehakelegnaw	Werie Lehe	2000	3-	2+	2+	2+
TD8121	DW	Tigray	Mehakelegnaw	Werie Lehe	1850	2+	2+	2	3-
TD8123	DW	Tigray	Mehakelegnaw	Werie Lehe	2000	2+	2+	2+	3-
TD8124	DW	Tigray	Mehakelegnaw	Werie Lehe	2000	3-	2	3-	3-
TD8504	DW	Oromiya	Misrak Shewa	Ada'a Chukala	1900	3-	2	2+	2+
TD8507	DW	Oromiya	Misrak Shewa	Lome	1860	;1+	2+	;1+	2+
TD8519	DW	Oromiya	Misrak Shewa	Ada'a Chukala	1980	3-	2+	2-	3-
TD8525	DW	Oromiya	Misrak Shewa	Ada'a Chukala	1900	2+	2+	2+	3-
TD8528	DW	Oromiya	Misrak Shewa	Ada'a Chukala	1950	3-	2+	2+	3-
McNair Universally *Pgt* susceptible host AARC						3	3	3	3

The scale described by [29,35] with IT readings of 3 (medium-size uredinia with/without chlorosis) and 4 (large uredinia without chlorosis or necrosis) considered as compatible (susceptible), while 0 (immune or fleck), 1 (small uredinia with necrosis), and 2 (small to medium uredinia with chlorosis or necrosis) as considered incompatible (resistant). Negative (-) = smaller uredinia than the normal size, and + larger than the normal uredinia

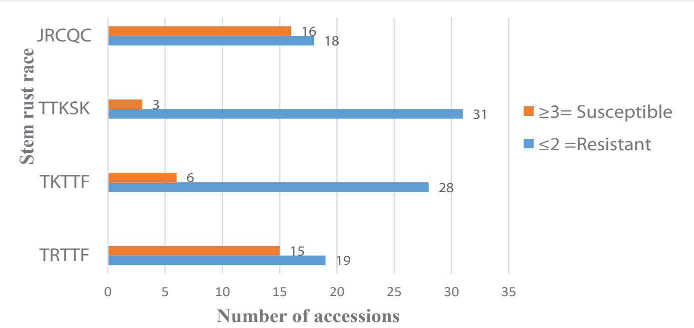

Figure 3: The frequency (number) of durum wheat landrace accessions under susceptible and resistant categories when exposed to four stem rust races (Susceptible≥ 3 and Resistance = ITs≤2.

estimated by disease severity at a certain crop development stage, Final Rust Severity (FRS), Final Coefficient of Infection (FCI), Average Coefficient of Infection (ACI) and Area Under Disease Progress Curve (AUDPC) were used from field phenotyping data and average seedling infection type from the seedling test as criterion to identify any possible source of partial resistance to stem rust disease [41].

Disease incidence and severity: The highest (92.5%) disease incidence was recorded from the accession TD8498, while the lowest incidence was detected from TD8778 (32.5%) and TD5917 (35%) (Table 5). TD8778 and TD5917 accessions reduced disease incidence by 64.86% and 62.16%, respectively, compared with TD8498. The highest (38.0%) mean disease severity was recorded from TD8119, followed by TD8498 (36.5%). The lowest mean disease severity was observed from TD8778 (6.8%) and TD5917 (7%) (Table 5). However, it was statistically at par with TD3750 (8.8%). TD8778 and TD5917 reduced mean disease severity by 82.19% and 81.68%, respectively, as compared to TD8119.

Final Rust Severity (FRS): Among the accessions evaluated, 10 accessions (29.41%) showed less than 30% FRS, with field responses varying from MR to MS-S. Five accessions had severities ranging from 30 to 50%, with field responses

Table 5: Responses of durum wheat accessions for wheat stem rust mean DI (%), DS (%), FRS, FCI, ACI, PSI, AUDPC (%-days), and r-AUDPC at DZARC, during the 2019/2020 main cropping season.

Genotype	DI	DS	FRS	FCI	ACI	PSI	AUDPC	$rAUDPC_1$	$rAUDPC_2$
TD8525	75.0^{a-g}	36.2^{cd}	63.0^{b-d}	56.7^{b}	31.33^{bc}	55.69^{cd}	1176^{b-d}	82.235^{b-d}	86.47^{b-d}
TD8218	60.0^{f-k}	25.6^{g-j}	53.0^{d-h}	47.7^{b-f}	20.51^{e-i}	39.38^{g-j}	792^{h-l}	55.385^{h-l}	58.235^{h-l}
TD8063	50.0^{h-m}	25.2^{h-k}	57.5^{d-f}	57.5^{b}	21.96^{d-h}	38.77^{h-k}	758^{i-l}	53.01^{i-l}	55.735^{i-l}
TD8781	62.5^{ek}	31.0^{d-h}	60.0^{c-e}	54.0^{bc}	24.15^{d-g}	47.695^{d-h}	980^{d-h}	68.53^{d-h}	72.06^{d-h}
TD8504	40.0^{k-m}	16.5^{m-o}	27.5^{jk}	24.75^{ij}	12.8^{j-m}	25.385^{m-o}	530^{m-o}	37.065^{m-o}	38.9^{m-o}
TD7226	47.5^{i-m}	21.9^{j-m}	52.0^{d-h}	52.0^{b-e}	19.6^{f-i}	33.695^{i-m}	648^{k-n}	45.315^{k-n}	47.65^{k-n}
TD8117	60.0^{f-k}	26.0^{g-j}	47.5^{f-h}	36.75^{f-h}	18.55^{f-j}	40.0g^{h-j}	830^{g-k}	58.045^{g-k}	61.03^{g-k}
Morocco	97.5^{ab}	42.0^{ab}	75.0^{a}	75.0^{a}	42.6^{a}	64.62^{ab}	1360^{ab}	95.1^{ab}	100^{ab}
TD6984	62.5^{e-k}	30.4^{d-h}	59.5^{c-e}	50.55^{b-e}	23.81^{d-g}	46.77^{d-h}	958^{e-i}	66.99^{e-i}	70.44^{e-i}
TD7364	47.5^{i-m}	18.0^{l-o}	25.0^{jk}	15.0^{j-m}	9.4^{lm}	27.69^{m-o}	600^{l-o}	41.96^{l-o}	44.12^{l-o}
TD8746	45.0^{j-n}	14.5^{n-p}	25.0^{jk}	15.0^{j-m}	7.9^{mn}	22.305^{m-o}	460^{n-p}	32.165^{n-p}	33.825^{n-p}
TD8118	57.5^{f-m}	26.5^{g-j}	50.0^{e-h}	40.0^{e-h}	18.1^{g-k}	40.77^{g-j}	840^{g-k}	58.745^{g-k}	61.765^{g-k}
TD5917	35.0^{l-m}	7.0^{q}	11.5^{m}	4.6^{mn}	2.34^{n}	10.77^{q}	222^{qr}	15.525^{qr}	16.325^{qr}
TD6985	72.5^{c-h}	27.3^{f-j}	56.5^{d-g}	56.5^{b}	22.6^{d-h}	42.0^{f-j}	846^{g-k}	59.16g^{h-k}	62.21^{g-k}
TD8119	87.5^{a-d}	38.0^{cb}	71.0^{ab}	42.6^{c-g}	20.22^{e-i}	58.77^{bc}	1224^{bc}	85.595^{bc}	90^{bc}
TD3750	42.5^{j-m}	8.8^{pq}	13.5^{lm}	5.4^{l-n}	2.88^{n}	13.54^{pq}	278^{p-r}	19.44^{p-r}	20.44^{p-r}
TD7365	50.0^{h-m}	16.5^{m-o}	30.0^{jk}	24.0^{ij}	11.8^{k-m}	25.385^{m-o}	520^{m-o}	36.365^{m-o}	38.235^{m-o}
TD8121	55.0^{f-m}	26.2^{g-j}	58.5^{d-f}	52.65^{b-d}	20.63^{e-i}	40.31^{g-j}	794^{h-l}	55.525^{h-l}	58.38^{h-l}
TD7227	50.0^{h-m}	19.5^{l-n}	35.0^{ij}	31.5^{hi}	15.0^{i-l}	30.0^{k-n}	620^{l-n}	43.355^{l-n}	45.59^{l-n}
TD3751	52.5^{g-m}	13.0^{op}	22.5^{kl}	18.0^{jk}	7.9^{mn}	20.0^{op}	400^{o-q}	27.97^{o-q}	29.415^{o-q}
McNair	100.0^{a}	44.0^{a}	77.5^{a}	77.5^{a}	43.4a	67.69^{a}	1430^{a}	100^{a}	105.15^{a}
TD6309	85.0^{a-e}	33.0^{c-f}	59.0^{de}	47.2^{b-f}	23.8^{d-g}	50.765^{c-f}	1064^{c-f}	74.405^{c-f}	78.235^{c-f}
TD3262	90.0^{a-c}	33.8^{c-e}	57.5^{d-f}	57.5^{b}	27.79^{cd}	52.0^{c-e}	1102^{c-e}	77.065^{c-e}	81.03^{cde}
TD8124	65.0^{d-j}	27.8^{e-j}	59.0^{de}	59.0^{b}	24.9^{d-f}	42.77^{e-j}	856^{g-k}	59.86^{g-k}	62.94^{g-k}
TD8211	75.0^{a-g}	31.5^{d-g}	57.5^{d-f}	57.5^{b}	23.7^{d-g}	48.465^{d-g}	1010^{d-g}	70.63^{d-g}	74.265^{d-g}
TD8123	92.5^{a-c}	33.5^{c-e}	60.0^{c-e}	51.0^{b-e}	26.9^{c-e}	51.54^{c-e}	1080^{c-f}	75.525^{c-f}	79.41^{c-f}
TD8528	70.0^{c-i}	28.2^{e-i}	57.5^{d-f}	48.75^{b-f}	20.11^{f-i}	43.385^{e-i}	878^{f-j}	61.395^{f-j}	64.555^{f-j}
TD8780	40.0^{k-m}	13.8^{n-p}	20.0^{k-m}	12.0^{k-n}	7.64^{mn}	21.23^{n-p}	452^{n-p}	31.61^{n-p}	33.235^{n-p}
TD3764	52.5^{g-m}	23.3^{i-l}	44.0^{hi}	32.4^{g-i}	17.58^{g-k}	35.845^{i-l}	736^{j-l}	51.47^{j-l}	54.12^{j-l}
TD8507	60.0^{f-k}	25.8^{g-j}	56.5^{d-g}	53.6^{b-d}	22.27^{d-h}	39.69^{g-j}	786^{h-l}	54.965^{h-l}	57.79^{h-l}
TD8778	32.5^{m}	6.8^{q}	10.0^{m}	3.0^{n}	1.56^{n}	10.46^{q}	212^{r}	14.83^{r}	15.59^{r}
TD8519	55.0^{f-m}	22.8^{i-l}	54.0^{d-h}	48.6^{b-f}	19.42^{f-i}	35.075^{i-l}	666^{k-m}	46.575^{k-m}	48.97^{k-m}
TD8217	60.0^{f-k}	22.3^{i-m}	46.0^{gh}	41.4^{d-h}	16.38^{i-k}	34.305^{i-m}	688^{j-m}	48.11^{j-m}	50.59^{j-m}
TD8777	77.5^{a-f}	31.0^{d-h}	62.5^{b-d}	44.0^{c-g}	18.9^{f-j}	47.69^{d-h}	970^{d-h}	67.835^{d-h}	71.325^{d-h}
TD3762	40.0^{k-m}	13.8^{n-m}	20.0^{k-m}	17.0^{j-l}	9.84^{lm}	21.23^{n-p}	452^{n-p}	31.61^{n-p}	33.235^{n-p}
TD8498	92.5^{a-c}	36.5^{b-d}	70.0^{a-c}	70.0^{a}	34.5^{b}	56.15^{cd}	1160^{c-e}	81.12^{c-e}	85.29^{c-e}
LSD (5%)	19.75	5.21	9.25	10.48	5.64	8.01	17.77	12.43	13.06
CV%	15.87	10.28	9.63	12.55	14.43	10.29	11.08	11.099	11.098

Abbreviation: DI: Disease Incidence; DS: Disease Severity; PSI: Percent Severity Index; FRS: Final Rust Severity; FCI: Final Coefficient of Infection; ACI: Average Coefficient of Infection; AUDPC: Area Under Disease Progress Curve; r-AUDPC: Relative Area under Disease Progress Curve; r-AUDPC-$_1$ and r-AUDPC-2: Relative Area under Disease Progress Curve with McNair and Morocco, respectively. Means in the same column followed by the same letter(s) are not statistically different at 5% level of significance according to DMRT (Duncan's Multiple Range Test).

varying from MR-MS to MS-S, while a greater number of the genotypes (19 accessions) displayed more than 50% final rust severities, which showed a susceptible type of reaction (MR-MS to S) (Appendix Table 1). Out of the 10 accessions in the first group (up to 30% FRS), TD3750, TD751, TD3762, and TD7365 had resistance seedling reactions (to 2+); TD7364, TD8504, and TD8780 had mixed seedling reactions (1+ to 3-) while TD5917, TD8746, and TD8778 showed susceptible (3- to 3) infection types. The susceptible check, Morocco, and McNair exhibited the highest disease severity of 77.5% with a completely susceptible (S) response.

Coefficient of Infection (CI): In this study eight accessions (TD7364, TD8746, TD5917, TD3750, TD3751, TD8780, TD8778 and TD3762) showed CI values between 0-20. These are designated as having a high level of slow-rusting. Six accessions (TD8504, TD8117, TD8118, TD73,65, TD7227, and TD3764) were under moderate levels of slow-rusting resistance (CI between 21 to 40). The other twenty accessions were grouped under low levels of slow-rusting resistance categories (CI value 40 – 60) (Table 5).

Area under the disease progress curve (AUDPC): The highest AUDPC (1430) and r-value (0.1312) were generated by the susceptible check variety, McNair, followed by Morocco (1360) with r-0.1235. Among the accessions, the highest AUDPC value was recorded from TD8119 (1224), and the lowest values were noted from TD8778 (212). Four accessions (TD5917, TD3750, TD3751, and TD8778) showed r-AUDPC values up to 30% of the check varieties McNair and Morocco. Twenty11 | Page-seven and twenty-four genotypes exhibited r-AUDPC1 and r-AUDPC2 values up to 70% of McNair and

Appendix Table 1: Durum wheat accessions under natural infection at Bishoftu Agricultural Research Center, during 2019 main season.(1). Wheat ranks as the second most signify.

Genotypes	FRR
TD8525	Ms^{ab}
TD8218	MR-MS^{bc}
TD8063	MSS^{ab}
TD8781	MSS^{ab}
TD8504	MSS^{ab}
TD7226	MSS^{ab}
TD8117	Ms^{abc}
Morocco	S^{a}
TD6984	MSS^{ab}
TD7364	MSS^{ab}
TD8746	MR-MS^{bc}
TD8118	MSS^{ab}
TD5917	Ms^{abc}
TD6985	Ms^{abc}
TD8119	Ms^{abc}
TD3750	MR^{b}
TD7365	MSS^{ab}
TD8121	MSS^{ab}
TD7227	MSS^{ab}
TD3751	Ms^{abc}
McNair	MSS^{ab}
TD6309	MR-MS^{bc}
TD3262	MSS^{ab}
TD8124	S^{a}
TD8211	S^{a}
TD8123	MSS^{ab}
TD8528	MSS^{ab}
TD8780	Ms^{abc}
TD3764	MSS^{ab}
TD8507	Ms^{abc}
TD8778	Ms^{abc}
TD8519	Ms^{abc}
TD8217	MSS^{abc}
TD8777	MR-MS^{bc}
TD3762	MSS^{ab}
TD8498	S^{a}
Lsd (5%)	2.7
Cv %	22.23

MR: Moderately-Resistance; MR-MS: Moderately-Resistance Moderately-Susceptible; MS: Moderately –Susceptible; MS-S: Moderately Susceptible- Susceptible and S: Susceptible field reaction response of wheat.

Morocco, respectively, expressing moderate slow rusting resistance, while the remaining had r-AUDPC >70% (Table 5).

Growth and yield-related components: The highest (92.05 cm) mean value for plant height was measured on the accession TD8121, while the shortest (51.9 cm) plant height was recorded from TD5917; the remaining accessions also varied from each other. TD3751 took the longest mean days to 50% flowering. TD5917 and TD8778 were ranked in the same mean height class, while the shortest duration was on TD8525, which was highly significantly different from TD3751, TD5917, TD8778, and TD8528 accessions. The longest mean day to 90% physiological maturity was recorded on TD8218, followed by TD3762. On the other hand, the shortest mean values were recorded on TD8525 accessions (Table 6). TD8525, TD8218, and TD3764 ranked in the same mean spike length class, while the shortest length was from the check variety Morocco, followed by accession TD8519. Accession TD8124 had the highest mean number of seeds per spike, followed by TD8778 and TD3751, which were statistically at par. Conversely, the lowest mean seed numbers were counted from the check variety Morocco, followed by TD 8519 (Table 6).

Grain yield: The result of the evaluation revealed that very highly negative correlation between yield and the stem rust disease parameter. About a 58.22% yield gap was recorded between the resistant (TD8778) and the susceptible accession (TD7227). The highest (3.59 t ha^{-1}) mean grain yield was obtained from TD8778, TD 3764 statistically at par; which was not significantly different from the mean grain yield obtained from TD8746 and TD8218. The lowest (1.5 t ha^{-1}) seed yield was recorded from the accession TD7227 which had significant grain yield reduction among tested accessions next to the check variety Morocco during the cropping season (Table 6). The final disease severity recorded on accessions TD8218 was 53% but the yield obtained from the accessions was higher than some accessions such as TD8504 and TD7227, that had low disease severities.

Among the slow-rusting accessions identified, TD8778 had the highest (3.59 t ha^{-1}) grain yield. The yields obtained from some of local wheat accessions, such as TD8781, TD8498, and TD7227, were below the yield of the susceptible variety McNair. Heavier (40.71 g) thousand seed weight was obtained from the accession TD8777 than others. But the lowest (25.32 g) seed weight was harvested from the accession TD8123 in the cropping season (Table 6).

Disease Progress Rate (DPR): Disease progress rates for the accessions ranged from 0.02315 to 0.11587 units/day. However, infection rates of all accessions were less than both Morocco and McNair. McNair had the highest (0.1312 units/day) disease progress rate than Morocco (0.1235 units/day) and landrace accessions. Most of the (18 accessions) had lower apparent infection rates, less than <0.10 units/day (Table 2). From the accessions, the highest (0.11587 units day^{-1}) disease progress rate was computed from TD8119, followed by TD8121 (0.1152 units day^{-1}) and TD8498 (0.11212 units day^{-1}). On the other hand, the lowest (0.02315 units day^{-1}) disease progress rate was calculated from TD8778, followed by TD3750 (0.03541 units day^{-1}) and TD5917 (0.04258 units day^{-1}). As compared to Morocco and McNair (susceptible check), TD8119, TD8121, and TD8498 had the highest disease development. On the contrary, the accessions TD8778, TD3750, and TD5917 had the lowest disease development. Accession TD8778 had the least disease progress rate compared to the whole treatments that were used or tested.

Correlation among slow-rusting parameters, thousand kernel weight, and disease parameters

The associations among disease parameters (DI, DS, FRS,

Table 6: Growth, yield, and yield-related components of durum wheat accessions were evaluated for their resistance reaction against wheat stem rust under field conditions at DZARC, Central Ethiopia, during the 2019/2020 main cropping season.

Genotype	DH	DTM	PH	SPL	NKPSP	TKW	BMY	GY	HI
TD8525	69.5^{i}	98^{h}	56.10^{h-j}	8.57^{a}	37.2^{a-d}	35.89^{a-e}	3.68^{d-g}	1.72^{ef}	46.83^{b-g}
TD8218	76^{c-i}	125.5^{a}	76.60^{a-g}	8.5^{a}	35.93^{a-d}	27.01^{hg}	5.79^{a-f}	3.27^{ab}	55.5^{a-f}
TD8063	82.5^{a-g}	103^{f-h}	58.00^{f-j}	7.1^{a-e}	35.28^{a-e}	38.61^{a-c}	3.23^{g}	1.91^{c-f}	58.49^{a-e}
TD8781	72.5^{e-i}	114.0^{a-f}	67.20^{b-j}	8.4^{ab}	38.32^{ab}	34.89^{a-f}	3.56^{e-g}	1.62^{f}	45.36^{c-g}
TD8504	86.5^{a-c}	109.5^{b-h}	74.10^{a-h}	7.14^{a-e}	36.67^{a-d}	30.97^{d-h}	6.0^{a-e}	2.56^{a-f}	51.26^{d-g}
TD7226	84 $^{a-e}$	117.5 $^{a-e}$	70.95^{b-j}	7.93^{a-c}	36.57^{a-d}	31.89^{d-h}	4.95^{a-g}	3.11^{a-d}	62.2^{a-d}
TD8117	75.5^{c-i}	112.5^{a-g}	83.65^{a-c}	6.33^{de}	31.4^{e-g}	26.92^{hg}	6.41^{a-c}	2.54^{a-f}	39.78^{f-h}
Morocco	72^{f-i}	116.1^{a-f}	67.20^{b-j}	5.97^{e}	27.44^{g}	27.32^{f-h}	3.45^{fg}	1.46^{f}	42.96^{d-h}
TD6984	71.5^{g-i}	109.5^{b-h}	78.80^{a-e}	7.07^{a-e}	34.85^{a-e}	32.12^{b-h}	6.17^{a-d}	2.5^{a-f}	41.86^{e-h}
TD7364	83.5^{a-f}	113^{a-g}	74.50^{a-h}	6.37^{de}	34.28^{a-e}	30.67^{f-h}	4.61^{a-g}	2.00^{b-f}	42.04^{e-h}
TD8746	84^{a-e}	100^{gh}	82.90^{a-d}	7.9^{a-c}	36.22^{a-d}	29.64^{f-h}	6.47^{a-c}	3.28^{ab}	51.76^{a-g}
TD8118	84.5^{a-d}	113.5^{a-f}	63.70^{d-j}	8.2^{ab}	37.33^{a-c}	39.9^{a}	4.61^{a-g}	2.67^{a-f}	57.74^{a-f}
TD5917	90.5^{a}	113^{a-g}	51.90^{j}	7.4^{a-e}	35.82^{a-e}	39.66^{ab}	4.33^{c-g}	2.52^{a-f}	58.24^{a-e}
TD6985	76 $^{c-i}$	109.5^{b-h}	57.50^{f-j}	7.07^{a-e}	34.1^{c-e}	36.68^{a-e}	4.06^{c-g}	2.34^{a-f}	57.41^{a-f}
TD8119	74^{e-i}	111^{b-h}	78.50^{a-e}	7.27^{a-e}	33.3^{c-f}	27.82^{f-h}	7.11^{a}	2.34^{a-f}	32.55^{gh}
TD3750	84.5^{a-d}	108^{c-h}	77.15^{a-f}	7.84^{a-d}	36.94^{a-d}	37.72^{a-d}	6.16^{a-d}	2.95^{a-e}	48.32^{a-h}
TD7365	83^{a-g}	114^{a-f}	57.65^{f-j}	7.9^{a-c}	36.75^{a-d}	31.29^{c-h}	5.17^{a-g}	2.61^{a-f}	50.4^{a-g}
TD8121	77^{c-i}	108^{c-h}	92.05^{a}	7.77^{a-d}	36.55^{a-d}	27.3^{f-g}	7.05^{ab}	2.33^{a-f}	33.09^{gh}
TD7227	86 $^{a-c}$	111.5^{b-g}	72.40^{a-h}	8.17^{ab}	37.43^{a-c}	40.23^{a}	4.11^{c-g}	1.5^{f}	39.13^{e-h}
TD3751	92^{a}	111.5^{b-g}	67.95^{b-j}	8.34^{ab}	37.75^{a-c}	36.01^{a-e}	4.67^{a-g}	2.67^{a-f}	57.68^{a-f}
McNair	70.5^{hi}	116.5^{a-f}	63.55^{d-j}	6.5^{c-e}	32.67^{d-f}	25.49^{h}	4.44^{c-f}	1.72^{fg}	38.75^{f-h}
TD6309	75^{c-i}	110.6^{b-h}	78.75^{a-e}	8.07^{ab}	37.42^{a-c}	31.66^{c-h}	6.06^{a-e}	3.11^{a-d}	51.11^{a-g}
TD3262	72^{f-i}	109.5^{b-h}	73.85^{a-h}	8.47^{ab}	37.25^{a-d}	30.93^{d-h}	5.0^{a-g}	2.42^{a-f}	47.67^{b-h}
TD8124	80.5^{a-i}	114.4^{a-f}	62.15^{e-j}	8.3^{ab}	38.88^{a}	31.57^{c-h}	4.56^{b-f}	3.0^{a-e}	66.2^{ab}
TD8211	72$_{f}^{-i}$	105.5^{d-f}	73.35^{a-h}	7.47^{a-e}	34.84^{a-e}	34.12^{a-g}	5.20^{a-g}	2.39^{a-f}	45.67^{c-g}
TD8123	72^{f-i}	120.5^{a-c}	84.00^{ab}	6.97^{c-e}	34.66^{a-e}	25.32^{h}	6.12^{a-d}	1.84^{d-f}	30.35^{h}
TD8528	71.5^{g-i}	112^{b-g}	69.10^{b-j}	7.8^{a-d}	37.24^{a-d}	29.62^{e-h}	5.12^{a-g}	2.45^{a-f}	47.44^{b-g}
TD8780	88^{ab}	109^{c-h}	63.95^{d-j}	7.74^{a-d}	37^{a-d}	27.81^{f-h}	4.17^{c-g}	2.39^{a-f}	57.4^{a-f}
TD3764	83^{a-g}	119^{a-d}	54.65^{h-j}	8.5^{a}	37.1^{a-d}	29.23^{e-h}	5.61^{a-g}	3.55^{a}	63.5^{a-c}
TD8507	83^{a-g}	117.5^{a-e}	66.65^{b-j}	7.97^{a-c}	35.65^{a-e}	27.74^{f-h}	5.28^{a-g}	1.72^{ef}	32.9^{gh}
TD8778	90.5 ^{a}	118.1^{a-e}	52.65^{ij}	7.97^{a-c}	38.54^{ab}	35.77^{a-e}	5.45^{a-g}	3.59^{a}	65.88^{ab}
TD8519	80.5^{a-h}	118.5^{a-d}	70.70^{b-j}	6.0^{e}	32.55^{gf}	34.78^{a-f}	5.39^{a-g}	2.56^{a-f}	47.26^{b-g}
TD8217	78.5^{b-h}	119^{a-d}	56.65^{h-j}	7.77^{a-d}	36.83^{a-d}	40.71^{a}	5.89^{a-f}	3.06^{a-d}	51.32^{a-g}
TD8777	71.5^{g-i}	104.5^{e-h}	52.55^{ij}	8.14^{ab}	37.49^{a-c}	31.09^{c-h}	5.56^{a-g}	3.17^{a-c}	57.26^{a-f}
TD3762	81.5^{a-h}	122.5^{ab}	56.95^{g-j}	8.23^{ab}	37.17^{a-d}	37.62^{a-d}	4.34^{c-g}	2.93^{a-e}	67.23^{a}
TD8498	72.5^{e-i}	118.5^{a-d}	68.15^{b-j}	8.3^{ab}	37.1^{a-d}	36.18^{a-e}	3.67^{d-f}	1.59^{f}	43.24^{d-g}
Lsd (5%)	9.54	12.34	15.89	1.41	4.21	6.84	2.07	1.12	15.27
Cv%	5.94	4.88	11.85	8.14	5.22	9.50	18.64	20.09	13.75

[a)] DH Days to 50% heading (days); DTM Days to 90% physiological maturity (days); PH Plant height (cm); SPL Spike length (cm); NKPSP Number of kernels per spike; TKW thousand kernel weight (g); BMY Biomass yield; GY Grain yield (t ha$^{-1)};$ and HI harvest index. Means in the same column followed by the same letter(s) are not significantly different at 5% level of significance according to DMRT.

FCI, ACI, PSI, and AUDPC), growth, yield, and yield-related components were examined using simple correlation analyses. Variable levels of relationships found among disease, growth, and yield parameters (Table 7). In this study, a high and strong positive correlation at the $p \leq 0.0001$ level of significance was noted among all the epidemiological parameters: FRS, FCI, ACI, PSI, and AUDPC, which were used to assess partial resistance (Table 7). These epidemiological parameters give a dependable rate of disease increase and are related to components of partial resistance, like low receptivity, longer latent period, and smaller pustules. The correlations among the field-based slow-rusting parameters are positive and highly significantly correlated with correlation coefficients ranging from 0.801 to 1. Association results showed a very strong positive correlation ($r = 0.999999^{,****}$ nearly approximate ($r = 1^{****}$) and very highly significant ($p < 0.0001$) level of association between disease severity and AUDPC values (Table 7). AUDPC becomes directly proportional to final disease severity, resulting in an approximately linear relation [42]. Both disease incidence and severity had positive and very highly significant ($p \leq 0.0001$) correlations with AUDPC, CI, and FRS. The high correlation coefficient was also computed between AUDPC and final rust severity.

Plant height had a significant and positive correlation with days to 50% heading, days to 90% physiological maturity, spike length, the number of kernels per spike, and thousand kernel weight. Days to 50% heading showed a significant and positive correlation with days to 90% physiological maturity. Number of kernels per spike had a significant ($p \leq 0.05$) and positive correlation ($r = 0.356^{*}$) with grain yield and a significant positive correlation ($r = 0.340^{*}$) with thousand kernel weight. The grain yield increases when the number

Table 7: Coefficients of correlation (r) among disease, growth, and yield parameters of durum wheat accessions at Bishoftu Agricultural Research Center, during the 2019 main cropping season.

Parameters	DH	DTM	PH	SPL	NKPSP	TKW	BMY	GY	HI	DI	DS	FRS	FCI	ACI	PSI	AUDPC
DH	1															
DTM	0.10*	1														
PH	0.23*	0.10*	1													
SPL	0.13	-0.01	-0.231	1												
NKPSP	0.29	0.08*	0.232*	0.875****	1											
TKW	0.36	-0.112	0.469***	0.271	0.340*	1										
BMY	-0.04	0.015	0.583***	-0.056	-0.019	-0.409*	1									
GY	0.35*	0.14	-0.127	0.329*	0.356*	0.047*	0.508**	1								
HI	0.45***	0.112	0.638****	0.404**	0.417*	0.423**	--0.305*	0.652****	1							
DI	0.83****	-0.001	0.171	-0.156	-0.348*	-0.370*	-0.068*	-0.433**	-0.456**	1						
DS	-0.88****	-0.038	0.182	-0.173	-0.369*	-0.394*	-0.101*	-0.485**	-0.471**	0.929****	1					
FRS	-0.83****	0.001	0.169	-0.154	-0.352*	-0.351*	-0.071	-0.424**	-0.417*	0.851****	0.961****	1				
FRC	-0.77****	0.049	0.112	-0.148	-0.336*	-0.266	-0.23	-0.480**	-0.345*	0.801****	0.907****	0.957****	1			
ACI	-0.79****	0.054	0.104	-0.205	-0.406*	-0.347*	-0.268	-0.546***	-0.400**	0.869****	0.944****	0.92****	0.953****	1		
PSI	-0.88****	-0.038	0.182	-0.173	-0.369*	-0.394*	-0.101	-0.485**	-0.471**	0.929****	1****	0.961****	0.907****	0.944****	1	
AUDPC	-0.88****	-0.048	0.182	-0.174	-0.367*	-0.399*	-0.108	-0.495**	-0.479**	0.936****	0.998****	0.939****	0.884****	0.939****	0.0.997****	1

DH: Days to 50% Heading (days); DTM: Days to 90% physiological maturity (days); PH : Plant Height (cm); SPL: Spike Length (cm); NKPSP: Number of Kernel Per Spike; TKW: Thousand Kernels Weight (g); BMY: Biomass Yield(t ha^{-1}); GY: Grain Yield (t ha^{-1}); HI: Harves index; DI: Disease Incidence; DS: Disease Severity; PSI: Percent Severity Index; FRS: Final Rust Severity; FCI: Final Coefficient of Infection; ACI: Average coefficient of Infection and AUDPC: Area Under Disease Progress Curve; **** Correlations is very highly significant at <0.0001 level. *** Correlations are highly significant at the 0.001 level. ** Correlation is significant at the 0.01 level. *Correlation is significant at the 0.05 level.

of kernels per spike increases. The correlation coefficients considered between pairs of the respective disease parameters (DI, DS, FRS, FCI, ACI, PSI, and AUDPC) and TKW were highly and negatively correlated. When the disease epidemiology increases, the plant pathogen affects the rate of photosynthesis and affects the nutrient supply of the host. This can affect reducing TKW, NKPSP, and the total above-ground biomass of the genotypes. Days to 50% heading have a highly significant ($p < 0.0001$) negative correlation with disease slow rusting parameters. The negative highly correlated (r = -0.88, $p < 0.0001$) of AUDPC and DH showed that early heading accessions tend to have higher late heading accessions show lower disease progression. A very strong correlation of DH and AUDPC, DS, DI, PSI, FRS, and ACI reinforces that the early heading is associated with more disease or favors disease development. Grain yield slightly positive correlation (r = 0.35*, $p < 0.05$) with DH, revealing that later heading tends to yield more due to a longer growth period or reduced disease exposure. On the other hand, higher HI increases yield (r = 0.45*, $p < 0.05$). A very strong positive correlation between SPL and NKPSP (r = 0.875*****, $p < 0.001$), HI and PH (r = 0.638, $p < 0.001$) indicates that longer spike gives more kernels and taller plants have better resources. AUDPC is very highly correlated with the disease parameter used as an integrated measure of disease progress [42]. Higher disease pressure significantly reduces grain yield, harvest index, and other yield components. This revealed that stem rust epidemics reduce photosynthetic area, causing significant loss [43]. The strongest impact is on GY and HI, which are direct indicators of plant productivity. Disease pressure is not strongly influenced by plant parameters. AUDPC negatively correlates with TKW because disease reduces grain filling through assimilated translocation disturbance [44].

Discussion

The identification of resistance traits of durum wheat landrace accessions, by exposing them to various *Puccinia graminis tritici* pathotypes, assesses the presence and effectiveness of resistance genes through seedling testing. The gene-for-gene theory is a fundamental concept that explains how specific resistance in plants, such as durum wheat accessions, is determined by the interaction between host resistance genes and pathogen avirulence genes. There is a corresponding avirulence gene in the pathogen for every resistance gene found in the host plant (Table 2). The interaction leads to a race-specific resistance mechanism, where the effectiveness of the plant's defense response depends upon the compatibility of these genetic components.

The compatible reaction of durum wheat landrace accessions (TD5917) and McNair indicates that it does not have any major gene or has fewer effective genes against the examined pathotypes. This result agrees with [45] and [40]; a high IT on a tested accession means that it lacked any of the resistance genes for the examined pathotype. However, these accessions may contain resistance genes to the races not included in this test or under natural settings. Because the TD5917 accession is resistant to natural epidemics.

Based on the result, incompatible reaction of 14 landrace accessions (TD7226, TD7227, TD7365, TD8489, TD3750, TD3751, TD3762, TD3764, TD8217, TD8218, TD8777, TD6309, TD6984 and TD8507) to different races may possess identified resistance genes and may also have more unidentified resistance genes, because these accessions either have other resistance genes that are not yet recognized or most likely carry the resistance gene Sr24, which is effective against all tested races or might have any of the genes, either alone or in combination, for which the test pathotypes exhibited avirulence [45]. This result revealed that [46] and [47] suggested that the presence of two or more minor genes may imply multiple (horizontal) disease resistance, or the presence of an effective main R-gene against several races may be indicated by an incompatible response to two or more races.

Most of the accessions used in this greenhouse investigation showed low compatible infection reactions. The seedling evaluation result revealed some varying degrees of accessions variability in responses to the TTKSK, TKTTF, TRTTF, and JRCQC races. This may be the presence of an effective main R-gene against several races [47].

All the races employed in this investigation demonstrate variation in reactivity among test genotypes, with the majority of the genotypes exhibiting resistance reaction with scores ranging from 0 to 2+ (Figure 2). Identifying these sources of resistance and creating resistant cultivars are essential in relation to stem rust outbreaks. Seedling resistance to stem rust is often conferred by specific resistance (R) genes. These genes can provide effective resistance against various races of the pathogen. Notable R genes include Sr31, Sr24, and Sr36, which have been widely studied and utilized in breeding programs. The results of this evaluation (Table 4) highlight the diversity of resistance among the landrace accessions and also serve as a valuable resource for breeding programs aimed at enhancing disease resistance in durum wheat. This finding confirms that Ethiopian durum wheat landrace accessions have high levels of stem rust resistance [48].

Disease parameters, yield, and yield-related components data showed significant variation among treatments. Typical characteristic symptoms of the rust first appeared on check varieties. The mean rust severity on durum accessions revealed different levels of damage. Analysis of variance showed that there were highly significant ($p < 0.0001$) differences among the tested accessions for disease incidence and disease severity (Table 5). This result revealed that genetic diversity among accessions can lead to varying levels of resistance to diseases [49].

There was a wide variation in the stem rust mean FRS, ranging from 10 to 77.5% during the cropping season (Table 4). Diverse field reactions ranging from Resistant (R) to susceptible (S) responses were observed. Analysis of variance showed that there were highly significant ($p < 0.0001$) differences among tested accessions for final rust severity. There was considerable variation in the final rust severities of the accessions tested, which might be due to differences in the number of resistance genes present and the mode of gene action. Wheat accessions with FRS values of 1%–30%, 31%–50% and 51%–70% were regarded as possessing high, moderate, and low levels of slow rusting resistance, respectively [50]. Accessions (TD3750, TD751, TD3762 and TD7365, TD7364, TD8504, TD8780, TD5917, TD8746 and TD8778) with a low FRS (1%-30%) under high disease pressure may possess more additive genes or genes with larger effects [51]. FRS represents the cumulative result of all resistance factors during the progress of epidemics. [52] and [21] also used final severity as a parameter to assess the slow rusting behaviour of wheat.

Some of the accessions showed low to moderate severity (<20) at natural epidemics, and this would give a chance to identify valuable accessions for future breeding and pathological research. From the seedling and field response against stem rust of wheat at natural epidemics, three accessions (TD3750, TD3751, and 3762) showed resistance for both the seedling and adult-plant stages (Tables 4 and 5). Possibly, these accessions might have all-stage resistance [53]. Accessions (TD7226, TD7227, TD8489, TD3764, TD8217, TD8218, TD8777, TD6309, TD6984, and TD8507) possessed seedling resistance (Table 4), but failed to protect at the adult-plant stage (Table 5). The seedling resistance is not growth stage-dependent, does not always protect against rust at adult-plant stages [53]. A genotype resistance at the seedling stage alone is not sustainable and effective for long-term deployment [44]. Often, seedling resistance is governed by major gene(s), and frequent mutations in corresponding avirulence genes in the rust pathogen may lead to catastrophic failure of the crop [54].

Three accessions, TD5917, TD8746, and TD8778, showed susceptible seedling reaction but resistance to natural epidemics. However, three accessions (TD7364, TD8780, and TD8504) showed intermediate seedling reaction and field-resistant reaction at natural epidemics. Field resistance is often effective against a wide range of pathogen races and considered more durable, providing resistance without being readily overcome by the change in pathogen virulence when the cultivar is widely grown in an area where the disease is prevalent [55]. The deployment of cultivars carrying APR based on multiple genes is particularly preferred to delay infection, growth, and reproduction of the pathogen in adult plants and circumvent "boom-and-bust" cycles [56].

Based on host plant and pathogen interaction, there was a highly significant ($P < 0.0001$) difference in the CI value. Eight accessions (TD7364, TD8746, TD5917, TD3750, TD3751, TD8780, TD8778, and TD3762) showed CI values between 0-20, designated as having a high and good level of slow-rusting (Table 5). Six accessions (TD8504, TD8117, TD8118, TD7365, TD7227, and TD3764) showed moderate levels of slow-rusting resistance, which means CI value between 21 to 40 categories; the other twenty accessions were grouped under low levels of slow-rusting resistance categories (CI value 40 - 60) [57]. Slow-rusting resistance to wheat stem rust using the coefficient of infection expresses the presence of different partial resistance conferring genes in wheat accessions [58-60].

According to ANOVA results, there was a highly significant ($p \leq 0.0001$) difference in AUDPC. According to [61-63], AUDPC is a good indicator of adult plant resistance under field conditions. It is directly related to yield loss according to [64] for each 1 percent increase in AUDPC, there is a corresponding 1.8–2.0 kg/ha drop in grain yield, and provides critical information for designing effective disease management practices for accessions with different levels of resistance [42]. Accession TD5917, TD3750, TD3751, and TD8778, which had low AUDPC and terminal severity values may have high level of field resistance [32] These Accession had AUDPC up to 30% of the check varieties and had MR to MS types of infection in the field and were considered to have good levels of partial resistance and expressing good levels of slow- rusting. This revealed that accession with variable field infection responses of MR-MS to S are expected to possess genes that confer partial resistance [65,66]. Therefore, selection of an accession having low AUDPC with terminal disease score is normally accepted for practical purposes where slow rusting resistance is utilized as one of the slow resistances [67,68].

According to analysis of variance (ANOVA), days of 50% heading, days to 90% physiological maturity, plant height, spike length, number of kernels per spike, and thousand kernel weight were highly significant ($p < 0.001$) for the tested accessions. Biomass yield and harvest index were significantly ($p \leq 0.05$) varied (Table 6). Grain yield and TKW were highly significant ($p < 0.001$) differences among the tested accessions. From the outset, it should be emphasized that the differences in grain yield among the entries could be explained not only by differences in the levels of disease attack, but also in the yield potential of the varieties. Stem rust reduces the grain yields of wheat cultivars [69-71]. Thus, the best accession for grain yield was selected and advanced to the next stage of evaluation. Even if accession TD8121 had the highest plant height and high spike length, the yield was not high because the FRS (58.5) and AUDPC (794) were high, i.e, the accession was highly infested with rust. The lowest (1.5 t ha^{-1}) seed yield was recorded from the accession TD7227, which had a significant grain yield reduction among the tested accessions. The yield from heavily rusted plants is, therefore, much reduced, and the quality of the grain is lowered, and the grains would shrivel. The effect of rust on grain yield is due to the great injury to the photosynthetic surface of the plant [72,73] and the energy expenditure in plant defence mechanisms rather than for growth and grain formation [43] According to [74] rust infection lowers leaf water potential and turgor in both infected and adjacent uninfected tissues, highlighting impairment of water relations even under well-watered conditions. Also, [75] and [76] suggested that the fungus also reduces the food and water supply within the plants. The fungus needs food and water for spore production that would otherwise be used in the formation of well-developed kernels. Further, there is a loss of water by evaporation through the numerous ruptures caused by the fungal pustules. The final disease severity recorded on accession TD8218 was 53% but the yield obtained from the accession was higher than some accessions, such as TD8504 and TD7227, that had low disease severities. These revealed that accessions that have high disease severity recorded gave higher yield than some accessions that had low disease severity [52]. Accession (TD8778) that had comparatively better yield (3.59 t ha^{-1}) makes it a superior candidate as a gene donor parent for the incorporation of durable resistance into the durum wheat improvement programme. The yields obtained from accessions TD8781, TD8498, and TD7227 were below McNair due to their lower genetic potential for yield. Although there were variations in grain yields among the entries, there was no protected check plot established for each accession to obtain information to calculate yield loss (Table 6).

Disease development showed significantly different rates of progression. Accession TD8778 had the least disease progress rate (0.023) compared to the whole treatments that were evaluated. Infection rate showed more variation among the tested accessions than disease severity and AUDPC, and it did not distinguish accessions displaying different levels of slow-rusting resistance regarding other parameters. For example, the accession TD5917 had FRS, CI, and r-AUDPC less than the accession TD3750, but its infection rate was higher (0.425) (Table 7). These results were in agreement with the stem rust and leaf rust of wheat [57,77-79] infection rate should be used in combination with other disease parameters.

A very high and strong positive correlation was noted among all the epidemiological parameters: FRS, FCI, ACI, PSI, and AUDPC, which were used to assess partial resistance at $p \leq 0.001$. These epidemiological parameters give a dependable rate of disease increase and are related to components of partial resistance, like low receptivity, longer latent period, and smaller pustules [80]. Association results showed a very strong positive correlation ($r = 1^{****}$) and a very highly significant ($p < 0.0001$) association between disease severity and AUDPC values. The high correlation coefficient was also computed between AUDPC and final rust severity($r = 0.939^{****}$). This implies that there is an increase in disease parameters. This finding was in agreement with [52] and [81], who found that severity and AUDPC have the highest and very strong positive correlation. Severity and AUDPC also had positive and very highly significant ($p \leq 0.0001$) correlations with disease incidence. The positive correlations among the parameters observed are in agreement with the results of other researchers on cereal rust patho-systems [78,79,82]. All disease parameters were highly correlated in the present study, suggesting that FRS and CI are considered as preferable selection parameters or criteria. There were strong negative correlations ($r = -0.424^{**}$ and -0.546^{**}) between final severity, coefficient of infection) and grain yield, respectively. This implies that when there is an increase in disease parameters, there is a decrease in yield parameters and vice versa. The overall results of the correlation analysis suggest a strong negative association between stem rust and the yield component. TD8778 had a low AUDPC (212) (Table 5) and a low coefficient of infection. It has a good level of resistance [50,83,84] reported higher selection gains of slow rusting resistance using low final ratings CI and AUDPC under field conditions.

The correlation coefficients considered between pairs of the respective disease parameters (DI, DS, FRS, FCI, ACI, PSI, and AUDPC) and TKW were highly and negatively correlated (Table 7). The negative relationship between TKW and disease parameters showed the harmful effects of stem rust on this yield component (TKW). The large negative correlations between TKW and stem rust parameters could be attributed the fungus damages vascular system of the susceptible host plant extensively limiting the transportation of water and nutrients from the soil to the developing kernel and other organs as well as interfering with translocation of photosynthate, which leads to shrivelled grains [84-86]. Further, the present study detected high correlations for infection parameters and yield variables suggesting that the ranking of the wheat accession for these variables did not change significantly over time. Several other studies also concluded that disease and yield parameters have negative associations [87-89] for various reasons and could result in recognizable yield reductions.

Based on the above investigation of the coefficient of infection (0-20) and AUDPC TD8778, TD5917, TD3750, TD3751, TD3762, TD8746, and D7364 accessions had better field resistance and performance. Accessions TD3750, TD3751 3751 and TD3762 were resistant to the prevailing race at the seedling stage. [90,91] suggested that when genotypes show rust resistance at both seedling and adult plant stages, it can be referred to as all-stage resistance. However, accession TD5917 was susceptible to all races, and TD8778 was susceptible to three race combinations at the seedling stage. The deployment of accession carrying adult plant resistance based on multiple genes is particularly preferred to delay infection, growth, and reproduction of the pathogen in adult plants and circumvent "boom-and-bust" cycles [70]. Based on FRS (<30s), CI (<20), and AUDPC (30%) of the check variety, the accessions TD3750, TD751, TD5917, and TD8778 exhibited a high level of partial resistance. While accession TD3762, TD7365, TD8746, TD7364, TD8504, TD8780 had FRS (<30s), CI (<20), and AUDPC above30% and 70% of the chick variety expressing moderate slow rusting resistance. The remaining accessions have a low level of resistance.

Conclusion and recommendation

A high level of variability in responses of accessions to the prevailing races (TTKSK, TKTTF, TRTTF, and JRCQC) and the majority (fourteen landrace accessions) of the accessions showed resistance reaction (to 2+). All races were positive and highly correlated with each other's i.e, have some common virulence and avirulence genes for the pathogens. From the field experiments, there was phenotypic variation of infection types and level of stem rust severity for wheat accessions with terminal scores ranging from 10 (MR) to 75 S (highly susceptible). Between the check and accessions, there are highly significant ($P \leq 0.0001$) differences among different disease parameters (DI, DS, FRS, FCI, AUDPC, and ACI) and TKW. The greater number of accessions were grouped under the MR and S types of reaction to final rust. Landrace accessions TD3750, TD3751, and 3762 showed both seedling and adult-plant stages resistance at natural epidemics, which can be referred to as all-stage resistance. However, three accessions, TD5917, TD8746, and TD8778, showed seedling susceptibility but adult plant resistance at natural epidemics.

Correlation coefficients for slow rusting parameters were positive and highly significant ($P \leq 0.0001$). Yield parameters also had a positive correlation among themselves. The disease parameters maintained a negative and highly significant relationship with yield traits. Grain yield had a highly significant ($p \leq 0.001$) and positive correlation with the number of kernels per spike and a significant positive correlation with thousand kernel weight. However, slow rusting parameters and TKW were highly and negatively correlated.

In conclusion, developing novel resistant wheat cultivars may benefit from the use of these accessions in breeding operations. By pyramiding several stem rust resistance genes, it is crucial to increase the genetic base of stem rust resistance in future wheat cultivars. The effectiveness of these landrace accessions found in the current study, which also includes other Sr genes, requires additional molecular investigation in order to determine the cause of their resistance and apply it to wheat breeding initiatives. Based on field and greenhouse evaluation, accessions TD3750, TD751, TD5917, and TD8778 exhibited a high level of partial resistance. Of these, TD5917 and TD8778 have true slow rusting resistance, and TD3750 and TD3751 were resistant to prevailing races in the greenhouse and have a good level of field resistance. So, they have all-stage resistance. Among the slow-rusting accessions, comparatively better TKW and grain yields were produced by TD5917 (39.66 g) and TD8778 (3.59 t ha^{-1}), respectively. The slow-rusting accession (TD3750, TD751, TD5917, and TD8778) identified from this study can be used for durable stem rust resistance breeding. Such Ethiopian durum wheat landraces accessions accessions are an important source to develop resistant cultivars for rust disease outbreaks and other major diseases. Further study is required across locations for the compatibility study and factors contributing to the disease epidemic for early warning, and to assess the association of wheat stem rust intensity and yield loss of the identified accessions with the comparison of protected standard check. Molecular investigation is necessary to identify an effective source of genes for their resistance.

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Availability of data

The article includes the data that was utilized to support the study's conclusions.

Contributions of the authors'

The authors made meaningful contributions to this study in data collection and editing of the manuscript.

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