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STEM RUST SEEDLING RESISTANCE GENES IN ETHIOPIAN WHEAT CULTIVARS AND BREEDING LINES

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ABSTRACT

Stem rust caused by *Puccinia graminis* f. sp. *tritici* is one of the major biotic limiting factors for wheat production in Ethiopia. Host plant resistance is the best option to manage stem rust from its economic and environmental points of view. Wheat cultivars are released for production without carrying race specific tests against stem rust. Hence, genes responsible for resistance in commercial wheat cultivars are not known. The objective of this study was to postulate stem rust resistance genes present in Ethiopian commercial wheat cultivars and advanced breeding lines. Thirty durum wheat (19 commercial cultivars and 11 breeding lines) and 30 bread wheat (20 commercial cultivars and 10 breeding lines) were tested for gene postulation. Stem rust infection types produced on wheat cultivars and breeding lines by ten Pgt races was compared with infection types produced on 40 near isogenic lines carrying single stem rust resistance genes. A total of 11 stem rust resistance genes (*Sr5, Sr7a, Sr7b, Sr8a, Sr9e, Sr11, Sr21, Sr27, Sr29, Sr30* and *Sr37*) were postulated to be present either singly or in combination in the durum and wheat cultivars and breeding lines. Except *Sr30*, the other postulated genes were susceptible to most of the prevalent *Puccinia graminis* f. sp. *tritici* races in Ethiopia. Since *Sr30* is also ineffective against Ug99, a gene management strategy that incorporates a combination of genes (gene pyramiding) that provide sufficient protection should be devised to achieve a durable control of stem rust. In addition, the significance of *Sr27*, *Sr29* and *Sr37* has to be investigated for Ethiopian agriculture.

Key Words: Durum wheat, isogenic lines, *Puccinia graminis*

RÉSUMÉ

La rouille de tiges causée par*Puccinia graminis* f. sp. *tritici*est un facteur majeur limitant de la production du blé en Ethiopie. La résistance de la plante hôte constitue une meilleure optionpour la gestion de cette rouille sur le plan économique et environnemental. Les cultivars du blé sont émis pour la production sans aucun test spécifique contre la rouille de tiges. Ainsi, les gènes responsables de résistance dans les cultivars de blé commercial ne sont pas connus. L'objectif de cette étude était de postuler les gènes de résistance de la rouille de la tige présents dans les cultivars de blé commercial et lignées améliorées.Trente variétés de blé dur (19 cultivars de blécommercial et 11 variétés améliorées) et 30 variétés de blé pour pâtisserie (20 cultivars de blé commercial et 10 de lignéesaméliorées) étaienttestés).Les types d'infections de la rouille produits sur les cultivars de blé et sur les lignées améliorées par 10 races *Pgt* étaient comparésaux types d'infection produits sur 40 lignées isogoniques portant des gènes de résistance à la rouille de tiges. Un total de 11 gènes de résistance à la rouille (*Sr5, Sr7a, Sr7b, Sr8a, Sr9e, Sr11, Sr21, Sr27, Sr29, Sr30* and *Sr37*) étaientprésumées présents soit singulièrement ou en combinaison dans les cultivars deblé dur et lignéesaméliorées.A l'exception de Sr30, d'autres gènes postulés étaient susceptibles à la plupart des races prévalences de*Puccinia graminis* f. sp. *tritici*en Ethiopie. Du fait que *Sr30*est aussi inefficace contre Ug99, une stratégie de gestion génétique incluant une combinaison des gènes (*gene pyramiding*) qui fournitune protection suffisante pourrait être formulée pour un control durable de la rouille de tiges. En plus, une recherche sur l'implication de *Sr27*, *Sr29*et*Sr37* devra être faite en agriculture éthiopienne.

Mots Clés: Blé dur, lignées isogéniques, *Puccinia graminis*

INTRODUCTION

Stem rust caused by *Puccinia graminis* Pers. f. sp. *tritici* Eriks. & E. Henn. (*Pgt*) is one of the major and economically important diseases of wheat in Ethiopia (CIMMYT, 2005). Host resistance is the most effective, and economically and environmentally friendly method of disease control. An effective deployment of resistance genes for the management of stem rust in wheat requires knowledge about the resistance status and the diversity of resistance genes in cultivars under consideration. Moreover, knowledge on the prevailing races is crucial as pathogens like *Pgt* are known to evolve their virulence frequently, thereby compromising the durability of resistance. This has been documented on a number of occasions (Pretorius *et al*., 2000; Jin *et al*., 2008; Jin *et al*., 2009). Therefore, achievement of durable resistance against wheat stem rust requires constant characterisation of the pathogen, and identification and deployment of new resistance genes that overcome the prevailing virulent races.

Gene postulation is the classical method of detecting resistance genes likely present in crop cultivars. It is based on the gene-for-gene specificity, where the infection types produced by pathogen isolates on cultivars under study is compared to infection types produced by the same isolates on near-isogenic lines carrying single known resistance gene (Pathan and Park, 2007). Provided that well characterised pathogen isolates with diverse combination of virulence and avirulence are used, this method enables postulation of genes present in cultivars. In addition to postulating the type of gene(s) contained in a cultivar, gene postulation allows the identification and characterisation of new resistance genes, helps to study the variation in the resistance spectrum in a cultivar, and other aspects of host pathogen interactions (Singh *et al*., 2001). Gene postulation has been commonly utilised to postulate resistance genes in wheat to stem, yellow and leaf rusts (Kolmer, 2007; Pathan and Park, 2007) not in reference section and other crop-disease complexes (Jensen *et al*., 1992; Dreiseitl and Steffenson, 2000).

Hexaploid (*T. aestivum* L) and tetraploid mainly represented by durum wheat (*T. turgidum var. durum*) are the two major wheat species cultivated in Ethiopia. Bread wheat cultivars are developed from introduced materials from international sources, mainly from CIMMYT. Although wheat lines released by the CIMMYT programme are selected based on their stem rust resistance (Singh *et al*., 2008), it is essential to have data on the local pathotypes, and it is even greater advantage to know the actual genes responsible for resistance in each cultivar. On the other hand, Most of the durum wheat cultivars were developed from local landraces as Ethiopia is the centre of diversity of this species (Harlan, 1969; Tesemma and Bechere, 1998). The national breeding programme undertakes multi location tests in hot spot areas to determine the resistance level of newly developed wheat cultivars to stem rust and other diseases. Race specific tests have not been conducted; hence, there is no data that shows which stem rust resistance genes are responsible for the resistance conferred in the cultivars. The objective of the present study was to postulate seedling resistance genes present in Ethiopian wheat cultivars and advanced breeding lines.

MATERIALS AND METHODS

Wheat germplasm. Sixty wheat genotypes, 30 bread and 30 durum wheat cultivars and breeding lines, were tested to determine their resistance spectrum to stem rust. Of these, 39 were commercially grown cultivars and 21 were advanced breeding lines (Table 1). Fourty near iso-genic wheat lines, carrying known stem rust resistance genes, were used as tester lines (Table

TABLE 1. List of bread and durum wheat cultivars and breeding lines, and their pedigree tested for postulation of stem rust resistance genes in Ethiopia

Genotype	Pedigree
Durum wheat cultivars	
Cocorit 71	RAE/4* TC 60// STW 63/3/ AA "S" DZ 27617 -18-64-OM
Gerardo	VZ 466/61- 130XLD SX GII " S" CM 9605
Ld 357	LD-357/ CL 8155 NO 58-40
Boohai	COO "S" / CANDEAL II CD 3062- BS OGR
Foka	CIT 71 CANDEAL II CD 3369
Kilinto	ILUMILO/INRAT 69// BHA /3/ HORA /4/ CIT 71/ JORO , DZ 918
Bichena	ILUUMILO / COCORIT 71 DZ 393-4
Tob 66	-
Quamy	ADS // PGO / CANDEAL II /7/ JO "S"/ CR "S"// GS "S"/SBA81 /3/ FG"S" /4/ FG"S" /CR "S" /5/ FG "S" DOM "S /6/ HUI "S" CD 75533-A
Assasa	CHO "S"/ TARUS//YAV "S" 3/FG"S" /4/ FGS/CR "S" /5/ DZ 2085
Robe	HORA/ CIT "S" // JO 'S' / GS 'S' /3/ SOME 'S' /4 / HORA RESPINEGRO// CM 9908 /3/ RAHUM DZ 1640
Ude	CHEN / ALTAR- 84// JO69 CD 95294-9M-030Y-040 PAP-2Y-OB
Yerer	CHEN/TEZ // GULL /3/ CII CII CD 94026-4Y- 04OM-O3OY –PAP-04
Ilani	IMILO/RAHUM//A4#72/3/GERARDO
Oda	DZ046881/IMLO//CIT 71/3/RCHI/LD 357//IMLO/4/YEMEN/CIT'S'//PLC'S'/3/ TAGANROY
Obsa	ALTAR 84//ALTAR 84/SERI/3/6*ALTAR 84
Ejersa	LABUD/NIGRIS 3// GAN CD98206
Bekelcha	98 OSN GEDILFA/GUEROU
Leliso	COCORIT 71/3/GERARDO//61-130/G//"S"/4/BOOHAI/HORA//GERARDO/3/ BOOHAI
Durum wheat breeding lines	
CDSS97-B00845S	-
CDSS97-B00983S	-
CDSS97-B00983S...3Y..6Y	-
CD196B00S5S	-
CDSS96-B00540S	-
CDSS96-B00540S...3B...2Y	-
CDSS96B00540S...3B...2Y...AY	-
13-1DZOS-ODZR—ODZO-5DZR	-
13-1DZOS-ODZR—ODZO-1DZR	-
49-2DZOS-ODZR—ODZO-1DZR	-
49-2DZOS-ODZR—ODZO-2DZR	-
Bread wheat cultivars	
Enkoy	(HEBRARD SEL/WIS245XSUP51)X(FR-FNM)^2.A
Pavon 76	VCM//CNO//7C/3/KAL/BB
Simba (HAR 2536)	PRL/VEE6//MYNA/VUL
Katar (HAR 1899)	Cook/Vee''S''/Dove''S''/Seri/3/Bjy''S''
Galama (HAR 604)	4777(2)//FNK/GB/3/PVN''S''
Kubsa (HAR 1685)	ND G9144//KAL/BB/3/YACO''S''/4VEE#5''S''
Sirbo (HAR 2192)	VS73.600/MRL/3/BOW///YR/TRF
Wetera (HAR 1920)	MON''S''-BUC''S''
Bobitcho (HAR 2419)	PEG/PF70354/KAL/BB/ALD/3/MRNG

TABLE 1. Contd.

Genotype	Pedigree
Digelu (HAR 3116)	-
Meraro (FH 11-6-24)	-
KBG-01	300/SM+501M)/HAR 1709
Abola (HAR 1522)	BOW''S''/BUC''S''
ET-13A2	ENKOY/UQ105
Tussie (HAR 1407)	COOK/VEE''S''//DOVE''S''/SERI
K6295-4A	ROMANYxGB-GAMENYA
Hawi (HAR 2501)	CHIL/PRL
Madda Walabu	TL/3/FN/TH/NAR59*2/4/BOL"S"
Sofumer	LIRA "S"/TAN "S"
Dure	BOW "S"/YD 'S'//Z 'S'
Bread wheat breeding lines	
IBWSN1225	Croc//AE.Squarrosa(224)//OPA1A/3/KAVZ*2/...
HRWSN675	PGO/SER//BAO/3/DUCULA
IBWSN1375	VEE#8//JUP/BJY/3/F3.71/TRM/4/2*WEAVER/5/...
ESWYT275	CROC.1/AE.Squarossa(224)//OPA1A/3/KAVZ*2/...
IBWSN75	ACC.8528
HRWYT165	ALD/CEP75630//CEP75234/PT7219/3/BVC
HRWYT465	Croc.1/AE.Sqarossa(213)//PGO/3/SODA1/...
ESWYT295	VEE#8//JUP/BTY/3/F3.71/TRM/4/2*Weaver/5/...
HRWSN565	ESDA/LIRA//MILAN/3/VEE#5/SARA
HK-14-R278	HAR1871/Jagger

2). The universally susceptible cultivar Morocco, with no known stem rust resistance gene, was used as a susceptible check.

Pathogen isolates. Ten *Pgt* races (PTHSR, RMTTM, RRTTR, TTHSR, HRTSH, DPBTR, KRHST, KCCST, QQQCM, TTTTR) were used to test the 60 wheat genotypes and 40 near isogenic tester lines in a greenhouse. The races were derived from stem rust samples collected from commercial farms in Ethiopia. Purification of bulked samples, development of single pustule isolates, characterisation and nomenclature of the isolates were described in Fetch and Dunsmore (2004). The ten races were selected based on their virulence spectra on the various stem rust resistance genes.

Inoculation and disease assessment. Five seeds from each of the wheat cultivars, advanced breeding lines and near isogenic lines were sown in pots, and grown in a greenhouse. Spores of *Pgt* were suspended in sterile water, and sprayed onto leaves of two weeks old seedlings. Pots containing inoculated seedlings were covered with cellophane bags (145 mm x 235 mm) and tied up at the base with a rubber band to avoid cross contamination (Fetch and Dunsmore, 2004). Immediately after inoculation, seedlings were incubated in the dark for 18 hours at 18 ^{o}C; and high (95.%) relative humidity in a humid chamber. Thereafter, the seedlings were exposed to fluorescent light for three hours. Then, they were transferred to a growth chamber and grown constantly at 22 - 25^{o}C, a light intensity of 10,000 lx and a photoperiod of 16 hours.

Disease assessment was carried 14 days after inoculation using the 0 – 4 infection type (IT) scoring system (Stakman *et al*., 1962). Infection types 0 to 2+ were regarded as incompatible (low infection types), whereas infection types 3 to 4+ were considered as compatible (high infection types). The experiment was repeated twice, and only differential hosts that produced similar infection types in the two experiments were considered for the data analysis. When there was

TABLE 2. Near isogenic lines (NILs) and corresponding resistance genes used for gene postulation of Ethiopian wheat cultivars and advanced breeding lines

NIL	Sr-gene	NIL	Sr-gene
Isr5RA	*Sr5*	LCsr 19MG	*Sr19*
W2691 sr6	*Sr6*	LCSR 20MG	*Sr20*
Mendos/w2691/w3498	*Sr7a*	T. Monococcum Deriv	*Sr21*
Isr 7bRA	*Sr7b*	SW sr22T.B.	*Sr22*
Isr 8aRA	*Sr8a*	BT sr24	*Sr24*
Barleta Benvenuto	*Sr8b*	N A	*Sr 26*
Isr9aRA	*Sr9a*	WRT.238.5	*Sr27*
W2691 sr9b	*Sr9b*	Pusa/EDCH	*Sr29*
W2691 sr9d	*Sr9d*	BTsr30 WST	*Sr30*
Verstein	*Sr9e*	Line-E/KUZ	*Sr31*
CNS Sr9g	*Sr9g*	ER.5155	*Sr32*
W2691Sr 10	*Sr10*	Tetra Canth TCH/Ag.Squarros	*Sr33*
ISr 11RA	*Sr11*	Compare	*Sr34*
BTSr 12TC	*Sr12*	W3763	*Sr35*
W2691sr13	*Sr13*	W2691Sr36TT1	*Sr36*
Line. A Selection	*Sr14*	W2691Sr36TT2	*Sr37*
W2691 srNK	*Sr15*		*RL 6076*
Isr 16RA	*Sr16*		*Sr 39*
LC/Kenya Hunter	*Sr17*		*Sr Tmp*
LC Sr18RL	*Sr18*		*Sr McN*

infection type 0 (immune reaction) in the two tests, the test was repeated to exclude the possibility of disease escape.

Postulation of resistance genes. Postulation of seedling resistance genes in the wheat genotypes was done using the classical gene-for-gene method. The presence of one or more known resistance gene was postulated by comparing the IT pattern of isolate-test cultivar with that of IT pattern of an isolate-differential line combination (Pathan and Park, 2007). A high IT on the test cultivar indicated that it did not have any of the resistance genes for which the test isolate was avirulent. Hence, cultivars or breeding lines exhibiting the same reaction pattern as a specific differential line were postulated to carry that respective Sr-gene.

RESULTS

Based on the multipathotype tests, 11 seedling stem rust resistance genes (*Sr5, Sr7a, Sr7b, Sr8a, Sr9e, Sr11, Sr21, Sr27, Sr29, Sr30* and *Sr37*) and some unknown genes were postulated to be present in some of the genotypes either singly or in combinations.

Group 1: Cultivars with single seedling resistance gene. Two stem rust resistance genes (*Sr8a* and *Sr27*) were postulated singly in five cultivars. The stem rust resistance gene *Sr8a* was postulated to be present in three bread wheat cultivars, Abola, Tussie and Madda Walabu. These cultivars gave low IT to six of the ten races (Table 3). This pattern was identical to the differential cultivar Barleta Benvenuto that carries the stem rust resistant gene *Sr8a*, indicating the presence *Sr8a* in these cultivars. Cultivars Enkoy and Gerardo, bread and durum wheat cultivars, respectively, displayed low ITs to nine of the ten races. Only race QQQCM produced high IT against these two cultivars. This pattern was similar to that displayed by the differential host WRT.238.5 that carries the resistance gene *Sr27* (Table 3). Hence, cultivars Gerardo and Enkoy were postulated to carry the stem rust resistance gene *Sr27*.

TABLE 3. Infection types produced on genotypes postulated to carry single resistance gene, and on the tester NIL (control) with ten *Pgt* races

Genotype	Race										Postulated gene
	PTHSR	RMTTM	TTHSR	HRTSH	DPBTR	KRHST	KCCST	QQQCM	RRTTR	TTTTR	
Abola	3	;	3	2	3	2	1	2-	2	3	*Sr8a*
Tussie	3	;1	3	1+2	3	1	;	1	1	3	*Sr8a*
Madda Walabu	3	1	3	1	3	1	1	2	1	3+	*Sr8a*
ISr 8aRA[1]	3	1	3	2	3	2	2	2	2	3	
Enkoy	1	;	1+	2-	2	1	1	3-	2	2	*Sr27*
Gerardo	1-	;	1	1	0;	1	2	3	1	1	*Sr27*
WRT.238.5[2]	2	;	1	2	2	2	1	3	2	2	

1 = NIL used as differential for *Sr8a* ; 2 = NIL used as differential for *Sr27*

Group 2: Cultivars and breeding lines with two seedling resistance genes. Five cultivars (Simba, Katar, Wetera, Bobitcho and Dure) and two breeding lines (HRWYT165 and ESWYT295) produced low ITs with races RMTTM, HRTSH, DPBTR, KRHST, KCCST and QQQCM. A differential line carrying Sr5 had produced low ITs to four of the above six races (HRTSH, DPBTR, KRHST and KCCST); while another differential line, Verstein, that carries the resistance gene 9e, had produced low ITs with the remaining two races (RMTTM and QQQCM) (Table 4). Hence, the combination of the IT patterns of the two differential lines matched to that of the IT pattern of the genotypes in this group. Therefore, these seven genotypes were postulated to carry the stem rust resistance genes *Sr5* and *Sr9e* in combination. All of the genotypes in this group are bread wheat.

The other group of genotypes with two stem rust resistance genes consisted two cultivars (Pavon 76 and Galama) and an advanced breeding line (HRWSN675), both of which are bread wheat. They gave low ITs with *Sr9e* and *Sr11* avirulent races (Table 4), indicating the presence of these two stem rust resistance genes in the three geotypes. Similarly, an advanced bread wheat breeding line ‘HRWYT465’ and a durum wheat cultivar ‘Assassa’ produced low ITs with *Sr7a* and *Sr7b*, and *Sr9e* and *Sr30* avirulent races, respectively (Table 4). Therefore, HRWYT465 was posulated to carry *Sr7a* and *Sr7b* while Assassa *Sr9e* and *Sr30*.

Group 3: Cultivars with more than two seedling resistance genes. A durum wheat cultivar ‘Boohai’ was postulated to carry three resistance genes in combination. *Sr8a*, *Sr21* and *Sr37* were postulated because Boohai had low ITs to all races that are avirulent to these three genes (Table 5). The IT pattern of the bread wheat cultivar ‘Digelu’ matched the combination of IT patterns of differential cultivars that carry the resistance genes *Sr5*, *Sr21*, *Sr29* and *Sr37* (Table 5), indicating the presence of these genes in the cultivar ‘Digelu’. Another durum wheat cultivar ‘Foka’ gave low ITs to all races that are avirulent to genes *Sr5*, *Sr9e*, *Sr21* and *Sr37* (Table 5), hence, it was postulated to carry a combination of these four resistance genes.

TABLE 4. Infection types produced on genotypes postulated to carry two resistance genes, and on the tester NIL (control) with ten *Pgt* races

Genotype	Race										Postulated gene
	PTHSR	RMTTM	TTHSR	HRTSH	DPBTR	KRHST	KCCST	QQQCM	RRTTR	TTTTR	
Simba	3	;	4	1	2	2+	2-	1	3	3	Sr5 + Sr9e
Katar	3-	1	3	1	1	2	2	2	3	4	Sr5 + Sr9e
Wetera	3	1	3	1	0;	2	;	1	3	3	Sr5 + Sr9e
Bobitcho	3	1	3	12-	1	1+	1	1	3	3	Sr5 + Sr9e
Dure	3	;	3	1	1	;	1	1	3	3	Sr5 + Sr9e
HRWYT165	3	1	4	1	1	1	;	1	3	3	Sr5 + Sr9e
ESWYT295	3+	;	4	1	;	1	2	1	4	4	Sr5 + Sr9e
ISr 5RA[1]	3-	3	3	2	1	2	2	3	3	3	
Verstein[2]	3+	1	4	2	3	3	3+	2	4+	4+	
Pavon 76	3	2+	3+	1	3	3+	2	2	3	3	Sr9e + Sr11
Galama	3	;1	3	2	3	3	1	2	3+	3	Sr9e + Sr11
Verstein[2]	3+	1	4	2	3	3	3+	2	4+	4+	
ISr 11RA[3]	4	4	4	3	4	3+	2+	3	4	4	
HRWYT465	3+	3	3	2+	1	3	3	1	34-	3	Sr7a + Sr7b
Mendos/w2691/w3498[4]	3	3	3+	2+	3	3	3	3	3+	3+	
ISr 7bRA[5]	3	3	3	3	2	3+	3	1	3	3	
Assassa	1	1	12-	1	2	1	2	1	1	3	Sr9e+Sr30
Verstein[2]	3+	1	4	2-2	3	3	3+	2	4+	4+	
BTSr30 WST[6]	1	3+	1	4	2-	1	2	;	2	4	

1 = NIL used as differential for *Sr5*; 2 = NIL used as differential for *Sr9e*, 3 = NIL used as differential for *Sr11*; 4 = NIL used as differential for *Sr7a*; 5 = NIL used as differential for *Sr7b*; 6 = NIL used as differential for *Sr30*

TABLE 5. Infection types produced on genotypes postulated to carry more than two resistance genes, and on the tester NIL (control) with ten *Pgt* races

Genotype	Race										Postulated gene
	PTHSR	RMTTM	TTHSR	HRTSH	DPBTR	KRHST	KCCST	QQQCM	RRTTR	TTTTR	
Boohai	1	2	3+	2	2	2	1	2	1	2	Sr8a+Sr21+Sr37
Digelu	2	3	2	2	1	;1	1	2	3-	1	Sr5+Sr21+Sr29+Sr37
Foka	2	2+	3	22+	1	2	1	1	3	2	Sr5+Sr9e+Sr21+Sr37
ISr8aRA[1]	3	1	3	2	3	2	2	2	2	3	
ISr5RA[2]	3	1	3	2	3	2	2	2	2	3	
T. Monococcum Deriv[3]	2	3	3	4	2	3+	3	3-	3	3	
W2691Sr36TT2[4]	3	3	3	3	3	3	2	2	3	2	
Pusa/EDCH[5]	4-	3	;	3	2+	3	3+	3	3-	3	
Verstein[6]	3+	1	4	2	3	3	3+	2	4+	4+	

1 = NILs used as differential for *Sr8a*;2 = NILs used as differential for *Sr5*; 3 = NILs used as differential for *Sr21*; 4 = NILs used as differential for *Sr37*; 5 = NILs used as differential for *Sr29* ; 6 = NILs used as differential for *Sr9e*

Group 4: Cultivars and breeding lines with unidentified resistance genes. This group comprised 11 genotypes: one durum wheat cultivar, six bread wheat cultivars and four bread wheat breeding lines (Table 6). They were categorised as genotypes with unidentified resistance genes because they had low IT to at least one of the races, but the IT patterns produced on these genotypes did not conform to any of the IT patterns exhibited on tester lines.

Group 5: Genotypes without resistance genes. All races produced high ITs on three bread wheat breeding lines, which was similar to the universally susceptible cultivar Morocco (Table 7). Hence, the three lines in this group 'GIBWSN75', 'HRWYT465' and 'HK-14-R278' were postulated to have no known resistance genes when tested with the ten races used in this study.

Group 6: Genotypes resistant against all races. Twenty four durum and 2 bread wheat genotypes were placed under this group. All the genotypes in this group displayed low ITs against all of the races (Table 8). It was difficult to postulate the resistance gene(s) responsible for this, as there were five differential lines that carry the stem rust resistance genes *Sr22*, *Sr24, Sr26, Sr33* and *Sr39* that had similar IT patterns to that of the genotypes. Either a single gene or a combination of the five genes could be responsible for the resistance.

DISCUSSION

Eleven seedling stem rust resistance genes in Ethiopian wheat cultivars and advanced breeding lines to be present either singly or in combination (Tables 3-8). The frequency of occurrence of *Sr9e* was the highest among the postulated genes (occurring in 18.3% of the genotypes), followed by *Sr5* and *Sr8a* each occurring in 15 and 6.7% of the genotypes, respectively. Other genes that occurred at low frequencies include *Sr21* and *Sr37* (5%), *Sr11* and *Sr27* (3.3%), and *Sr7a*, *Sr7b*, *Sr29* and *Sr30* (1.7%). Only three genotypes, (5%) were postulated to have no known stem rust resistance genes.

A big proportion of the genotypes (26 durum wheat cultivars and breeding lines, and one bread wheat cultivar) were effective against all *Pgt* races (Table 8), which made it difficult to postulate the types of genes present in these genotypes. The low ITs on these genotypes could be either due to one or more of the Sr-genes that had similar IT patterns (*Sr22*, *Sr24*, *Sr26*, *Sr33* and *Sr39*) with the genotypes. Moreover, it could also be due to a combination of other two or more resistance genes that produced low ITs with all races. For example, a combination of ITs of differential cultivars carrying *Sr14*, *Sr15* and *Sr35* produced low ITs with all of the races. Hence, additional races each with virulence to one of the five resistance genes but avirulent to the other four are required to identify the likely source of resistance in these genotypes. On the other hand, a significant proportion of the genotypes (18.3%) was postulated to carry unknown resistance genes. This requires further analysis using additional races with a wider virulence spectra than the present races to determine the type(s) of gene(s) that are responsible for the low ITs displayed by the genotypes against some of the races.

A significant variation in resistance spectra was observed between durum and bread wheat genotypes (Tables 3-8). In general, durum wheat genotypes showed broad resistance spectrum than bread wheat (Tables 3-8). This might be associated with the fact that most of the durum wheat genotypes were developed from local landraces, which have co-evolved with indigenous pathogen population. This finding is in agreement with previous reports that established the importance of Ethiopian cultivated tetraploid wheat accessions as good sources of stem rust resistance (Knott, 1996; Beteselassie *et al*., 2007; Bonman *et al*., 2007; Klindworth *et al*., 2007). On the other hand, bread wheat genotypes were introduced into the country *via* different means, including by the national breeding programme. Hence, their narrow resistance spectrum against indigenous pathogen isolates was not surprising.

Most of the resistance postulated in this study are known to confer seedling resistance against wide range of races. However, *Sr27*, *Sr37* and

TABLE 6. Infection types produced on genotypes postulated to carry unknown resistance genes with ten *Pgt* races

Genotype	Race										Postulated gene
	PTHSR	RMTTM	TTHSR	HRTSH	DPBTR	KRHST	KCCST	QQQCM	RRTTR	TTTTR	
Ejersa	1	;	;	;	1	1	3	1	1	;	Unknown
Sirbo	3	2	3	1	;	2	1	3	3+	2	Unknown
Meraro	3	2	3	2	2	1	1	3-	3+	1	Unknown
ET-13A2	2+	12-	3	1	2	2	;	3	3	2	Unknown
KBG-01	3-	;	2	1	1	2	3	2	3	2	Unknown
Hawi	2	1	3	1	2	1	2	3	3+	;	Unknown
Sofumer	2+	1	3+	1	3	1	0;	1	3	;	Unknown
IBWSN1225	3	3	3	3-	3+	2+	1	1	3	3-	Unknown
IBWSN1375	2	1	3	;	3	2	1	;	3	;	Unknown
ESWYT275	3-	3	3	3	3	1	1	2	3	4	Unknown
HRWSN565	3	;	2	1	1	1	4	;1	3	2	Unknown

TABLE 7. Infection types produced on genotypes postulated to have no known resistance genes, and on the tester cultivar 'Morocco' (control) with ten *Pgt* races

Genotype	Race										Postulated gene
	PTHSR	RMTTM	TTHSR	HRTSH	DPBTR	KRHST	KCCST	QQQCM	RRTTR	TTTTR	
IBWSN75	4-	3+	3+	3	3	3	4	3	4	3	None
HRWYT465	3+	3	3	3+	34-	3	3	4-	3	3	None
HK-14-R278	3	3	3-	3+	3	3	3-	3-	4-	4+	None
Morocco[1]	4-	3	3	3+	3	3	3	3	3	4	

1 = A universally susceptible wheat cultivar with no known stem rust resistance gene

TABLE 8. Infection types produced on genotypes resistant against all races, and on the tester NILs (control) with ten *Pgt* races

Genotype	Race									
	PTHSR	RMTTM	TTHSR	HRTSH	DPBTR	KRHST	KCCST	QQQCM	RRTTR	TTTTR
Cocorit 71	;	;	1	1	0;	1	1	1	1	;
LD375	;	;	;	;	;	1	1	1	1	2-
Kilinto	1	1	1	1	1	2	1	2	1	;
Bichena	1	;	1	1+	2	1	1	2	2-	1
Tob 66	1	1	1	1	2	1	2	1	1	1
Quamy	1	1	;	1	1	1	;	1	1	1
Robe	;	;	1	1	;	2	1	1	2-	1
Ude	1	1	1	1+2	1	2	1	1	1	1
Yerer	1	;	1	1	;	1	2	;	1	1
Ilani	1	;	;1	1	1	2	2	2	1	;
Oda	1	1	;	1	;	1	1	1	1	;
Obsa	1	;	1	;	1	1	2-	1	;	;
Bekelcha	1	1	1	;	1	;	2-	1	1	;
Leliso	1	1	1	1+2	1-	1	1	1	1	1
CDSS97-B00845S	1	0;	1	1	1	1	2+	1	2-	;
CDSS97-B00983S	1	;	1	1	1	;	2	1	1	;
CDSS97-B00983S...3Y..6Y	1	1	1	;	1	1	2	1	1	;
CD196B00S5S	1+	;	1	;1	1	1	2	;	1	0;
CDSS96-B00540S	1	;	;	1	0;	1	1	;	1	;
CDSS96-B00540S...3B...2Y	1	;	1	1	;	;	0	;	;	1
CDSS96B00540S...3B...2Y...AY	2-	;	1	;	;	;	1	;	1+	1
13-1DZOS-ODZR—ODZO-5DZR	2	;1	1	;	;	2	1	12-	2	1
13-1DZOS-ODZR—ODZO-1DZR	1	;	2-	1	;	;	2	1	2-	1
49-2DZOS-ODZR—ODZO-1DZR	1	1	1	1	1	1	2	;	;1	;
49-2DZOS-ODZR—ODZO-2DZR	1	;	1	1	;	2	2	1	2-	1
K6295-4A	2	1	1+	2-	2	2	;	2	2	1
SW Sr22T.B[1]	1	;	2	2	2	1	2	2	2	2
BT Sr24[2]	;	2	2	;	1	1	2	;	1	1
Sr26[3]	1	1	1	2	2	2	2	2	2	2+
Tetra Canth TCH/Ag.Squarros[4]	2-	;	1	2	2	2	2	2	2	2
Sr39[5]	;1	2	2	1	2	2	2	2	1	0

1 = NIL used as differential for *Sr22*; 2 = NIL used as differential for *Sr24;* 3 = *Sr26* gene; 4 = NIL used as differential for *Sr33;* 5 = *Sr39* gene

Sr39 have not been exploited in cultivated durums or common wheat (McIntosh *et al*., 1995). Hence, these genes might not actually be responsible for the resistance in those wheat genotypes postulated to carry them.

A study by Beteselassie *et al.* (2007) had detected five of the stem rust resistance genes that were postulated in this study (*Sr7b*, *Sr24*, *Sr27*, *Sr29* and *Sr30*) in Ethiopian durum and emmer wheat accessions. The significance of some of the postulated genes for agriculture was established earlier (McIntosh *et al*., 1995). Unfortunately, an earlier study had shown that most of the postulated resistance genes (*Sr5*, *Sr7a*, *Sr7b*, *S8a*, *Sr9e*, *Sr11* and *Sr21*) were ineffective against most of the prevalent races in Ethiopia (Admassu *et al*., 2009). The exception here is *Sr30*, which was relatively effective against most of the races prevalent in Ethiopia. The problem with *Sr30* is its ineffectiveness against race Ug99 (Singh *et al*., 2008). Hence, a gene management strategy that incorporates a combination of genes (gene pyramiding) that provide sufficient protection against the races prevalent in the country has to be devised to achieve a durable control of stem rust. In addition, the significance of the other remaining postulated genes, *Sr27*, *Sr29* and *Sr37*, which had not been utilised for agriculture up to now need to be investigated from the perspective of Ethiopian pathogen population-wheat interaction. In addition to gene pyramiding, varietal diversification should be encouraged to get the advantage of horizontal resistance from vertical resistance.

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