Indian Phytopathology (2019) 72:23–34
https://doi.org/10.1007/s42360-018-00110-9

RESEARCH ARTICLE

Physiologic specialization and shift in *Puccinia triticina* pathotypes on wheat in Indian subcontinent during 2013–2016

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Received: 9 November 2018 / Revised: 13 December 2018 / Accepted: 21 December 2018 / Published online: 22 January 2019

Abstract

Brown (leaf) rust of wheat (*Puccinia triticina*) was widely prevalent in all the wheat growing areas of India and neighbouring countries during 2013–16. To have an effective rust management strategy, monitoring of virulence patterns of *P. triticina* on wheat were undertaken. Brown rust samples were analyzed from the wheat growing areas in India, Bangladesh, Bhutan and Nepal using standard differential Indian System and named as per the binomial system of nomenclature. A new pathotype 77-12 was also identified during this period. Thirty seven pathotypes of *P. triticina* were identified in 1427 samples. Five predominant pathotypes 121R63-1(77-5 = THTTM), 121R60-1(77-9 = MHTKL), 21R55 (104-2 = PHTTL), 21R63 (104-3 = PHTTL) and 77-11(125R28 = MGTTL) accounted for 75.1% of the population. All of the prevalent pathotypes are virulent to *Lr1*, *Lr3*, *Lr10*, *Lr11*,*Lr12 Lr13*, *Lr14a*, *Lr16*, *Lr17*, *Lr23*, *Lr26*. Virulences for *Lr9* and *Lr19* though recorded from India long back, however, were not observed during present surveys whereas virulence on *Lr28* was identified in 0.4% samples only. The proportion of pathotype 121R60-1 (77-9 = MHTKL) has increased during these years and was recorded in 23.7% samples against 12% in the previous report. Brown rust of wheat was not observed on *Lr*9, *Lr24*, *Lr25*, *Lr32*, *Lr39* and *Lr45* in the field population of Indian subcontinent during 2013–16. Diversity of pathotypes detected during this period could, to some extent, be related to cultivation of different varieties but was also appeared to be affected by different weather patterns in different agro-ecological areas.

Keywords Wheat · Leaf rust · Pathotypes · *Puccinia triticina* · Resistance · Virulence

Introduction

Rusts are very damaging pathogens of wheat worldwide. Brown (leaf) rust of wheat caused by *Puccinia triticina* occurs in all the wheat growing areas and causes more yield losses than any other rust (Samborski 1985). It is a quick evolving pathogen and generally renders rust resistant varieties of wheat susceptible in a short span of about 4–5 years (Sawhney 1995). Most of the resistance genes present in bread wheat are susceptible to brown rust in India. Even genes *Lr9, Lr19, Lr26, Lr28* transferred from alien sources have also become susceptible to new virulences of *P. triticina*. Virulence to these genes emerged much before the varieties based on these genes were commercialized (Bhardwaj et al. 2016; Nayar et al. 2003). In India, brown rust mostly appears in late December in Peninsular India whereas in most of the wheat growing areas of Northern and Central India initial infections occur by the end of January or sometimes may be later. Among the various options, cultivation of resistant wheat is cost effective, environmentally safe and effective way to manage wheat brown rust. However, frequent emergence of new virulent pathotypes can overcome the hitherto functional resistance, and therefore, breeding wheat for rust resistance is an ever going process.

Keeping in view quick emergence of virulent pathotypes of *P. triticina*, monitoring of rust incidence, identification of new pathotypes and mapping of pathotype distribution is undertaken regularly. Information on racial distribution of *P. triticina* provides the background data for the identification of novel resistance, resistance breeding of wheat and pathotype situation based strategic deployment of wheat

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genotypes in different wheat growing areas. Variability in brown rust of wheat is being monitored in India for the last about 90 years and previous results of pathotype distribution of *P. triticina* were published in 2016 (Bhardwaj et al. 2016). Patterns of physiologic race diversity observed during 2013–16 in the Indian subcontinent are described in this publication.

Materials and methods

Brown rust samples of wheat were collected/received from different growing areas of India and neighbouring nations during 2013–16. The leaf scrapings of uredospore infected samples were inoculated on 7-day old plants of Agra Local (susceptible local bread wheat). Fresh uredospores were collected from the inoculated plants after a fortnight. Uredosporic dust of each sample was inoculated on three sets of differentials. Naming of pathotypes (Pts., singular Pt.) was done by following Indian system of binomial nomenclature (Nagarajan et al. 1983), with some modifications (Table 1) necessitated by the emergence of new pathotypes of *P. triticina* (Bhardwaj et al. 2012). All the optimal greenhouse procedures of inoculation, infection, post-inoculation care and recording of observations were followed (Stakman et al. 1962; Nayar et al. 1997). For the understanding of Wheat Pathologists of other countries, the Indian designations were also coded according to the North American system of racial nomenclature (Kolmer et al. 2009) as illustrated in Table 2.

Growing of seedlings, inoculation and recording observations

Brown rust of wheat was established on Agra Local grown in small plastic pots (4 inch size). Sets of differentials were grown in aluminum bread pans (29 cm long × 12 cm wide × 7 cm deep size) containing fresh loam soil and farmyard manure (3:1). A week old plants were inoculated through gentle application of uredospores with a lancet needle. Seedlings were then sprayed with a fine mist of water and incubated in dew chambers at 22 ± 2 °C for 24 h. Saturated relative humidity and 12 h of daylight were maintained in these chambers. Inoculated materials were then transferred on to the greenhouse benches having temperature of 22 ± 2 °C, relative humidity of 40–60% and light of about 15,000 lx for 12 h. Wheat-rust infection response (low or high) were recorded on differentials after a fortnight of inoculations using the scale of Stakman et al. (1962) with some modifications. Response 0 to 2 (micro flecks to small-moderate uredial pustules with or without chlorosis) were categorized as resistant whereas 3 to 4 (large uredial pustules with or without chlorosis) were designated susceptible. Response 33 + was categorized where both 3 and 3 + pustules occurred simultaneously. When the infection type data was different to the known/published pathotypes, new pathotype was designated and added to the culture collection.

Table 1 The revised composition of sets of differentials for the identification of pathotypes of *Puccinia triticina* on wheat in India

Set 0	Set A	Set B
IWP 94 (*Lr23*+)	*Lr14a*	Loros (*Lr2c*)
Kharchia Mutant (*Lr9*)	*Lr24*	Webster (*Lr2a*)
Raj 3765 (*Lr13*+*10*+)	*Lr18*	Democrat (*Lr3*)
PBW 343 (*Lr26*)	*Lr13*	Thew (*Lr20*)
UP 2338 (*Lr26*+*34*+)	*Lr17*	Malakoff (*Lr1*)
K 8804 (*Lr26*+*23*+)	*Lr15*	Benno (*Lr26*)
Raj 1555	*Lr10*	HP1633 (*Lr9*+)
HD 2189 (*Lr13*+*34*+)	*Lr19*	
Agra Local	*Lr28*	

Results and discussion

Pathotype distribution

In 1427 wheat brown rust samples, 35 pathotypes were identified from India and three neighboring countries during 2013–16. Three pathotypes 121R63-1(77-5 = THTTM), 121R60-1(77-9 = MHTKL), 21R55 (104-2 = PHTTL) were found to be present in most of the samples ranging from 12 to 38% and were also widespread across different states of the country. Other pathotypes namely 109R63 (77-1 = THTTQ), 125R55 (77-3 = THTTS), 121R55-1 (77-6 = THTTQ), 77-11(125R28 = MGTTL), 21R63 (104-3 = PHTTL) and 162-2 (93R39 = KHTTL) were identified in 5–7% samples across more than five states of the country. The avirulence/virulence formulae of these pathotypes are depicted in Table 3. Pathotypes of 77 group comprised 58% of the population against 22% of 104 group. Pathotype (pt.) 77-5 (26.6%), has been predominant for about 20 years and now is being replaced gradually by 77-9 (23.8%) identified in 2008, indicating a clear shift in pathotype predominance observed in the population of 77-9 and decreasing trend was observed for the other pathotypes 77-5,104-2 and 104-3 (Fig. 1). *Lr9, Lr24, Lr25, Lr32, Lr39* and *Lr45* remained resistant to the field population of wheat brown rust pathogen in India and neighboring countries during 2013–16.

Among the 793 samples of brown rust of wheat analyzed from 15 states of India and three neighbouring countries, 30 pathotypes were observed during 2013–14. Pathotype 77-5, virulent to *Lr23* and *Lr26* genes which occur in many of the wheat varieties, was the most widespread and occurred in 14 Indian states, Nepal, Bhutan and Bangladesh. Similarly,

Table 2 International equivalents of Indian pathotypes observed during 2003–16

S. No.	Indian pathotype	International equivalent
1	13R19(10)	SGHLL
2	0R8(11)	BBBBB
3	5R5(12)	FGTTB
4	5R37 (12-1)	FHPTL
5	1R5 (12-2)[a]	FGTTL
6	49R37 (12-3)	FHTTQ
7	69R13 (12-4)	FGTTN
8	29R45 (12-5)	FHTKL
9	5R45 (12-6)	FHRTQ
10	93R45 (12-7)[c]	FHTTL
11	93R37(12-9)[d]	FHTTL
12	5R13 (12A)[b]	FGTTL
13	109R63 (77-1)[e]	THTTQ
14	109R31-1 (77-2)[g]	TGTTQ
15	125R55 (77-3)[j]	THTTS
16	125R23-1 (77-4)[h]	TGTTQ
17	121R63-1 (77-5)[k]	THTTS
18	121R55-1 (77-6)[f]	THTTQ
19	253R31 (77-8)[e]	TGTTQ
20	121R60-1 (77-9)[l]	MHTTS
21	377R60-1(77-10)[m]	MHTTS
22	125R28(77-11)	MGTTS
23	121R52-1(77-12)	MGTNL
24	109R31(77A)	TGTTB
25	109R23 (77A-1)[i]	TGTTQ
26	21R55 (104-2)	PHTTL
27	21R63 (104-3)	PHTKL
28	93R57(104-4)	NHKSP
29	21R31 (104A)	MGTGL
30	29R23 (104B)	MGTQN
31	0R9(106)[n]	BBBBB
32	45R35(107-1)	JCGKG
33	93R7 (162)[o]	KGTTL
34	93R15 (162A)[p]	KGTTL
35	93R47 (162-1)[q]	KHTTL
36	29R7(162-3)	KGTPL
37	93R39 (162-2)r	KHTTL

[a]Virulent on *Lr*23
[b]Avirulent on *Lr*23
[c]Virulent on Thew
[d]Avirulent on Thew
[e]Avirulent on *Lr*23
[f]Virulent on *Lr*23
[g]Virulent on Thew, *Lr*23
[h]Virulent on *Lr*23
[i]Avirulent on *Lr*23, avirulent on *Lr*19 and Thew
[j]Avirulent on *Lr*23
[k]Virulent on *Lr*23
[l]Avirulent on *Lr*28
[m]Virulent on *Lr*28
[n]Virulent on Thew, Loros
[o]Avirulent on Thew
[p] Virulent on Thew
[q]Virulent on Thew
[r]Avirulent on Thew

pathotype 104-2, also virulent to *Lr23* and *Lr26* was the second most frequent and was identified from 12 states of India, Nepal and Bangladesh. The proportion of pathotype 77-9 has increased in Nilgiris, as compared to the previous years, as it was sampled in 56% of the samples from Nilgiris. In Karnataka, three predominant pathotypes were 77-9, 12 and 77-11, and other pathotypes 77-5, 12-2 and 104-2 were also identified in substantial number of samples. In the remaining samples, 18 other pathotypes were identified.

Surprisingly, the dominant trend was in favour of pt.12 in Maharashtra followed by pathotype 77-5 whereas remaining pathotypes were observed in few samples only. It hints at cultivation of some indigenous or local wheat germplasm in Maharashtra. Pathotype 104-2 was the most frequent in the states of Gujarat, Rajasthan and Madhya Pradesh. A total of 25 samples were analyzed from Bihar and West Bengal and pathotype 77-5 was the most common. In Uttar Pradesh, both pts. 77-5 and 104-2 were identified in most of the samples and twelve other pathotypes were identified in few samples only. Pathotype 104-2 was most frequent in Uttarakhand whereas in Himachal Pradesh both pts 77-5 and 104-2 were more common and had equal frequency. Pathotype 77-3 along with other five pathotypes were picked up in samples from Punjab. In Jammu and Kashmir, pt. 12-9 was identified in two samples whereas 104-2 occurred in one sample only. In Nepal, Bhutan and Bangladesh, both pts. 77-5 and 104-2 were identified in most of the samples analyzed whereas fifteen other pathotypes occurred in few samples only (Table 4). During this year, a new pathotype designated as 77-12 was identified in few samples analyzed from the Nilgiris hills. The new pathotype is close to the pathotype 77-9 but has avirulence to *Lr20*.

Population of wheat brown rust during 2014–15 comprised twenty five pathotypes intercepted in 386 samples received from nine states of India and three neighbouring countries. The frequency of 77-9 was found to increase in Tamil Nadu, Karnatka, Maharashtra, MP and Punjab. Three predominant pathotypes i.e., 77-9 (38%), 77-5 (32%) and 104-2 (14.5%) comprised 85% of the flora. Among these, both pathotypes 77-5 and 104-2 occurred in eight states of India and three neighboring countries. In Madhya Pradesh, pt. 77-5 was most frequent, followed by 77-9 whereas in

Table 3 Avirulence/virulence structure and frequencies of predominant pathotypes of *Puccinia triticina* in Indian wheat fields

S.no	Pathotype	Avirulence/virulence structure	Percentage
1	121R63-1(77-5)	*Lr9, Lr 18**, *Lr 19, Lr 24, Lr 25, Lr 28, Lr 29, Lr 32,Lr39 Lr 40, Lr 45/Lr 1, Lr 2a, Lr 2b, Lr 2c, Lr 3, Lr 10, Lr 11, Lr 12, Lr 13, Lr 14a, Lr 14b, Lr 14ab, Lr 15, Lr 16, Lr 17a, Lr 20, Lr 21, Lr 22a, Lr 22b, Lr 23, Lr 26, Lr 27+31, Lr 30, Lr 33, Lr 34, Lr 35, Lr 36, Lr 37, Lr 38, Lr 42, Lr 43, Lr 44, Lr 48, Lr 49*	26.6
2	121R60 (77-9)	*Lr2a, Lr2b, Lr2c, Lr9, Lr19, Lr24, Lr25, Lr28, Lr32, Lr39, Lr45/Lr1, Lr3, Lr10, Lr11, Lr12, Lr13, Lr14a, Lr14b, Lr14ab, Lr15, Lr16, Lr17a, Lr17b, Lr18, Lr20, Lr21, Lr22a, Lr22b, Lr23, Lr26,Lr27+31, Lr30, Lr33, Lr34, Lr35, Lr36, Lr37, Lr38, Lr42, Lr44, Lr46, Lr48, Lr49*	23.7
3	21R55 (104-2)	*Lr9, Lr 10**, *Lr 13**, *Lr 15, Lr 19, Lr 20, Lr 24, Lr 25, Lr 28, Lr 29, Lr 32, Lr 36, Lr39, Lr 40, Lr 43, Lr 45/Lr 1, Lr 2a**, *Lr 2 Lr b, Lr 2c, Lr 3, Lr 11, Lr 12, Lr 14a, Lr 14b, Lr 14ab, Lr 16, Lr 17a, Lr 18, Lr 21, Lr 22a, Lr 22b, Lr 23, Lr 26, Lr 27+31, Lr 30, Lr 33, Lr 34, Lr 35, Lr 37, Lr 38, Lr 42, Lr 44, Lr 48, Lr 49*	17.7
4	21R63 (104-3)	*Lr9, Lr 10**, *Lr 13**, *Lr 15, Lr 19, Lr 24, Lr 25, Lr 28, Lr 29, Lr 32, Lr 36, Lr39 Lr 40, Lr 43, Lr 45/Lr 1, Lr 2a**, *Lr 2b, Lr 2c, Lr 3, Lr 11, Lr 12, Lr 14a, Lr 14b, Lr 14ab, Lr 16, Lr 17a, Lr 18, Lr 20, Lr 21, Lr 22a, Lr 22b, Lr 23, Lr 26, Lr 27+31, Lr 30, Lr 33, Lr 34, Lr 35, Lr 37, Lr 38, Lr 42, Lr 44, Lr 48, Lr 49,*	4.2
5	121R28 (77-11)	*Lr2a, Lr2b, Lr2c, Lr9, Lr19, Lr24, Lr25, Lr26, Lr28, Lr32, Lr39, Lr45/Lr1, Lr3, Lr10, Lr11, Lr12, Lr13, Lr14a, Lr14b, Lr14ab, Lr15, Lr16, Lr17a, Lr17b, Lr18, Lr21, Lr22a, Lr22b, Lr23, Lr27+31, Lr30, Lr33, Lr34, Lr35, Lr36, Lr37, Lr38, Lr42, Lr44, Lr46, Lr48, Lr49*	2.7

*Temperature sensitive response

Gujarat and Haryana, pt.104-2 was the most prevalent. Pathotype 77-9 was observed only in seven states of India but not in the neighboring countries. Remaining 22 pathotypes occurred in few samples only. The brown rust population in Bangladesh, Bhutan and Nepal was similarly dominated by three pathotypes. Among these, pt. 77-5 was most frequent followed by 104-2 and 12-4 (Table 5).

Diversity of pathotypes was lower during 2015–16. Among the 248 samples analyzed from 13 states of India, Nepal and Bhutan, 19 pathotypes of *P. triticina* were identified. Increased frequency in favour of pathotype 77-9 (121R60-1) continued as it was identified from 37.9% samples, succeeded by pts.77-5 (121R63-1) and 104-2 (21R55), which occurred in more than 15% samples each (Table 6). Pathotype 77-9 was the most frequent in Tamil Nadu, Chhatisgarh, Karnataka and Himachal Pradesh whereas 77-5 was frequent in Haryana, Maharashtra and Madhya Pradesh. The most dominant pt. was 104-2 in Uttarakhand. *P. triticina* population was quite diverse in Karnataka and Himachal Pradesh where eight pts. each were observed in these states. In Karnataka pathotype 77-9 was predominant followed by pathotypes 77-5 and 104-2. Remaining pathotypes were identified in few samples only. In Himachal Pradesh, both pts. 77-9 and 104-2 were equally

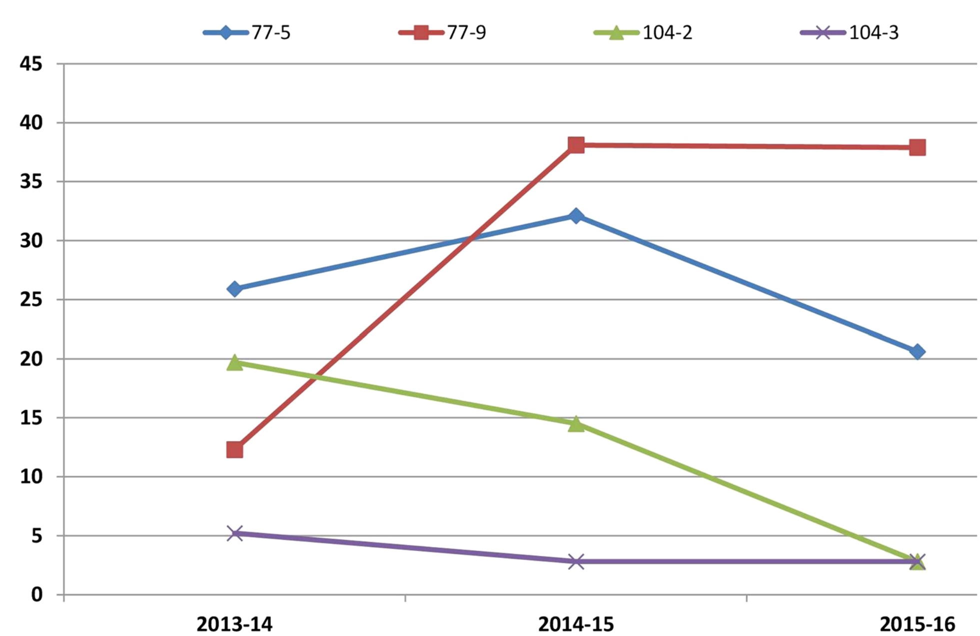

Fig. 1 Shifting pattern (frequency) of four predominant pathotypes between 2013 and 2016

Table 4 Pathotype distribution of *P. triticina* (brown rust) in India and neighboring countries during 2013–2014

S. no.	State/ country	No. of Samples	Pathotypes identified													
			12(5R5)	12-1 (5R37)	12-2 (1R5)	12-3 (49R37)	12-4 (69R13)	12-5 (29R45)	12-6 (5R45)	12-9 (93R37)	12A (5R13)	77-1 (109R63)	77-2 (109R31-1)	77-3 (125R55)	77-4 (125R23-1)	77-5 (121R63-1)
1	Tamil Nadu	71	–	–	–	–	–	–	–	–	–	1	–	–	–	12
2	Karna-taka	185	36	2	14	3	2	1	1	–	1	1	1	1	1	21
3	Maha-rashtra	52	28	–	–	–	1	–	–	–	1	–	–	1	–	7
4	Gujarat	19	–	–	–	–	–	–	–	–	–	–	2	–	–	5
5	Chhattis-garh	2	–	–	–	–	–	–	–	–	–	–	1	–	–	1
6	Madhya Pradesh	73	1	–	–	–	–	–	–	–	–	1	–	–	–	2
7	Rajasthan	29	–	–	–	–	–	–	–	–	–	–	–	–	–	7
8	Bihar	10	–	–	–	–	–	–	1	–	–	–	2	–	–	4
9	West Bengal	15	–	–	–	–	–	–	–	–	–	–	–	–	–	9
10	Uttar Pradesh	75	1	2	–	–	–	1	–	1	–	3	–	1	–	25
11	Haryana	16	–	–	–	2	1	–	–	–	–	–	–	1	–	3
12	Punjab	7	–	–	–	1	–	–	–	–	–	1	–	2	–	1
13	Uttara-khand	36	–	3	–	–	–	–	–	2	–	2	–	–	–	6
14	Himachal Pradesh	47	–	1	–	–	–	–	–	1	–	1	–	2	–	14
15	Jammu Kash-mir	3	–	–	–	–	–	–	–	2	–	–	–	–	–	–
Other countries																
1	Nepal	64	1	–	–	2	2	–	–	–	–	–	–	1	–	39
2	Bhutan	17	–	1	–	–	–	–	–	–	–	–	–	–	–	15
3	Bangla-desh	72	–	4	2	2	2	–	–	–	–	1	–	2	–	35
	Total	793	67	13	16	10	8	2	2	6	2	11	6	11	1	206

Table 4 (continued)

S. No.	Pathotypes identified															
	77-6 (121R55-1)	77-9 (121R60-1)	77-10 (377R60-1)	77-11 (125R28)	77-12 (121R52-1)	77A (109R31)	77A-1 (109R23)	104-2 (21R55)	104-3 (21R63)	104-4 (93R57)	104A (21R31)	104B (29R23)	162 (93R07)	162-1(93R47)	162-2(93R39)	162A (93R15)
1	8	40	–	–	9	–	–	–	–	–	–	–	–	1	–	–
2	3	38	–	29	3	2	2	15	2	–	1	–	3	–	2	–
3	1	3	1	4	–	–	–	3	–	–	1	–		–	1	–
4	–	–	–	–	–	–	–	10	–	–	–	–	1	–	1	–
5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
6	3	3	–	1	–	–	–	45	10	–	1	2	2	–	2	–
7	2	2	–	–	–	–	–	11	2	–	–	–	–	4	1	–
8	–	–	–	–	–	–	–	2	1	–	–	–	–	–	–	–
9	5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1
10	1	8	–	–	–	–	–	22	4	–	–	–	1	3	1	–
11	–	1	–	1	–	–	–	3	1	2	–	–	–	–	–	1
12	–	1	–	–	–	–	–	1	–	–	–	–	–	–	–	–
13	1	–	–	–	–	–	–	11	5	1	1	–	1	–	2	–
14	5	–	–	1	–	–	–	14	5	2	–	–	–	–	–	1
15	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–
Other countries																
1	–	2	–	–	–	–	–	13	2	–	1	–	1	–	–	–
2	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
3	1	–	–	–	–	–	–	6	10	1	1	–	–	3	–	2
	31	98	1	36	12	2	2	157	42	6	6	2	9	11	10	5

Table 5 Pathotype distribution of brown rust (*P. triticina*) in India and neighboring countries during 2014–15

S. no.	State	Pathotypes identified												
		No. of samples	10 (13R19)	12-2 (1R5)	12-3(49R37)	12-4 (69R13)	12-5 (29R45)	12-7 (93R45)	12 A (5R13)	77-1 (109R63)	77-2(109R31-1)	77-5(121R63-1)	77-6(121R55-1)	77-9(121R60-1)
1	Tamil Nadu	74	–	–	1	–	–	–	–	–	–	30	1	33
2	Maharash-tra	37	–	–	–	–	–	–	–	–	–	7	–	29
3	Karnataka	109	–	–	–	–	–	–	–	1	–	26	–	56
4	Gujarat	05	–	–	–	–	–	–	–	–	–	–	–	–
5	Madhya Pradesh	30	–	1	–	–	3	–	–	–	–	13	–	11
6	Punjab	18	–	–	–	–	–	–	–	–	–	1	–	15
7	Haryana	06	–	–	–	–	–	–	–	–	–	1	–	1
8	Uttarakhand	32	–	–	–	–	1	–	–	1	–	8	–	2
9	Himachal Pradesh	18	–	–	–	–	1	1	–	–	–	6	–	–
10	Jammu & Kashmir	–	–	–	–	–	–	–	–	–	–	–	–	–
Other countries														
1	Nepal	42	–	–	–	5	–	–	–	2	1	25	–	–
2	Bangladesh	11	1	–	–	–	–	–	2	–	–	4	–	–
3	Bhutan	04	–	–	–	–	–	–	–	–	–	3	–	–
Total		386	1	1	1	5	5	1	2	4	1	124	1	147

S. no.	Pathotypes identified												
	77-10(377R60-1)	77-11(125R28)	77-12(121R52-1)	77A(109R31)	104-2(21R55)	104-3(21R63)	104-4(93R57)	104B(29R23)	162(93R7)	162-2(93R39)	162-3(29R7)	162A(93R15)	162-1(93R47)
1	2	–	5	–	1	1	–	–	–	–	–	–	–
2	1	–	–	–		–	–	–	–	–	–	–	–
3	1	–	–	–	21	1	–	–	–	2	1	–	–
4	–	–	–	–	5	–	–	–	–	–	–	–	–
5	–	–	–	–	2	–	–	–	–	–	–	–	–
6	–	–	–	–	2	–	–	–	–	–	–	–	–
7	–	–	–	–	4	–	–	–	–	–	–	–	–
8	–	–	–	–	9	4	5	–	1	–	–	1	–
9	–	1	–	–	5	2	1	–	–	–	–	–	1
10	–	–	–	–	–	–	–	–	–	–	–	–	–

Table 5 (continued)

S. no.	Pathotypes identified												
	77-10(377R60-1)	77-11(125R28)	77-12(121R52-1)	77A(109R31)	104-2(21R55)	104-3(21R63)	104-4(93R57)	104B(29R23)	162(93R7)	162-2(93R39)	162-3(29R7)	162A(93R15)	162-1(93R47)
Other countries													
1	–	–	–	1	5	1	1	1	–	–	–	–	–
2	–	–	–	–	1	2	1	–	–	–	–	–	–
3	–	–	–	–	1	–	–	–	–	–	–	–	–
	4	1	5	1	56	11	8	1	1	2	1	1	1

common. Pathotype 77-9 was found in maximum number of samples analyzed from Chhattisgarh indicating its spread to other states. Both pts. 77-5 and 104-2 were identified in one and three samples, respectively. Some of the historical virulences like 11, 12-1, 106, 107-1, 162, 162A and other recent ones namely 12-6, 77-8, and 77-10, were observed in one sample each. Eighteen samples of brown rust were analyzed from Nepal and Bhutan. Six pathotypes with pt.77-5 as more frequent followed by 104-2 were observed in these countries.

Large number of pathotypes detected from Nilgiri Hills (Tamil Nadu), Karnatka and Himachal Pradesh, different agro-ecological areas provided further evidence that these areas continue to remain active source area for the brown rust spread in the country.

Pathotypes and wheat material in farmer's fields

Information was also generated on the pathotypes in relation to the cultivated wheat varieties in the farmers' fields. Fourteen pathotypes were identified from ten states of India and neighboring countries Nepal and Bangladesh. Mostly, pts. 77-5, 77-9, 104-2 and 104-3 occurred on the popular wheat varieties (Table 7). It means that present day varieties are providing enough surviving space for these pathotypes. Our observations could not validate based on host resistance, existence of different virulences in the farmers field. However, it does hint at weather conditions existing in different agro ecological areas which most likely have impacted the prevalence of different pathotypes independent of their virulences.

Per cent effectiveness of *Lr* genes

Effectiveness of different rust resistance genes in Indian wheat material to brown rust population is presented in Table 8. *Lr9*, *Lr19*, *Lr24* and *Lr28* were highly effective against field population of *P. triticina* in India and adjoining countries whereas *Lr1*, *Lr10*, *Lr23* and *Lr26* were not effective. In addition, *Lr3*, *Lr13*, *Lr14a* were susceptible to all the prevalent pathotypes of *P. triticina* in India, Bangladesh, Bhutan and Nepal. Evaluation of resistance genes/lines against field isolates revealed that *Lr9, Lr24*, *Lr25*, *Lr32*, *Lr39* and *Lr45* were resistant to the brown rust population of the Indian sub-continent during 2013–16 (Table 8).

During 2008–2013, a diverse population of 37 races of *P. triticina* were identified (Bhardwaj et al. 2016) in 2424 samples, likewise during 2013–16 also, 37 pathotypes were identified in 1407 samples analyzed from India, Bangladesh, Bhutan and Nepal. Pathotypes 121R63-1 (77-5 = THTTS) in 26.6% samples, 121R60-1(77-9 = MHTTS) in 23.8%, 21R55 (104-2 = PHTTL) in 17.7%, 21R63 (104-3(PHTKL) in 4.2% and 77-11(125R28 = MGTTL) in 2.7% samples were the five most widespread virulences during 2013–16.

Table 6 Pathotype distribution of brown rust (*P. triticina*) in India and neighboring countries during 2015–16

S. No.	State/ country	Samples analyzed	Pathotypes identified																		
			11(0R8)	12-1(5R37`)	12-5 (29R45)	12-6 (5R45)	77-1 (109R63)	77-5 (121R63-1)	77-8 (253R31)	77-9 (121R60-1)	77-10 (377R60-1)	77-11 (125R28)	77A-1 (109R23)	104-2 (21R55)	104-3 (21R63)	106 (0R9)	107-1 (45R35)	162 (93R7)	162-1 (93R47)	162-2 (93R39)	162A (93R15)
1	Tamil Nadu	15	–	–	1	–	1	7	–	5	–	–	–	–	–	–	–	–	–	1	–
2	Karnataka	90	–	1	1	–	1	12	–	63	1	–	–	7	1	–	–	–	–	3	–
3	Maharashtra	15	–	–	–	–	–	6	–	5	–	–	–	–	2	–	–	–	–	2	–
4	Gujarat	2	–	–	–	–	–	1	–	–	–	–	–	1	–	–	–	–	–	–	–
5	Chhattisgarh	14	–	–	–	–	–	1	–	10	–	–	–	3	–	–	–	–	–	–	–
6	Madhya Pradesh#	19	–	1	–	–	–	7	1	1	–	–	–	4	–	–	–	–		4	–
7	Rajasthan	3	–	–	–	–	–	–	–	3	–	–	–	–	–	–	–	–	–	–	–
8	West Bengal	13	–	–	–	–	1	2	–	–	–	–	7	–	2	–	–	–	–	–	1
9	Uttar Pradesh	10	–	–	–	–	–	2	–	1	–	–	–	6	–	–	–	1	–	–	–
10	Haryana	7	–	–	–	–	–	3	–	–	–	–	–	2	–	–	–	–	2	–	–
11	Punjab	1	–	–	–	–	–	1	–		–	–	–	–	–	–	–	–	–	–	–
12	Uttarakhand	16	–	–	–	1	1	–	–	1	–	–	1	9	–	–	–	–	–	2	1
13	Himachal Pradesh	25	–	–	1	–	3	–	–	6	–	2	–	5	–	–	1	–	2	5	–
Other countries																					
1	Bhutan	3	–	–	–	–	–	1	–	–	–	–	–	–	1	–	–	–	–	1	–
2	Nepal	15	1	–	–	–	–	8	–	–	–	–	–	4	2	1	–	–	–	–	–
Total		248	1	2	3	1	6	51	1	95	1	2	8	41	8	1	1	1	4	18	2

Table 7 Pathotypes of *P. triticina* on different wheat varieties/elite lines during 2013–16

Area	Pathotype	Variety/elite line
Tamil Nadu	77-5	HW4059
Karnataka	77-9	DWR162, DWR195,NIDW295
	162-2	Amrut, DWR195, GW322
	77-5	DWR162
	12	DWR162,Gulab
	104-2	A-9-30-1, DWR162, HD2204
Chhatisgarh	77-9	GW273
Madhya Pradesh	104-2	DWR195, WH147
	104-3	GW322,
	77-9	MACS 2486
	77-5	DWR195, GW273, HI8361
	162	Lok-1
Maharashtra	77-9	GW496, Lal Bahadur, Lok-1
	77-5	GW496
	162-2	HD2189
	12	HD2189
Uttar Pradesh	104-2	DBW90, HD3086, PBW343,WH711
	77-9	DBW88, PBW343, PBW373
	77-5	WH1105
	77-2	HUW234,WH1105
	162-2	DBW71
	12-6	PBW550
Punjab	77-9	HD2967
Haryana	104-2	KH65 (is it kharchia 65 or something else)
Uttarakhand	12-1	WH147
	104-3	VL804
Himachal Pradesh	77-1	PB343
	104-3	PBW343
Bangladesh	77-5	Bari Gom26, Prodip
	104-2	Prodip
	104-3	Prodip
	12-2	Prodip
	104-4	Prodip
	12-4	Bari Gom25
	12-6	Bari Gom26
	162A	Bari Gom25, Bari Gom26,Prodip
Nepal	104-2	B913, B1126,NL292
	104-3	WK1204
	77-5	BL4547, Gautam,PM93, WK1204,WK1481
	77-9	Nepal 297
	77A	Gautam

In Indian subcontinent the proportion of five predominant pathotypes has increased from 68 to 75% with a shift in virulence pattern in favour of a new pathotype 77-9(121R60-1), which was identified in 23.8% of the samples during these years against 12% in the last survey. Based on the recent studies, it has been observed that pathotype 121R60-1 is more competitive and has high fitness potential in comparison to 121R63-1 (Bhardwaj et al. 2014). In Maharashtra pt. 12 was predominant, which hints at cultivation of some old/indigenous wheat varieties. Simple pathotypes are promoted by varieties having no effective leaf rust resistance (Bhardwaj et al. 2014).In China PHT (23.7%), THT (14.7%), PHJ (11.4%) and THJ (4.2%) were the four most predominant races. Among *Lr* genes; *Lr9*, *Lr24*, *Lr25*, *Lr28*, *Lr32*, *Lr39* and *Lr45* were resistant (Liu and Chen 2012). The racial pattern is comparable to that of India, however, in

Table 8 Effectiveness of *Lr* genes in Indian wheat material against brown rust in different areas during 20013–16

Area	States	Percent effectiveness of resistance genes					
		Lr1	*Lr10*	*Lr19*	*Lr23*	*Lr26*	*Lr28*
1	Tamil Nadu	0.02	0.01	100	0.01	0	98.7
2	Karnataka, Gujarat, Maharashtra	60	1.5	100	9.6	9	99.2
3	Chhattisgarh, Madhya Pradesh, Rajasthan	16.4	3	99	15.5	11.3	100
4	Bihar, Jharkhand, Assam, West Bengal	7.8	2.6	100	23.6	28.3	100
5	Uttar Pradesh, Delhi, Haryana, Punjab, Chandigarh	11.5	5.7	100	15.1	5	100
6	Jammu &Kashmir, Himachal Pradesh, Uttarakhand	21.6	5.7	100	23.7	0.7	100
7	Bangladesh	20.4	6	100	20.5	8.2	100
8	Bhutan	8.3	4.1	100	8.3	0	100
9	Nepal	9.9	4.9	100	12.3	9.9	100

**Lr3, Lr13, Lr14a* were ineffective whereas *Lr9, Lr24* were effective against brown rust of wheat

China predominant pathotype resembles to 104-2 (PHTTL) whereas in India, predominant pts. are 77-5(THTTS) or 77-9(MHTTS). The races of *P. triticina* from China are coded on old system; however, if the first three letters are seen, Indian flora matches partially.

Virulence to *Lr9*, 19, 28 did not exist in Pakistan (Fayyaz et al. 2008), though in India, we have virulence for all these genes, however, virulence to *Lr9* was not observed in the field population during these years. On the other hand predominant races in Slovakia (Hanzalova et al. 2008) are virulent to *Lr9, Lr24* and *Lr28* to which Indian pathotypes identified during this period were avirulent except for the few samples virulent to *Lr28*. When compared with the pathotypic flora of United States of America, Indian pathotypes are strikingly different as pathotypes MBTNB, TBBGS and TCRKG were widespread (Kolmer and Hughes 2016). Prevalent population of wheat rust in United States of America is virulent to *Lr9, 24, 28* and *39* whereas avirulent in India. Population of *P. triticina* in Middle East and central Asia (Kolmer et al. 2011) is also strikingly different to that of India. The wheat leaf rust population of Zimbabwe, Zambia and Malawi was quite different to that of India as races MCDS (74.6%), TCPS (12.7%), FBPT (16.3%) and SCDS(6.3%) were predominant (Pretorius et al. 2014). In Egypt, most frequent races of *P triticina* observed during 2012–14 were PTTTT, TTTST, TTTTT and PKTST (El-Orabey et al. 2015), which are different to that of the Indian sub-continent.

Since rust resistant variety lasts for about 5 years (Sawhney 1995), therefore, identification of new pathotypes and pathotype distribution becomes a guiding force to re-orient the wheat breeding program. Like previous surveys (Bhardwaj et al. 2016) brown rust population remained avirulent to *Lr9, 24, 25, 32, 39* and *45*. With the shift in brown rust population, resistance of seedling, adult and slow rusting types are being identified in upcoming wheat material by screening against most virulent and predominant pathotypes including 77-9 also. Likewise the pathotype distribution information of brown rust is being used for wheat varietal deployment. The success of the programme can be envisaged from the fact that there was no wheat rust epidemic during the last 46 years.

Acknowledgements The authors are grateful to the Director, ICAR-IIWBR, Karnal, Haryana for providing liberal resources and first author also acknowledges the financial assistance received from Department of Biotechnology, Govt. of India through the Project '*Puccinia triticina* genomics network on *De novo* genome sequencing, fitness, variation and pathogenicity'. Help of all the partners in monitoring wheat rusts and sampling is thankfully acknowledged.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Research involving human participants or animals This article does not contain any studies with human participants or animals performed by any of the authors.

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