Revista Mexicana de Ciencias Agrícolas

DOI: https://doi.org/10.29312/remexca.v16i4.3688

Article

Yield stability and yellow rust infection levels in rainfed wheat in Mexico

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Abstract

Yellow rust is the biotic factor that most affects the yield of rainfed wheat in the High Valleys of Mexico, and currently, the most effective management strategy for this disease is the use of resistant varieties, which must also be stable in grain yield when exposed to this rust. In order to understand the correlation between yield stability and the severity of yellow rust, between 2017 and 2020, trials were established in 37 localities in the High Valleys of Mexico, where 14 wheat genotypes were evaluated. The correlation between yield and the incidence of yellow rust was analyzed and different stability parameters were determined. A moderate negative correlation was found between yield and disease incidence. The advanced lines Kone 's', Nely 's', Terre 's', and the varieties Texcoco F2016 and Valles F2015 were the most stable in yield and the most resistant to rust, whereas the least stable and the most susceptible to the disease were Náhuatl F2000, Triunfo F2004, and Nana F2007, so they should no longer be recommended for sowing.

Keywords:

Puccinia striiformis, Triticum aestivum, correlation, High Valleys.

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DOI: https://doi.org/10.29312/remexca.v16i4.3688

Introduction

Globally, wheat production has been affected by high input costs, extreme droughts, and diseases, which has put the population's food security at risk for the acquisition of this grain (The World Bank, 2024). In Mexico, yellow rust (*Puccinia striiformis* W) is the disease that most affects the crop in the High Valleys of central Mexico, this region being one of the most important in terms of production of this cereal. Due to the presence of new yellow rust races in 2014 that caused yield losses of 84% (Díaz *et al*., 2018), wheat production was reduced to 65 551 t reported in 2023 (SIAP, 2024).

To resume national production, it is necessary to have varieties that are resistant to yellow rust and also have good grain yield and that this trait is not affected when planted in varied climatic conditions.

The development of varieties that are stable in yield and resistant to yellow rust is one of the purposes of the INIFAP Wheat Program since this ensures the production of this grain in different environments, even when the incidence of rust is high (Villaseñor, 2015). In Mexico, there is no information on the correspondence between the stability of wheat genotypes yield and yellow rust.

Therefore, this study aimed to understand the correlation between the parameters of grain yield stability and the percentage of yellow rust severity measured in different rainfed environments. This stability analysis can be useful as a tool for the selection of outstanding genotypes.

Materials and methods

Fourteen rainfed wheat genotypes (11 varieties and three advanced lines) from the INIFAP Wheat Program were evaluated (Table 1). Genotypes were established in trials in 37 localities in the states of Mexico, Tlaxcala, Oaxaca, and Puebla, during the spring-summer (SS) cycles from 2017 to 2020 (Table 2). These localities are classified as favorable and intermediate environments for the crop due to their average annual rainfall of between 400 and 600 mm (Villaseñor and Espitia, 2000).

Table 1. Wheat genotypes evaluated in the rainfed trials established in the spring-summer cycles from 2017 to 2020.

Genotypes[†]	
Temporalera M87	Nana F2007
Romoga F96	Don Carlos M2015
Náhuatl F2000	Valles F2015
Tlaxcala F2000	Texcoco F2016
Rebeca F2000	Kone 's'
Triunfo F2004	Nely 's'
Altiplano F2007	Terre 's'

[†] = the letter after the name indicates its gluten type and year of release. F= strong; M= medium; 's'= advanced line.

Table 2. Localities where the trials were established during the spring-summer cycles from 2017 to 2020.

		Localities			
1	Juch17[†]	Juchitepec, Mex. 17	20	Terre19	Terrenate, Tlax. 19
2	Tlal17	Tlalmanalco, Mex. 17	21	Mox19	Moxolahuac, Pue. 19
3	Mira17	Miraflores, Mex. 17	22	Nana19	Nanacamilpa, Tlax. 19
4	Terre17	Terrenate, Tlax. 17	23	Mir19	Miraflores, Mex. 19
5	Nana17	Nanacamilpa, Tlax. 17	24	Tlal19	Tlalmanalco, Mex. 19
6	Ixta17	Ixtafiayuca, Tlax. 17	25	Juch19	Juchitepec, Mex. 19
7	Cha1F[††]17	Chapingo, Mex. 1F17	26	Cha19	Chapingo, Mex. 19

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		Localities			
8	Cha2F[†††]17	Chapingo, Mex. 2F17	27	Luc1F19	Sta. Lucía, Mex. 1F19
9	Luc1F17	Sta. Lucía, Mex. 1F17	28	Luc2F19	Sta. Lucía, Mex. 2F19
10	Luc2F17	Sta. Lucía, Mex. 2F17	29	Yan19	Yanhuitlán, Oax. 19
11	Juch18	Juchitepec, Mex. 18	30	Cha1F20	Chapingo, Mex. 1F20
12	Mir1f18	Miraflores, Mex. 1F18	31	Cha2F20	Chapingo, Mex. 2F20
13	Mir2F18	Miraflores, Mex. 2F18	32	Luc1F20	Sta. Lucía, Mex. 1F20
14	Nana18	Nanacamilpa, Tlax. 18	33	Luc2F20	Sta. Lucía, Mex. 2F20
15	Terre18	Terrenate, Tlax. 18	34	Terre20	Terrenate, Tlax. 20
16	Cha1F18	Chapingo, Mex. 1F18	35	Nan1F20	Nanacamilpa, Tlax. 1F20
17	Cha2F18	Chapingo, Mex. 2F18	36	Nan2F20	Nanacamilpa, Tlax. 2F20
18	Luc18	Sta. Lucía, Mex. 18	37	Juch1F20	Juchitepec, Mex. 1F20
19	Yan18	Yanhuitlán, Oax. 18			

[†] = 17, 18, 19, 20= years 2017, 2018, 2019 and 2020; [††]1F= first sowing date; [†††]2F= second sowing date.

The trials were established under a randomized complete block design (RCBD) with two replications. The experimental plot consisted of four rows 0.3 m apart, with a seedbed of 1.5 m × 3 m long, with the useful plot being the total of the experimental plot (4.5 m^2).

The considered variables were grain yield in kg ha^{-1} (YIE) and the percentage of yellow rust (Yr), which was recorded with the modified visual Cobb scale (Roelfs *et al*., 1992), taking the first reading at the flag leaf stage and subsequently taking readings every 10 to 15 days until physiological maturity, reporting the final reading for the present study.

An analysis of variance combined with their interactions and a Tukey comparison of means (α= 0.05) were performed. An analysis of correlation between the variables, a stability analysis for grain yield using the standard deviation (Si) and the coefficient of variation (CVi) proposed by Francis and Kannenberg (1978), Eberhart and Russell's (1966) stability indices, and Lin and Binns's (1988) superiority indices, were also performed using the SAS package version 9.2 for Windows.

Results and discussion

Table 3 shows the analysis of variance of the 37 localities, where there were highly significant differences among localities, genotypes, and in the locality × genotype (G×E) interaction for the variables evaluated. As mentioned by Hortelano *et al*. (2013), this analysis confirmed the contrast that exists between rainfed wheat production environments, where genotypes behave differently when changing environments.

Table 3. Analysis of variance of the variables evaluated in wheat genotypes evaluated in rainfed environments during the SS cycles from 2017 to 2020.

SV	df	YIE	Yr
Loc	36	44 900 269**	1 399.12**
Rep (Loc)	1	52 260 27	85.71
Gen	13	301 452 54**	19 037.79**
Loc*Gen	468	480 105**	103.92**
Error	517	275 558	34.96
Total	1035		
CV (%)		14.56	29.07
Mean		3 604.7[†]	20.3[††]

SS= spring-summer; SV= source of variation; df= degrees of freedom; YIE[†]= grain yield; Yr[††]= yellow rust; **= highly significant differences.

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Eberhart and Russell (1966) results mention that G×E interactions are important for the development of varieties; however, when they are planted in different environments, their categorization differs, which causes difficulty in observing their superiority. To solve this problem, it is necessary to detect stable genotypes that interact less with the environments where they are planted and that are classified as such by stability parameters such as those determined below.

Table 4 presents the comparison of means for the different localities, where it is observed that the average yield varied from 2 to 7.4 t ha^{-1} and the percentage of yellow rust ranged from 6.8 to 43.8%.

Table 4. Overall means of grain yield and yellow rust percentage in 14 wheat genotypes evaluated in 37 rainfed localities during the SS cycles from 2017 to 2020.

Locality	YIE	Yr	Locality	YIE	Yr
Juch17	3 905 ghi	20.5 defghij	Terre19	4 130 fgh	15.1 ijkl
Tlal17	2 003 s	36.7 b	Mox19	5 396 cd	20.2 efghij
Mira17	2 553 pqr	43.8 a	Nana19	4 580 ef	25.5 cde
Terre17	2 631 opqr	23.9 cdef	Mir19	4 594 ef	24.6 cdef
Nana17	2 305 qrs	15.5 ijk	Tlal19	6 704 b	20.1 efghij
Ixta17	2 713 opqr	20 efghij	Juch19	5 394 cd	16.4 hijk
Cha1F17	2 426 qrs	18.6 fghij	Cha19	3 303 jklmn	23.5 cdef
Cha2F17	3 453 ijkl	14.8 ijkl	Luc1F19	5 655 c	21.8 cdefgh
Luc1F17	3 358 jklm	15.3 ijkl	Luc2F19	2 753 opqr	19.6 efghij
Luc2F17	3 140 jklmno	11.5 klm	Yan19	3 034 lmnop	19.8 efghij
Juch18	3 520 ijkl	6.8 m	Cha1F20	3 317 jklmn	20 efghij
Mir1F18	4 996 ed	8.07 m	Cha2F20	2 739 opqr	26.4 cd
Mir2F18	4 228 fg	25.3 cde	Luc1F20	2 456 qrs	15.4 ijkl
Nana18	2 786 nopqr	18.7 fghij	Luc2F20	2 031 qrs	20.6 defghi
Terre18	3 632 hijk	27.3 c	Terre20	2 818 mnopqr	22.4 cdefgh
Cha1F18	3 099 klmno	22.6 cdefg	Nan1F20	3 652 hij	21.6 cdefgh
Cha2F18	4 073 fgh	9.3 lm	Nan2F20	2 277 rs	27.4 c
Luc18	3 164 jklmno	14.5 jkl	Juch1F20	7 450 a	22.3 cdefgh
Yan18	2 839 mnopq	16.8 ghijk			

† YIE= grain yield in kg ha^{-1}; †† Yr= percentage of yellow rust; means with the same letter in each column are not significantly different (Tukey α= 0.05).

With these results, three response groups were formed for localities: 1) with the highest yields, $\bar{x}$= 5 932 kg ha^{-1}, eg., Juchi1F20, Tlal19, and Luc1F19 with an average percentage of yellow rust of 18%; 2) with intermediate yields, $\bar{x}$= 3 658 kg ha^{-1}, Juch17, Nan1F20, and Terre18 with an average percentage of yellow rust of 19%; and 3) with the lowest yields, $\bar{x}$= 2 543 kg ha^{-1}, Mira17, Luc1F20, and Cha1F17 with an average percentage of yellow rust of 23%. This suggests that higher percentages of rust lead to lower yields and vice versa, a trend observed by Ramírez *et al*. (2016) when evaluating rainfed wheat and by González and Rodríguez (2023) in barley attacked by leaf rust.

The Table 5 shows the grain yield and the percentage of yellow rust observed in the genotypes, where Kone ‘s’, Nely ‘s’, and Terre ‘s’ surpassed Nana F2007, Triunfo F2004, and Náhuatl F2000 by up to 1.4 tons, the latter varieties are considered outstanding varieties for rainfed environments, but they are currently already susceptible to yellow rust (Díaz *et al*., 2018).

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Table 5. Grain yield and percentage of yellow rust in 14 wheat genotypes, average of 37 rainfed localiti es during the SS cycles from 2017 to 2020.

Varieties	2017		2018		2019		2020		Average	
	YIE†	Yr††	YIE	Yr	YIE	Yr	YIE	Yr	YIE	Yr
Kone 's'	4 012	1	4 514	1	5 564	1	4 224	1	4 600 a	1 e
Nely 's'	3 949	3	4 509	3	5 635	3	4 071	3	4 568 a	3 e
Terre 's'	3 930	4	4 371	1	5 391	1	4 240	2	4 499 a	2 e
Valles F2015	3 057	8	4 258	1	4 653	2	3 686	5	3 917 b	4 e
Texcoco F2016	3 044	8	4 077	2	4 819	2	3 654	4	3 907 bc	4 e
Don Carlos M2015	2 988	22	3 431	18	4 727	27	3 258	31	3 624 cd	25 cd
Temporalera M87	2 806	27	3 502	19	4 201	27	3 340	25	3 468 de	25 cd
Altiplano F2007	2 749	25	3 667	17	4 449	23	3 275	26	3 546 d	23 d
Rebeca F2000	2 427	32	3 279	24	4 275	24	3 433	28	3 351 def	27 c
Tlaxcala F2000	2 342	27	3 186	20	4 308	29	3 084	25	3 239 ef	26 cd
Romoga F96	2 298	24	3 176	22	4 138	27	2 839	29	3 126 f	25 cd
Triunfo F2004	2 166	32	3 070	29	4 247	29	2 947	35	3 117 e	31 b
Náhuatl F2000	2 397	35	2 984	21	3 971	36	3 042	34	3 105 f	32 b
Nana F2007	1 716	62	2 275	53	3 378	59	2 172	59	2 400 g	58 a

† YIE= grain yield; ††Yr= yellow rust percentages; means with the same letter in each column are not significantly different (Tukey α= 0.05).

These higher yields are due to the fact that these three advanced lines presented the lowest percentages of yellow rust (<3%) and, as mentioned by Ramírez *et al*. (2016); Villaseñor *et al*. (2021), as part of the advances of the Wheat Program, the obtaining of genotypes with higher yields and greater resistance to rusts should be gradual and ascending over the years. For this reason, Kone 's', Nely 's' and Terre 's', as candidates to be released as varieties, showed these results.

Genotypes considered to be resistant, with percentages of yellow rust <5% (Roelfs *et al*.,1992) (Table 5), were Valles F2015, Texcoco F2016, Kone 's', Nely 's', and Terre 's', which had the highest yields and were considered the most stable in terms of this trait and, as mentioned by Ramírez *et al*. (2016), they would be the genotypes that have a wide range of adaptation.

These same authors mention that the varieties released in the 2000s are the ones with the lowest yield and most susceptible to yellow rust, coinciding with what was observed in this study since Náhuatl F2000, Triunfo F2004, and Nana F2007 showed a greater severity of the disease and lower yields (Table 5).

For the correlation analysis between YIE and Yr, a moderate negative correlation was obtained (-0.41821, <0.0001) (Schober and Boer, 2018); that is, the lower the percentage of yellow rust, the higher the grain yield and according to Table 4, in most of the localities where the highest yields

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DOI: https://doi.org/10.29312/remexca.v16i4.3688

were obtained, the percentages of yellow rust were lower, and this same trend was observed among varieties (Table 5). Similar results were reported by Sánchez-Martín *et al*. (2013) in oats and crown rust and by Solomon *et al*. (2023) in bread wheat and stem rust.

On the other hand, considering that small values of the coefficient of variation (CVi) and standard deviation (Si) indicate greater stability (Francis and Kannenberg, 1978) and that the desirable genotypes would be those with higher yield and lower CVi (De Vita and Maggio, 2006; Hortelano *et al*., 2013), then, Valles F2015 followed by Terre 's', Nely 's', and Kone 's' were the most stable in all the environments evaluated (Table 6); these three lines were also the most stable in the environments with the highest incidence of yellow rust (Table 7); likewise, these genotypes presented a lower percentage of yellow rust in the four years of evaluation (Table 5).

Table 6. Stability parameters of 14 wheat genotypes evaluated in 37 rainfed environments in the High Valleys. SS 2017 to 2020.

Variety	YIE	Si[$]	CVi(%)[&]	Eberhart and Russell		Lin and Binns	
				#i	$S^2di(10^3)$	$Pi(10^4)$	MS (GxE)(10^4)
Temporalera M87	3 468	1 302	37.56	0.967	75.9	110.3	24.7
Romoga F96	3 126	1 194	38.21	0.906	-12.9	163.9	29.2
Náhuatl F2000	3 105	1 300	41.87	0.979	30.8	166.4	28.3
Tlaxcala F2000	3 239	1 290	39.84	0.969	38.7	150.2	33.1
Rebeca F2000	3 351	1 455	43.4	1.094	78.3	134.5	33.6
Triunfo F2004	3 117	1 414	45.36	1.056	92.3	170.5	34.5
Altiplano F2007	3 546	1 285	36.24	0.979	-8.5	98.5	22.5
Nana F2007	2 400	1 127	46.96	0.717	331.5	333.3	57.9
Don Carlos M2015	3 624	1 365	37.66	1.032	33.1	94.4	27.7
Valles F2015	3 917	1 348	34.42	0.989	129.7	57.9	20.1
Texcoco F2016	3 907	1 411	36.12	1.057	78.9	55.8	17.1
Kone 's'	4 600	1 468	31.92	1.087	142.0	5.5	3.4
Nely 's'	4 568	1 497	32.77	1.136	50.7	6.8	4
Terre 's'	4 499	1 410	31.35	1.031	167.5	9.1	4.4
	3 605[§]					39.4[#]	39.5[£]

[$] standard deviation; [&]coefficient of variation; [§]overall mean; [#]Pi cut-off point; [£]cut-off point of MS(GxE).

Table 7. Stability parameters of wheat genotypes evaluated in seven rainfed environments of the High Valleys where there was a higher incidence of yellow rust. SS 2017 to 2020.

Variety	YIE	Si[$]	CVi(%)[&]	Eberhart and Russell		Lin and Binns	
				#i	$S^2di(10^3)$	$Pi(10^4)$	MS (GxE)(10^4)
Temporalera M87	2 946	1 193	38.18	1.003	258	175.3	72.3
Romoga F96	2 554	911	33.23	0.853	-91.7	219.6	57.5
Náhuatl F2000	2 670	923	33.3	0.88	-126.4	197	52.5
Tlaxcala F2000	2 408	1 093	44.14	1.011	-38.4	266.9	83.8

DOI: https://doi.org/10.29312/remexca.v16i4.3688

Variety	YIE	Si[$]	CVi(%)[&]	Eberhart and Russell		Lin and Binns	
				#i	$S^2di(10^3)$	$Pi(10^4)$	MS (GxE)(10^4)
Rebeca F2000	2 717	942	33.07	0.784	121.4	217	84
Triunfo F2004	2 253	972	33.95	0.863	22.8	291.1	79.9
Altiplano F2007	3 261	1 065	31.82	0.919	119.8	118.5	50.3
Nana F2007	1 877	1 047	53.36	0.976	-66.1	364.1	78.1
Don Carlos M2015	2 796	1 151	38.53	1.076	-56	179.2	53.4
Valles F2015	3 699	1 293	32.43	1.228	-94	65.1	34.3
Texcoco F2016	3 627	1 583	40.22	1.493	-30.6	81.6	46.9
Kone ‘s’	4 517	1 332	27.8	1.039	581	3.7	3.4
Nely ‘s’	4 237	1 077	23.78	0.966	36.1	11.1	5
Terre ‘s’	4 461	1 132	23.77	0.909	319.5	3.1	1.9
	3 145[§]					54.7[#]	56.6[£]

[$] = standard deviation; [&]= coefficient of variation; [§]= overall mean; [#]= Pi cut-off point; [£]= cut-off point of MS(GxE).

The stability parameter #i resulted in regression coefficients less than one (the lowest) in Nana F2007 and Romoga F96 for all environments (Table 6) and in Rebeca F2000 and Romoga F96 for environments with the highest incidence of yellow rust (Table 7), indicating that these varieties present relative adaptation to unfavorable environments (Hortelano *et al*., 2013).

For all environments in Table 6, it was observed that seven genotypes had #i values between 0.96 and 1.05 and that five genotypes did so for the environments with the highest incidence of rust (Table 7); this range mentioned by Hortelano *et al*. (2013) was applied to those genotypes with stable yields across environments and years. Rodríguez-González *et al*. (2014); Aula *et al*. (2023) mention that genotypes with #i and S^2di greater than 1 and equal to 0, respectively, have a good response to favorable environments and are stable. In this sense, Rebeca F2000, Triunfo F2004, Texcoco F2016, Kone ‘s’, and Nely ‘s’ presented a #i greater than one (the highest) in all environments (Table 6) and Don Carlos M2015, Valles F2015, and Texcoco F2016 did so in the environments with the highest incidence of rust (Table 7), indicating that all these genotypes respond positively to environmental production improvements (Hortelano *et al*., 2013).

The variances of the regression deviations (S^2di) in both analyses (Tables 6 and 7) were different from zero and, as mentioned by Hortelano *et al*. (2013), the linear model used is not appropriate to describe the response of genotypes as a function of the environment.

According to Lin and Binns (1988) superiority parameters, the genotypes with the lowest Pi values are considered the most stable and present a behavior parallel to the maximum response across environments, being the genotypes with the highest yield and stability in terms of this trait (Rodríguez *et al*., 2002; El-Hashash and Agwa, 2018). For this study, for all environments (Table 6) and environments with the highest incidence of rust (Table 7) were the Kone ‘s’, Nely ‘s’, and Terre ‘s’ lines followed by the Texcoco F2016 and Valles F2015 varieties, a categorization that coincided with that observed with the coefficient of variation (CVi) in both analyses.

These genotypes were the ones that had the highest yields and presented the lowest percentages of yellow rust (Table 5) and as they obtained the lowest values of the MS(G×E) parameter, they have good adaptation (stability) to all the environments studied (Rodríguez *et al*., 2002; Sabaghnia *et al*., 2013).

On the other hand, for all environments, Nana F2007 was the variety that exceeded the value of the critical cut-off point for the mean square of the G×E interaction, so it has specific adaptation only in certain environments (Rodríguez *et al*., 2002), with the lowest yield and the highest percentage of yellow rust (Table 5). For the environments with the highest incidence of rust (Table 7), Nana F2007 together with Temporalera M87, Romoga F96, Tlaxcala F2000, Rebeca F2000, and Triunfo F2004

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exceeded the value of the critical cut-off point for G×E, so since they have specific adaptation to certain environments, their yield could be drastically decreased if they are planted in localities with a high incidence of yellow rust.

Conclusions

The advanced lines Kone ‘s’, Nely ‘s’, Terre ‘s’, and the varieties Texcoco F2016 and Valles F2015 were the most stable genotypes in grain yield, even in the localities where there was a higher incidence of yellow rust. These genotypes had the lowest percentages of rust across environments, so there was a moderate negative correlation between yield and disease incidence.

Due to their stability and resistance to yellow rust, Texcoco F2016 and Valles F2015 can be recommended for planting in the High Valleys of Mexico. On the other hand, Náhuatl F2000, Triunfo F2004, and Nana F2007, which presented lower stability, low yields, and high susceptibility to yellow rust, are no longer recommended for planting.

The determination of yield-stable genotypes with resistance to yellow rust can be a useful tool for the selection of outstanding genotypes. The higher yield of the three advanced lines is an indication that INIFAP Wheat Program continues to make progress in the generation of genotypes with higher yields and resistant to yellow rust.

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Yield stability and yellow rust infection levels in rainfed wheat in Mexico

Journal Information
Journal ID (publisher-id): remexca
Title: Revista mexicana de ciencias agrícolas
Abbreviated Title: Rev. Mex. Cienc. Agríc
ISSN (print): 2007-0934
Publisher: Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias

Article/Issue Information
Date received: 01 March 2025
Date accepted: 01 June 2025
Publication date: 13 June 2025
Publication date: May-Jun 2025
Volume: 16
Issue: 4
Electronic Location Identifier: e3688
DOI: 10.29312/remexca.v16i4.3688

Categories

Subject: Articles

Keywords:

Keywords:

Puccinia striiformis

Triticum aestivum

correlation

High Valleys

Counts

Figures: 0

Tables: 7

Equations: 0

References: 22

Pages: 0