Article

Evaluation of combining abilities and heterosis effect for a better selection of hybrid barley

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Abstract

Heterosis effect and the combining ability are two main indices of hybrids performance. Predicting hybrid performance and heterosis effect is an important approach in the breeding of hybrid barley. In order to i) combine the local and introduced genetic material; ii) study the combining abilities of parents and hybrids; and iii) analyze the relationships between the heterosis effect, the combining ability and the performance of hybrids, the present research has been initiated. In this study, five cultivars of barley (*Hordeum vulgare* L.) were crossed according to a full diallel plan comprising P^2 combinations. The twenty hybrids F2 were assessed by the general combining ability analysis (GCA); by the specific combining ability (SCA) as well as by the calculation of the heterosis effect of six agronomic characters, namely, the weight of the spike (WE), the number of grains per spike (NGE), the weight of a thousand grains (WTG), plant earliness at flowering (PRF), plant harvest index (IR) and plant productivity (P P). The results indicate that GCA for all parameters was significant except for the WE trait while SCA was significant for three of the six traits studied: WTG, IR and PRO. The GCA/SCA ratio revealed that non-additive effects were the main effect on traits assessed in the hybrids F2. Heterosis was significantly correlated with SCA for all traits tested, indicating that non-additive effects were the main effect of heterosis. Hybrids from two parents with a high GCA have consistently shown better SCA and better hybrid performance. Indeed, the selection of parents should be mainly based on their GCA.

Keywords: breeding program, general combining ability, heterosis effect, parental performance, specific combining ability.

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Introduction

The breeding of hybrid barley has had remarkable success in recent decades. However, a small number of hybrid varieties have been published, at the same time great progress has been made in studies of the hybrid vigor of barley (Longin *et al*., 2002). In 2002, the first commercial hybrid variety ‘Cotossus’ was sold in the United Kingdom (Zhang *et al*., 2013). Since then, around ten hybrid varieties of barley have been marketed. As a result, more than 200,000 ha have been sown by hybrid barley in Europe (Longin *et al*., 2002; Zhang *et al*., 2013).

In Algeria, there are eight varieties of six-row barley multiplied out of thirteen varieties authorized for production and consumption (Zeghouane *et al*., 2008), this varietal range underwent a change between 1994 and 2006, which resulted in the decrease in the number of varieties. imported, in return, the autochthones varieties (Saida and Tichedrett) have always been favored by farmers (Gardner and Eberhart, 1966; Melchinger, 1987; Bagheri and Jelodar, 2010), Saida is a cultivar in great demand throughout the national territory with an occupancy rate 74%, while Tichedrett is located in the highlands with an occupancy rate of 15% (Zeghouane *et al*., 2008). In fact, the local genotypes exhibit good productivity with a high susceptibility to lodging. On the other hand, the introduced genotypes are characterized by a high sensitivity to environmental variations (Ali Dib and Monneuveux, 1992; Khaldoun *et al*., 2001).

Faced with such a situation, the Algerian farmer does not have enough choice. As variety is one of the most important factors in improving yields, good management of the variety range would be necessary. It is believed that increased barley production is possible through the adoption of hybrid varieties (Djili and Daoud, 2000).

Improved varieties that stand out from existing varieties by high yield and flexibility of adaptation to climatic constraints. According to Gallais (2009), the hybrid state makes it possible to obtain varieties with greater vigor, more productive, associating complementary characteristics from the parents: resistance to diseases, good technological quality and generally presenting more great flexibility of adaptation than their homozygous counterparts. According to Zhang *et al*. (2013), one of the key questions for successful use of hybrid barley is to identify which parents have good combining ability to produce hybrids with significant heterosis.

The general combining ability is considered a useful indirect criterion for the selection of better parents. The GCA provides a simple approach to predict additive effects contributing to heterosis Melchinger *et al*. (1987) and the SCA also plays an important role in heterosis Gardner and Eberhart (1966).The Combining abilities has been used successfully to identify superior combinations in rice Bagheri and Jelodar (2010); Tiwari *et al*. (2011), maize, (Gissa *et al*. (2007); Abdel-Moneam (2009); Gouda *et al*. (2013) and wheat (Li *et al*. (1997); Krystkowiak *et al*. (2009). Regarding barley, the combining abilities has been reported for several characteristics, notably the length of the spike and the height of the plants; the harvest index; the precocity of the plant and the yield and its components (Madić *et al*., 2014).

It is in this context that we initiated the present work with the aim of combining local and introduced genetic material; to study the combining abilities of parents and hybrids and to analyze the relationships between heterosis effect, combining ability and hybrid performance in order to select the best parents and descendances.

Materials and methods

Experimental protocol

The experiences were carried out during three successive agricultural campaigns (2015-2016; 2016-2017 and 2017-2018) at the level of the Amira Ahmed pilot farm which is located in the northern zone of the city of Mila under a bioclimatic level wet. The plant material studied is composed of five cultivars of six-row barley used as parents, namely Saida (P1), Tichedrett (P2), Bahia (P3), Express (P4) and Plaisant (P5). Full diallel crossbreeding between the parents resulted in twenty hybrids which made up the first F1 generation afterwards; the F1 was reseeded to give F2. The experimental setup adopted was the complete block design with three repetitions.

Study methods

The performance of an individual is written by Yijkl which represents the performance of individual l in block k for the crossing i by j (Khaldoun *et al*., 2006), where: Yijkl= m + cij + bk + (bc) ijk + e ijkl; e ijkl= random residual; (bc) ijk = block x crossing interaction; bk = block k effect; cij = crossover effect i by j; m= overall average. According to the Griffing model (1956), general and specific aptitudes for the combination were estimated by the following formulas: Sg = $\frac{1}{2(p-2)}$ Σi (Yi+ + Y+i)2 - $\frac{2}{p(p-2)}$ Y2++; Ss = $\frac{1}{2}$ Σij<i (Yij + Yji)2 - $\frac{1}{2(p-2)}$ Σ (Yi+ + Y+i)2 + $\frac{1}{(p-1)(p-2)}$ Y2++. Where: Yij= average value of bn individuals of b repetitions of the male cross i per female j; Yi= total of measures where i is a male parent; Yj= total of measures where j is a female parent; Y= grand total.

Based on the mean value of the parental lines, the heterosis compared to the mid-parent (hm) and over the better parent, heterobeltiosis, (hs) for the traits evaluated was calculated by the formulas: hm = F 1 - [(P 1 + P 2)/2]; hs = F 1 - P b, where P b represents the performance of the better parent (Griffing model, 1956; Eberhart and Gardner, 1966; Frank and Nadine *et al*., 2007; Gallais, 2009).

Statistical analysis

Descriptive statistics, analysis of variance, and correlation analysis were implemented using IBM-SPSS Statistics software, version 24 (Statistics Package for the Social Science).

Results

Highlighting the genetic effects of the F2 generation

Analysis of variance for the genotype factor indicates very highly significant differences for all traits (Table 1).

Table 1. **Analysis of variance and expectation of mean squares.**

Characters evaluated	Hybrids F2		Average of square blocks	Mean of squares interaction
	General mean ± standard deviation	Average of genotype squares		
WE	2.48 ±0.8	0.71***	0.498	0.204
NG/E	76.66 ±9.2	242.138***	053.301	32.27
WTG	55.65 ±5.43	77.7***	4.65	6.842
PRF	122 ±2.64	3.665***	0.866	3.252
IR	57.93 ±15.19	613.842***	53.442	48.86
PP	45.75 ±3.91	466.726***	27.05	30.932

***= highly significant at $p \leq 0.001$.

The hybrids F2 expressed higher mean values than their parents for three of the six traits evaluated (Figure 1).

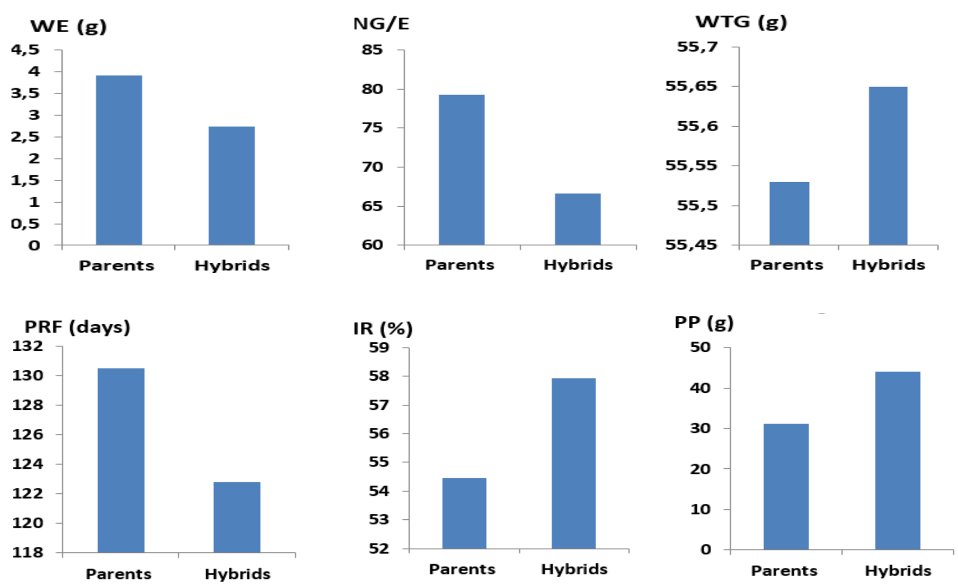

Figure 1. The average values of hybrids F2 and their parents.

The demonstration of the genetic effects of the F2 generation reveals very highly significant differences for all the variables evaluated. Indeed, the average values recorded in the hybrids are higher than the average values recorded in their parents. These results agree with those of Oury *et al*. (1990); Benmahammed (2005); Bouchetat and Aissat (2018); Bouchetat and Aissat (2019).

Heredity of traits

The analysis of the variance of the combining abilities, carried out according to the model of Griffing (1956), shows very highly significant of general combining ability (GCA) and specific combining ability (SCA) effects for all the parameters tested. The analysis of variance of general combining ability (GCA) reveals very highly significant differences for all parameters tested except spike weight.

On the other hand, the analysis of variance of the specific combining ability (SCA) indicates very highly significant differences for three out of six characters evaluated. The GCA/SCA ratio is less than unity. The narrow sense heritability, estimated for all traits, takes on low values (Table 2).

Table 2. Anova of the combining abilities for the different traits evaluated.

Traits evaluated	Average of squares		GCA/SCA	Heritability
	GCA	SCA		
WE	0.071 NS	0.318 NS	0.223	0.2
NG/E	23.639***	173.425 NS	0.136	0.195
WTG	3.203***	48.044***	0.066	0.082
PRF	0.614***	564.344 NS	0.001	0.334
IR	51.554***	521.654***	0.098	0.167
PP	20.464***	096.792***	0.211	0.087

***= highly significant at $p \leq 0.001$; NS= not significant.

Study of general combining ability (GCA)

The general combining ability of different varieties varied widely among traits. Indeed, the parent Plaisant (P5) transmitted to his descendants a weight of a thousand grains high; a certain delay in heading; an important harvest index and a considerable productivity. On the other hand, the two autochthones genotypes Saida and Tichedrett (P1, P2) express better GCA values (NG/E, PP and WTG, IR). In contrast, the cultivar Express (P4) transmitted to its descendants a reduced development cycle with better earliness at heading (Table 3).

Table 3. Values of the general combining ability of the parents used in the complete diallel cross.

Parents	WE	NG/E	WTG	PRF	IR	PP
P1	0.14	3.526	0.056	-0.426	1.18	2.27
P2	0.156	-0.79	0.973	0.033	4.936	-0.396
P3	-0.096	-4.103	0.106	-0.053	-3.86	-3.286
P4	-0.203	1.27	-1.653	-0.3	-4.7	-1.54
P5	0.006	0.086	0.766	0.736	2.446	2.966

Study of specific combining ability (SCA)

The hybrids (Exp × Sai), (Exp × Tich), (Plai × Tich), (Plai × Bah) and (Plai × Exp) expressed high SCA values. Five out of twenty combinations evaluated, (Tich × Exp); (Sai × Bah); (Sai × Plai); (Plai × Bah); and (Plai × Sai), gave better SCA values. On the other hand, the F2 hybrids (Sai × Plai); (Tich × Exp); (Sai × Tich); (Exp × Plai) and (Bah × Exp), recorded significant SCA values (Table 4).

Table 4. Values of the specific combining ability of the hybrids F2.

Genotypes	WE	NG/E	WTG	PRF	IR	PP
Sai × Tich	0.04	-0.49	-01.84	43.51	-25.24	07.46
Sai × Bah	0.49	-5.37	0.35	-0.73	2.35	2.03
Sai × Exp	-0.39	0.65	-0.13	-1.49	17.16	2.5
Sai × Plai	-0.14	1.3	-6.64	-1.19	13.74	12.45
Tich ×Sai	0.19	-3.82	0.82	-0.49	5.87	-4.86
Tich × Bah	0.12	-0.59	-1.89	1.13	-0.23	2.3
Tich × Exp	-0.01	3.43	0.89	-0.61	18.55	7.51
Tich × Plai	0.42	3.88	-2.89	1.34	-3.92	-2.14
Bah × Sai	-0.15	6.57	0.68	-0.73	6.52	-2.89
Bah × Tich	-0.26	23.38	0.43	0.47	5.27	-3.15
Bah × Exp	0.06	0.34	-8.27	-0.19	-0.26	3.9
Bah × Plai	0.02	6.26	3.97	1.64	-20.1	-6.99
Exp × Sai	0.63	12.71	5.78	2.84	-27.35	-6.45
Exp × Tich	-0.53	-4.5	4.86	-1.28	5.71	-10.06
Exp × Bah	-0.17	-2.78	-5.6	0.13	-13.19	-4.13
Exp × Plai	-0.3	1.55	-5.26	-0.98	0.36	4.09
Plai × Sai	-0.37	-3.03	0.69	11.3	9.33	-5.67
Plai × Tich	0.36	1.61	4.11	0.01	3.87	2.18
Plai × Bah	-0.27	17.58	3.97	-11.56	11.99	2.41
Plai × Exp	0.34	-05.14	3.07	45.22	-10.35	-0.4

Sai= Saida; Tich= Tichedrett; Bah= Bahia; Exp= Express; Plai= Plaisant.

Analysis of genetic effects by the Griffing (1956) method indicates that general and specific combining ability (GCA and SCA) play a significant role in the expression of thousand grains weight (WTG) traits; harvest index (IR) and productivity of plant (PP) whereas, the effects of GCA and SCA are not significant for the weight of ear parameter (WE), these results are in agreement with those of Jalata *et al*. (2019). According to Zhan *et al*. (1996), the eigenvalues of parental lines can be a good indicator of the effects of GCA. A cross between parents of different GCA values produces a positive SCA effect (Bhowmik *et al*., 1990), this genetic interaction responsible for high SCA values.

The variance ratio (GCA/SCA) is less than one for all the traits studied. Indeed, the nature of the actions of the non-additive genes is more important than the nature of the actions of the additive genes. The relatively low values of the narrow sense heritability expressed by the hybrids F2 for all the traits studied confirm that the variance of dominance is greater than the additive variance. Most of the research on the mode of gene action in the transmission of traits, in barley, has stated that non-additive effects are more important than additive effects, at least for one trait, indicating the predominance of dominance-type gene action (Nakhjavan *et al*., 2009; Patial *et al*., 2016; Pesaraklu *et al*., 2016; Yadav, 2016).

Study of the heterosis effect of the F2 generation

Analysis of the heterosis effect compared to the mid parent and the heterobeltiosis indicates the presence of very highly significant differences between the different crosses for all the traits evaluated (Tables 5 and 6). Indeed, the degrees of variation of heterosis of the middle parent and the superior parent vary in a very remarkable way depending on the trait studied.

The significant percentage of the heterosis compared to the mid parent varies between 20% for the harvest index parameter (IR) and 80% for the weight spike trait (WE), (Table 5). On the other hand, the significant percentage of the heterosis effect compared to the superior parent (heterobeltiosis) varies from 15% for the number of grains per spike (NG/E) parameter to 60% for the plant earliness at flowering characteristic (PRF) (Table 6).

Table 5. Degree of heterosis compared to the mid-parent estimated in hybrids F2.

Genotypes	WE	NG/E	WTG	PRF	IR	PP
Sai × Tich	68.28	37.01	36.96	1.1	25.91	55.24
Sai × Bah	6.96	5.25	-4.74	1.24	25.76	22.7
Sai × Exp	-5.82	-0.62	3.94	1.36	-42.03	-22.42
Sai × Plai	36.79	9	-3.51	0.27	-15.7	58.55
Tich × Sai	64.74	15.49	2.36	1.37	-14.34	41.68
Tich × Bah	4.2	-7.17	-9.67	1.78	-31.42	-40.29
Tich × Exp	14.27	-11.46	3.06	-0.52	-41.91	-14.61
Tich × Plai	33.11	1.44	2.57	-1.08	-49.86	27.32
Bah × Sai	1.45	-10.9	-8.15	1.24	-11.88	-34.36
Bah × Tich	8.43	-19.4	-0.78	2.6	7.57	6.07
Bah × Exp	-23.99	-17.83	09.38	0.15	-36.4	-50.76
Bah × Plai	10.53	-10.66	-03.8	-1.47	-26.35	10.16
Exp × Sai	63.85	13.31	12.11	0.27	-13.47	41.58
Exp × Tich	1.27	-12.72	14.61	-1.87	11.49	-4.34
Exp × Bah	-29.65	-27	0.89	-0.39	-14.37	-35.07
Exp × Plai	4.04	-24.87	03.04	-2.92	-50.8	-7.76
Plai × Sai	40.16	-01.27	18.16	0.02	-13.05	-1.58
Plai × Tich	59.64	04.16	17.3	0.54	-37.2	19.51
Plai × Bah	-08.46	-23.94	02.06	-0.95	-32.08	-27.36
Plai × Exp	0.59	-01.88	07.78	-2.13	-26.41	05.25
Significant percentage	80	35	70	40	20	50
Probability	0	0	0	0	0	0

Table 6. Degree of heterobeltiosis estimated in hybrids F2.

Genotypes	WE	NG/E	WTG	PRF	IR	PP
Sai × Tich	43.86	21.7	34.83	0.28	13.14	32.03
Sai × Bah	-10.82	-2.36	-10.5	0.55	17.35	4.63
Sai × Exp	-11.82	-7.23	-1.91	-0.51	-44.01	-25.39
Sai × Plai	24.77	-0.74	-4.99	-1.32	-30.97	50.25
Tich × Sai	40.08	2.6	0.75	0.55	-23.09	20.52
Tich × Bah	-24.16	-22.75	-15.87	1.65	-34.01	-55.33
Tich × Exp	-05.96	-25.96	-1.88	-1.82	-47.76	-27.09
Tich × Plai	05.29	-16.99	1.27	-2.14	-62.17	7.52
Bah × Sai	-15.69	-17.32	-13.69	0.56	-17.97	-44.01
Bah × Tich	-21.3	-32.94	-7.58	2.46	3.55	-20.64
Bah × Exp	-35.23	-18.28	-2.66	-1.03	-40.85	-57.93
Bah × Plai	-01.23	-12.52	-10.88	-2.38	-42.88	-04.97
Exp × Sai	54.68	05.71	05.75	-01.59	-16.49	36.25
Exp × Tich	-17.07	-27	09.1	-03.16	00.11	-18.23
Exp × Bah	-40	-27.44	-10.24	-01.6	-20.42	-44.63
Exp × Plai	-01.34	-26.90	-01.29	-03.17	-59.50	-14.77
Plai × Sai	28.41	-10.13	16.39	-01.56	-28.78	-06.48
Plai × Tich	26.03	-14.71	15.82	-00.52	-52.62	01.46
Plai × Bah	-18.15	-25.52	-05.46	-01.87	-47.32	-37.24
Plai × Exp	-04.12	-04.51	03.23	-02.39	-39.46	-02.78
Significant percentage	35	15	35	60	20	30
Probability	0	0	0	0	0	0

Ten out of twenty hybrids expressed a positive heterosis effect compared to mid parent. In contrast, seven out of twenty hybrids gave a positive heterosis effect compared to the better parent in expressing the productivity trait of the plant. The greatest heterosis compared to the mid and better parent is recorded in the hybrid (Sai X Plai). These results are in agreement with those of Immer (1941); Wienhues (1968); Bogomolov and Grib (1971); Hayes and Foster (1976); Lehmann (1982) who obtained significant increases in yield.

Assessment of the relationships existing between the performance of hybrids, the heterosis effect and the combining abilities. Significant correlations were noted between parental performance and general combining ability for only two of the six parameters evaluated (Table 7).

Positive and significant correlations were recorded between parental performance and general ability to combine for two traits, earliness early and plant productivity, meaning that parental performance reflects its general ability to breed combination for these two parameters. According to Zhan *et al*. (1996), the eigenvalues of the parental lines can be a good indicator of the effects of

GCA. Bouzerzour and Djekoun (1996) underline that in the case of a significant correlation between the mean values of the parent, for a given character, and its GCA, the improvement of this parameter is quickly approached by crosses between the genotypes possessing strong values. Otherwise, improvement of the trait under consideration can be obtained either by crosses between genotypes of high values or by crosses between genotypes with low values (Oury *et al*., 1990).

Table 7. Correlation between parental performance and combining abilities.

Traits	GCA	SCA
WE	-0.983 ^{NS}	-0.938 ^{NS}
NG/E	0.866 ^{NS}	-0.788 ^{NS}
WTG	-0.31 ^{NS}	-0.956 ^{NS}
PRF	0.999*	0.999*
IR	0.993 ^{NS}	-1*
PP	0.999*	0.29 ^{NS}

*= significant at $p\leq 0.05$; ^{NS}= not significant.

Significant to highly significant correlations were found between the performance of hybrids and the heterosis of mid-parent and the heterobeltiosis. Likewise for the relationship between hybrid performance and specific combining ability (SCA). Indeed, positive and very highly significant correlations were found between hybrid performance and ASC for all traits except weight of spike (WE) trait. On the other hand, insignificant correlations were observed between the performances of the hybrids F2 and the general combining ability (GCA) for all the variables evaluated, (Table 8).

Table 8. Correlation between hybrid performance and suitability for combination.

Traits	hm	hs	SCA	GCA
WE	0.832**	0.844**	0.108 ^{NS}	-0.176 ^{NS}
NG/E	0.822**	0.919**	0.737**	0.807 ^{NS}
WTG	0.87**	0.826**	0.952**	-0.335 ^{NS}
PRF	0.739**	0.618**	0.931**	0.934 ^{NS}
IR	0.397**	0.319*	0.443**	-0.192 ^{NS}
PP	0.572**	0.561**	0.519**	-0.86 ^{NS}

**= significant at $p\leq 0.01$; ^{NS}= not significant.

Strong relationships were found between hybrid performance, heterosis effect, and specific combining ability for all traits studied. However, insignificant correlations were found between the performance of hybrids and general combining ability (GCA). These results agree with those of Mühleisen *et al*. (2013).

Very highly significant correlations were recorded between the heterosis effect of the mid-parent and the superior parent and the specific combining ability (SCA) for all traits tested except the weight of ear parameter (WE). In contrast, insignificant correlations were noted between the heterosis effect, compared to the mid and better parent, and the general combining ability (GCA), (Table 9).

Table 9. Correlation between the heterosis effect and the combining ability.

Traits	Heterosis effect	SCA	GCA
WE	hm	0.114 ^{NS}	-1
	hs	0.114 ^{NS}	0.915
NG/E	hm	0.622**	0.917
	hs	0.697**	0.933
WTG	hm	0.813**	0.43
	hs	0.737**	0.888
PRF	hm	0.712**	-0.861
	hs	0.592**	0.889
IR	hm	0.826**	-0.638
	hs	0.733**	-0.76
PP	hm	0.755**	0.524
	hs	0.728**	0.802

**= significant at $p \leq 0.01$; ^{NS}= not significant.

Analysis of the relationship between the heterosis effect and the combining abilities indicates the presence of positive and significant linkages between the heterosis effect and SCA. In contrast, positive and negative correlation coefficients were found indicating the presence of a non-significant association between the heterosis effect and the general combining ability (GCA). These results are in agreement with those of Mühleisen *et al*. (2013) on barley and those of Yu *et al*. (2020) on corn. On the other hand, our results do not agree with those obtained by Zhang *et al*. (2015) on barley.

Conclusions

Evaluating the combining abilities (GCA and SCA) in order to select the best parents and the best hybrids is an effective approach. Indeed, for this study the best parents are Plaisant; Saida and Tichedrett. The best hybrid F2 is (Sai x Plai).

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