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Influence of genotype versus environment interaction on improving upland cotton yield

Influência da interação genótipo versus ambiente sobre o ganho em produtividade de algodão herbáceo

ABSTRACT: Considering the importance of the genotype versus environment interaction (GE) effects during the genetic breeding process, this work aimed to (1) evaluate the influence of GE interaction on gain from selection in seed cotton yield among seven sites in Mato Grosso; and (2) indicate sites of the experimental network for selection in initial and final phases of the breeding programs. We used productivity data from 16 genotypes evaluated in Primavera do Leste/PL (PLI and PLII), Pedra Preta/PP, Campo Verde/CV, Sapezal/SZ, Campo Novo dos Parecis/CNP, and Nova Ubiratã/NU and conducted analyses of variance, decomposition of the mean square of GE interaction (MSGEjj'), correlation between locals and gain prediction by direct and indirect selection and based on the overall mean and statistics Pi. The most similar sites are SZ-PLII, PLI-PLII and SZ-NU, while the most discrepant sites are CV-NU and PP-CV. SZ is the site with most GE interaction, and selection in PLII is the one that maximizes the gains in other sites. PLII is the most indicated local for selection in initial phases of breeding and the combination of PP, CNP and PLII is indicated for preliminary lineage trials. The forms of selection based on the overall mean and statistics Pi are indicated for final lineage trials.

RESUMO: *Devido à importância da interação genótipo versus ambiente (GA) durante o processo de melhoramento genético, os objetivos deste trabalho foram: (1) avaliar a influência da interação GA sobre o ganho por seleção em produtividade de algodão em caroço entre sete locais no Mato Grosso; e (2) indicar locais da rede experimental para seleção em fases iniciais e finais de programas de melhoramento. A partir dos dados de produtividade de 16 genótipos avaliados em Primavera do Leste/PL (PLI e PLII), Pedra Preta/PP, Campo Verde/CV, Sapezal/SZ, Campo Novo dos Parecis/CNP e Nova Ubiratã/NU, foram conduzidas análises de variância, de decomposição do quadrado médio da interação GA (QMGAjj'), de correlação entre locais e de predição de ganho pela seleção direta e indireta e com base na média geral e na estatística Pi. Os locais mais similares são SZ-PLII, PLI-PLII e SZ-NU, enquanto os locais mais discrepantes são CV-NU e PP-CV. Já SZ é o local que mais capitaliza a interação GA, ao passo que a seleção em PLII é a que maximiza os ganhos nos outros locais. Por sua vez, PLII é o local mais indicado para seleção em fases iniciais do melhoramento, e a combinação de PP, CNP e PLII é indicada para ensaios preliminares de linhagens. As formas de seleção com base na média geral e na estatística Pi são indicadas para ensaios finais de linhagens.*

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1 Introduction

Brazil has the world's largest rainfed upland cotton yield, standing out the central-west region, where the mean seed cotton yield is around 2,400 kg ha^{-1} (CONAB, 2016a). The crop has also great socioeconomic importance for the country, mainly to the savannas of the central-west and Bahia, where cotton is grown in extensive areas, fully mechanized and with use of high technology.

The main producing region is the central-west, where cotton is grown in Mato Grosso, Mato Grosso do Sul and Goiás. After the central-west, the largest production is in the northeast, especially in western Bahia and southern Maranhão and another strong producing region is the northwest of Minas Gerais. Of the whole country, the largest producing state is Mato Grosso, where the cultivated area and seed production are estimated at 577,900 ha and 2,283,300 t, in 2015/2016, respectively. The expectation of yield in the state of Mato Grosso is 4,095 kg ha^{-1} for the first crop long-cycle cotton and 3,951 kg ha^{-1} for the second crop dense type cotton (CONAB, 2016b). The high yield in the state and throughout the central-west is attributed to high technology in the management and to the new highly productive varieties. In turn, the most productive varieties for the region are recommended based on several multi-environmental trials.

The new cotton varieties for the central-west are recommended based on final trials of inbred lines, in about ten different locals and in at least five to eight locals in the state of Mato Grosso. And previously to this final step of evaluation of inbred lines, the new inbred lines are evaluated and selected in a smaller number of environments, usually in two or three locals, with the expectation of good performance of the selected inbred lines also in other locals of the region. It is known, however, that GE interaction produces differential response of the genotypes in the different environments, affecting with this also the gain with selection. Due to importance of the GE interaction effects during genetic breeding process, the objectives of this work are (1) to evaluate the influence of GE interaction on gain from selection in seed cotton yield among seven locals in Mato Grosso and (2) to indicate locals of the experimental network for selection in initial and final phases of breeding programs.

2 Material and Methods

To evaluate the reflection of GE interaction on the gain from selection we used yield data from seven competition trials of cotton materials conducted in different locals of Mato Grosso State in 2009 (Primavera do Leste I/PLI, Pedra Preta/PP, Campo Verde/CV, Sapezal/SZ, Campo Novo dos Parecis/CNP, Nova Ubiratã/NU, and Primavera do Leste II/ PLII). In Primavera do Leste we conducted trials in two different experimental fields, referred to as PLI and PLII. The edaphoclimatic characteristics of the municipalities where trials were installed are found in Table 1. In each trial we evaluated for yield 16 cotton genotypes (BRS ARAÇA, BRS BURITI, BRS 286, FMT 701, FM 993, FM 910, DELTA OPAL, IPR JATAI, LD CV 05, LD CV 02, BRS CEDRO, NUOPAL, CNPA MT 05-1245, CNPA MT 04-2080, CNPA MT 04-2088, and BRS 293) using the randomized block design with four replications. The plots of each trial consisted of four rows of 5 m, spaced by 0.9 m, with density of ten plants per meter. The seed cotton yield was evaluated by harvesting the two center rows of each plot, being the data analyzed as totals of plots.

From the data of seed yield in kg ha^{-1} we performed individual and combined analyses of variance, in which we considered the effect of genotypes as random and the effect of environments as fixed. The model adopted on the combined analysis is specified in the equation 1:

$$Y_{ijk} = \mu + G_i + E_j + GE_{ij} + B/E_{jk} + \varepsilon_{ijk} \quad (1)$$

in which, Y_{ijk}: observation of the k-th block evaluated in the i-th genotype and j-th environment; μ: overall mean; B/E_{jk}: effect of block k within the environment j; G_i: effect of genotype i; E_j: effect of environment j; GE_{ij}: effect of the interaction between genotype i and environment j; ε_{ijk}: random error associated with ijk observation. The heritabilities in the broad sense in individual analysis and in combined analysis of locals were calculated as indicated in the equations 2 and 3, respectively:

$$h^2 = \frac{\hat{\sigma}_g^2}{MSG / r} \quad \text{(in each local) (2)}$$

$$h^2 = \frac{\hat{\sigma}_g^2}{MSG / er} \quad \text{(in locals together) (3)}$$

in which: $\hat{\sigma}_g^2 = QMG - QMR / r$ in each local; $\hat{\sigma}_g^2 = MSG - MSR / er$ in combined analysis; MSG: mean square of genotypes; MSR: mean square of residue; e: number of environments; and r: number of replicates.

For detailed study of GE interaction we tested the significance of GE interaction between each pair of environments by F test.

Table 1. Edaphoclimatic conditions of the locals where experimental trials were conducted.

Tabela 1. Condições edafoclimáticas dos locais onde os ensaios experimentais foram conduzidos.

Local	Altitude (m asl)	Latitude	Longitude	Mean annual temperature (°C)	Mean annual rainfall (mm)	Climate
PLI/PLII	636	15º33' S	54º17' W	25.0	1804	Aw
PP	248	16º37' S	54º28' W	24.7	1533	Aw
CV	736	15º32' S	55º10' W	22.3	2726	Aw
SZ	370	13º32' S	58º48' W	22.5	1939	Aw
CNP	572	13º40' S	57º53' W	23.7	1945	Aw
NU	400	12º59' S	55º15' W	24.6	1838	Aw

Source: Wikipédia (2016), Climate-data.org (2016). PLI/PLII, Primavera do Leste; PP, Pedra Preta; CV, Campo Verde; SZ, Sapezal; CNP, Campo Novo dos Parecis; NU, Nova Ubiratã; Aw, semi-humid tropical climate.

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For the same purpose we calculated the percentages of the parts simple and complex of the mean square of GE interaction (MSGEjj’) (Cruz & Castoldi, 1991) and the genotypic correlation coefficients between each pair of environments were calculated by the equation 4:

$$r_{gjj'} = \frac{\hat{\sigma}^2_{gjj'}}{\hat{\sigma}^2_{gjj'} + \widehat{\sigma}^2_{gejj'}} \quad (4)$$

in which: $\hat{\sigma}^2_{gjj'}$: genotypic variance estimated in combined analysis of the environments j and j’; and $\widehat{\sigma}^2_{gejj'}$: variance due to GEjj’ interaction.

To evaluate the reflection of GE interaction on gain from selection in the network of locals we estimated the gains in each local by direct selection and indirect selection in another local, as well as the gain that will be obtained by selection based on the mean of locals and based on the statistics Pi (Lin & Binns, 1988), as follows (Equations 5, 6, 7 and 8):

$$GS_j = h_j^2 DS_j \quad \text{(direct gain) (5)}$$

$$GS_{j(j')} = DS_{j(j')} h_j^2 \quad \text{(indirect gain) (6)}$$

$$GS_{j(c)} = DS_{j(c)} h_j^2 \quad \text{(gain by selection based on the overall mean) (7)}$$

$$GS_{j(Pi)} = DS_{j(Pi)} h_j^2 \quad \text{(gain by selection based on the statistics Pi) (8)}$$

in which: j’: environment in which the selection is practiced; j: environment in which the direct or indirect response is evaluated; h_j^2: heritability in environment j; $DS_{j(j')}$: differential of selection in environment j given by the difference between the mean of the selected families whose superiority was evidenced in environment j’ and the overall mean in environment j; $DS_{j(c)}$: differential of selection in environment j by selection based on the overall mean of trills; and $DS_{j(Pi)}$: differential of selection in environment j by selection based on the statistics Pi. The statistics Pi is given by the distance between a particular genotype in relation to the genotype of maximum performance for each environment, according to the equation 9:

$$Pi = \frac{\sum_{j=1}^{e}\left(X_{ij} - M_j\right)^2}{2e} \quad (9)$$

in which X_{ij} is the mean of genotype i in the j-th environment, M_j is the maximum value obtained in the j-th environment, and e is the number of environments. The number of selected genotypes was five and the criteria used was to select higher values of the trait. All analyzes were performed with the aid of the program Genes (Cruz, 2013).

3 Results and Discussion

The analyses of variance indicated significant effect of genotypes for seed yield in each environment, in which the ratio between the highest and lowest residual mean square did not exceed 7:1, indicating difference among the genotypes and homogeneity in residual variances. The coefficients of variation were below 16% indicating good precision in controlling the causes of experimental variation. In the combined analysis of variance, the effects of genotypes, environments and GE interaction were significant by F test (p<0.01), also indicating contrast between the environments and differential response of the genotypes along the environments. This differential behavior is attributed to GE interaction, i.e. the interaction between the genotypic and environmental effects. Among the effects of variation, the effect of environments had the greatest contribution in phenotypic variation. The character heritability, in the broad sense, ranged from 0.52 to 0.76 between locals and the heritability in the combined analysis was 0.85, value considered elevated. The overall mean was higher in PP, followed by CNP, indicating these environments as the most favorable ones to the trait grain yield. Hoogerheid et al. (2007) and Silva Filho et al. (2008) also observed significant GE interaction for seed cotton yield between multi-environmental trials including locals in Mato Grosso.

The GE interaction was significant for 14 of the 21 pairs of locals by F test (p<0.05) and predominantly complex except in the pair of locals SZ-PLII, where the simple part of the MSGEjj’ was 55.68% (Table 2). Regarding to correlation of the trait between locals, we observed elevated genotypic correlation between SZ-PLII (1.09), PLI-PLII (1.06), SZ-NU (0.98), PLI-SZ (0.88), NU-PLII (0.86), and PLI-NU (0.86).

Table 2. Percentages of the parts simple and complex of the mean square of GE interaction (MSGEjj’) and genotypic correlation between pairs of locals for the character seed cotton yield.

Tabela 2. Porcentagens das partes simples e complexa do quadrado médio da interação GA (QMGAjj’) e correlação genotípica entre pares de locais para o caráter produtividade de algodão em caroço.

Ljj’		%S MSGEjj’	%C MSGEjj’	r_g
PLI	PP	15.96	84.04	0.58
PLI	CV	-3.26	103.26	0.40
PLI	SZ	31.56	68.44	0.88
PLI	CNP	15.35	84.65	0.62
PLI	NU	25.88	74.12	0.86
PLI	PLII	45.54	54.46	1.06
PP	CV	10.84	89.16	0.38
PP	SZ	27.50	72.50	0.69
PP	CNP	39.18	60.82	0.62
PP	NU	26.78	73.22	0.62
PP	PLII	17.02	82.98	0.55
CV	SZ	1.48	98.52	0.47
CV	CNP	-2.52	102.52	0.46
CV	NU	-7.25	107.25	0.36
CV	PLII	8.36	91.64	0.60
SZ	CNP	35.30	64.70	0.80
SZ	NU	41.24	58.76	0.98
SZ	PLII	55.68	44.32	1.09
CNP	NU	5.39	94.61	0.55
CNP	PLII	29.90	70.10	0.83
NU	PLII	23.03	76.97	0.86

PLI/PLII, Primavera do Leste; PP, Pedra Preta; CV, Campo Verde; SZ, Sapezal; CNP, Campo Novo dos Parecis; NU, Nova Ubiratã; Ljj’, pairs of locals; %S MSGEjj’, percentage of the simple part of the MSGEjj’; %C MSGEjj’, percentage of the complex part of the MSGEjj’; r_g, genotypic correlation.

Greater correlation occurs between pairs of locals where GE interaction is not significant, as expected. By the estimates, the most similar pairs of locals in terms of concordance in performance of genotypes are SZ-PLII, PLI-PLII and SZ-NU, and the most discrepant pairs of locals are CV-NU and PP-CV. The high magnitude correlations indicate absence or smaller effect of GE interaction.

Regarding to selection, it is known that the direct gain will be greater the higher the heritability. The indirect gain, in another environment, will be greater the higher the similarity between the environments with regard to behavior of genotypes and the higher the heritability in the environment of selection. The similarity between the environments is higher the higher the genetic correlation between the environments and the higher the simple part of the MSGEjj'. The complex part of the MSGEjj', on the other hand, is associated to the lack of genetic correlation when genotypes with superior performance occur in one environment, but not in another (Passos et al., 2011; Cruz et al., 2012, 2014). So it is expected that the direct gains are always greater than the indirect ones, as consequence of the expression itself used for calculation of the selective gains, and that the indirect gains are greater in the pairs of environments with high genetic correlation, no significant GE interaction and/or predominance of the simple part of the MSGEjj', as occurs in most estimates of the gain from selection. The means of the top five genotypes in each local and based on the overall mean and on the statistics Pi are presented in Table 3.

Robertson (1959) classifies the GE interaction in two types, simple and complex. The simple part is due to the difference of variability between the genotypes, so that the relative position of the genotypes is not changed with the environment, not resulting in problems to selection and to recommendation. On the other hand, the complex part is proportionate by different responses to environmental variations, which produces change in classification and/or inconsistency in performance of genotypes and brings difficulties mainly to selection.

Between the pairs of locals in general, the indirect gain should be small due to magnitude of the complex portion of the MSGEjj', although between SZ-PLII, where there is predominance of the simple part of the MSGEjj' and high genetic correlation, an expressive indirect gain is expected, as in fact occurs according to the gain from selection prediction (Table 4). From the direct and indirect gains in the pairs of locals, we observed that the local SZ is the one that most capitalizes GE interaction and that selection in PLII is the one that maximizes the gains in other locals. So between locals, PLII is the most indicated for selection in initial phases of breeding. After PLII, the locals SZ and PP, which also potentiate the indirect gains in the other environments, could be indicated. In turn, the combination of locals PP, CNP and PLII could be indicated for preliminary trials of inbred lines, because excluding SZ that is very similar to PLII these locals are those that most potentiate the indirect gain between the environments. The forms of selection based on the overall mean and on the statistics Pi could produce according to the estimates even greater gains, however they are forms of selection impracticable in initial phases of genetic breeding, due to the elevated number of genotypes. Nevertheless, the selections based on the overall mean and on the statistics Pi on the other hand can be useful in final trials of inbred lines, in which the number of genotypes is reduced and genotypes with wide adaptation are desired.

Until now, in the soil and climate conditions of Brazil, the effect of GE interaction on cotton yield gain has been only studied between few locals in the northeast region (Souza-PB, Surubim-PE, Caruaru-PE, and Palmas de Monte Alto-BA), where 25 inbred lines were evaluated to seed yield (Carvalho et al.,

Table 3. Means of cotton genotypes at locals and selected genotypes in each local and based on the overall mean and on the statistics Pi for the character seed coton yield.

Tabela 3. Médias dos genótipos de algodão nos locais e genótipos selecionados em cada local e com base na média geral e na estatística Pi para o caráter produtividade de algodão em caroço.

Genotypes	Kg ha^{-1}								Pi
	PLI	PP	CV	SZ	CNP	NU	PLII	Mean	
BRS ARAÇA	4671.69	6505.37	4050.90	5132.14	6247.66*	3189.71	4414.47	4887.42	287509.41
BRS BURITI	4597.86	5635.70	4609.12*	6119.25*	6312.97*	4124.49*	5012.17*	5201.65*	205703.40*
BRS 286	4249.41	6540.76	3622.31	5005.65	5677.09	3642.25*	3762.67	4642.88	500206.35
FMT 701	4841.91*	6688.28*	4192.18	5371.45	6023.36	4283.38*	4484.47	5126.43*	148439.48*
FM 993	4400.07	7150.62*	4340.88	5681.88*	6303.07*	3240.92	4740.65*	5122.58*	168840.77*
FM 910	4270.56	6953.26*	3974.97	5473.76	5929.85	3627.75	4593.98*	4974.87	231714.71*
DELTA OPAL	4827.11*	4199.60	4072.42	4888.20	5401.08	3408.89	4488.92	4469.46	983084.98
IPR JATAI	4434.78	5902.41	4811.15*	5344.24	5922.67	3387.23	4175.72	4854.03	349375.17
LD CV05	4738.46	6475.50	3691.51	5803.06*	6082.15	3402.55	4562.39	4965.09	244685.56
LD CV02	3180.29	5573.06	4379.00*	4082.60	5760.10	2724.61	3144.90	4120.65	1262259.12
BRS CEDRO	4573.87	6060.41	4211.71	5504.44*	6092.72	3559.79	4348.01	4907.28	262976.81
NUOPAL	5164.19*	7095.71*	4361.49*	5024.29	5628.85	3287.09	4377.60	4991.32	291033.21
CNPA MT05 1245	5097.97*	5845.99	3826.48	5395.63	6758.02*	3311.97	4675.72*	4987.40	304036.84
CNPA MT04 2080	5026.14*	6177.42	4482.04*	5501.98	5765.31	3613.56	4599.75*	5023.74*	218554.90*
CNPA MT04 2088	4686.15	6445.03	3998.72	5191.90	6150.45*	3696.76*	4160.52	4904.22	263213.22
BRS 293	4797.12	6820.53*	3574.94	5747.29*	5904.01	4177.44*	4138.43	5022.82*	243875.48

PLI/PLII, Primavera do Leste; PP, Pedra Preta; CV, Campo Verde; SZ, Sapezal; CNP, Campo Novo dos Parecis; NU, Nova Ubiratã; Pi, statistics Pi. The asterisk (*) indicates the selected genotypes in each environment.

Table 4. Direct and indirect cotton yield gain from selection in the different locals and based on the overall mean and on the statistics Pi.

Tabela 4. Ganho direto e indireto em produtividade de algodão em caroço a partir da seleção em diferentes locais e com base na média geral e na estatística Pi.

GSLjj' Kg ha^{-1}	Selection in Lj'							Total GSLj	Selection criteria	
	PLI	PP	CV	SZ	CNP	NU	PLII		Mean	Pi
PLI	255.47	63.15	-75.65	15.64	60.54	24.08	52.62	395.85	87.69	19.42
	(5.55)	(1.37)	(-1.65)	(0.34)	(1.31)	(0.52)	(1.14)	(8.58)	(1.91)	(0.42)
PP	-172.35	468.32	-120.94	118.69	42.37	117.00	66.94	520.03	163.63	181.72
	(-2.76)	(7.48)	(-1.94)	(1.89)	(0.67)	(1.87)	(1.07)	(8.28)	(2.62)	(2.91)
CV	31.69	-31.15	250.70	-33.24	17.78	-88.49	70.01	217.3	65.61	116.90
	(0.76)	(-0.76)	(6.05)	(-0.81)	(0.42)	(-2.14)	(1.69)	(5.21)	(1.59)	(2.83)
SZ	-70.21	98.59	-86.70	333.90	132.16	119.28	230.63	757.65	268.31	226.98
	(-1.32)	(1.85)	(-1.63)	(6.26)	(2.47)	(2.23)	(4.32)	(14.18)	(5.03)	(4.26)
CNP	-57.13	-27.57	-83.10	98.44	248.29	11.21	150.50	340.64	44.71	48.31
	(-0.96)	(-0.46)	(-1.39)	(1.64)	(4.13)	(0.18)	(2.50)	(5.64)	(0.75)	(0.81)
NU	20.15	94.48	-60.06	82.85	-15.47	231.07	21.59	374.61	180.46	123.05
	(0.56)	(2.66)	(-1.7)	(2.33)	(-0.44)	(6.52)	(0.60)	(10.53)	(5.09)	(3.47)
PLII	100.98	66.43	-55.15	121.76	145.71	-25.72	219.10	573.11	142.38	196.41
	(2.31)	(1.52)	(-1.27)	(2.79)	(3.34)	(-0.60)	(5.03)	(13.12)	(3.27)	(4.51)
Total GSLj'	108.60	732.25	-230.90	738.04	631.38	388.43	811.39	-	952.79	912.79
	(4.14)	(13.66)	(-3.53)	(14.44)	(11.90)	(8.58)	(16.35)	-	(20.26)	(19.20)

PLI/PLII, Primavera do Leste; PP, Pedra Preta; CV, Campo Verde; SZ, Sapezal; CNP, Campo Novo dos Parecis; NU, Nova Ubiratã; GSLjj', gain in local Lj from selection in Lj'; GSLj and GSLj', sum of the direct and indirect gains in horizontal and vertical, respectively; Pi, statistics Pi. In parentheses the percentage value.

1995). In this study, the indirect gain was greater among the locals with higher genetic correlation, also indicating importance of GE interaction in the works of varieties selection. The selection in Caruaru-PE maximized the indirect gain between locals, however in general the mean yield was low, where the best inbred line had mean of 1,534 ka ha^{-1}. These locals from PB and PE, in the semiarid, were strong cotton producers in the decades of 70-80, however the producing areas in the Northeast nowadays are in western Bahia and in the microregion of Bom Jesus da Lapa-BA and Caetité-BA (CONAB, 2016a). In turn, in the network of trials conducted in Mato Grosso, from this study, elevated productivities were obtained, where the best genotype had mean of 5,201.65 ka ha^{-1} and the overall mean yield was 4,887.61 ka ha^{-1}. In addition, among the network of locals evaluated in Mato Grosso, SZ, CV, PL, and CNP are among the five largest producing municipalities of the state and in the second largest producing area of the country, after western Bahia.

On the other hand, several studies about environmental stratification for cotton yield has been made from models of analysis AMMI and GGE biplot (Li & Xu, 2014; Xu et al., 2014; Zeng et al., 2014; Pretorius et al., 2015), in which environmental strata are defined and specific genotypes are recommended for each sub-region. Besides attenuating GE interaction, such methodologies make possible to evaluate the degree of representativeness of trials and to make decisions regarding the reduction of the number of locals, especially when there are technical problems or scarcity of resources. However, although useful for zoning, such methods do not completely prevent the occurrence of GE interaction. So that's why it is also important to evaluate the gain with selection among locals of the experimental network, for then make the choice of the locals of selection, especially for initial phases of breeding and when GE interaction is predominantly complex.

4 Conclusions

SZ is the local that most capitalizes GE interaction and selection in PLII is the one that maximizes the gains in other locals. PLII is the most indicated local for selection in initial phases of breeding and the combination of PP, CNP and PLII is indicated for preliminary trials of lines. The forms of selection based on overall mean and on statistics Pi are indicated for final trials of lines.

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