Post-harvest performance of experimental green corn hybrids via topcross

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Abstract: *Despite their economic relevance, studies on the physical, chemical, and sensory traits of green corn are still scarce. Therefore, this work aimed to identify superior hybrid combinations for post-harvest traits. For this purpose, 36 genotypes were evaluated in two different seasons, including 34 experimental hybrids and 2 testers (AG1051 and FT2015). AG1051 is a double hybrid of green corn, and FT2015 is a single hybrid of sweet corn. pH and °Brix in raw and cooked grains and weight loss were evaluated. It is concluded that there are promising crosses for the evaluated post-harvest traits. The crosses L111 x FT2015 and L33 x FT2015 showed high °Brix values in raw (means of 9.83 and 7.00) and cooked (means of 8.08 and 7.08) grains, low pH values in raw (means of 7.21 and 7.29) and cooked (means of 7.04 and 7.22) grains, and low weight loss (means of 1.66 g and 1.49 g).*

Keywords: Zea mays *L., partial diallel, hybrid breeding*

INTRODUCTION

Brazil has great potential for the production of green corn and sweet corn. Both are classified as horticultural products due to their high added value, short cycle, intensive cultivation, and direct destination for human consumption (Silveira et al. 2021). Despite their economic importance, studies on the physical, chemical, and sensory characteristics of green corn and sweet corn are still scarce, with information predominantly related only to yield. However, high yields do not always mean ears suitable for processing and consumption (Souza et al. 2021).

Green corn has a high starch content, while sweet corn has a higher sugar content controlled by mutant genes (Laosatit et al. 2022). The mutant genes that confer the sweet corn characteristic are sugary 1 (su1), shrunken 2 (sh2), brittle 1 (bt1), sugary enhancer (se), and brittle 2 (bt2). These mutant genes are recessive and, when crossed with starchy genotypes, will produce genotypes with high starch content and low sweetness (Suzukawa et al. 2018).

The increased demand for green corn is accompanied by a corresponding increase in the quality of the fresh product (Becerra-Sanchez and Taylor 2021). One of the main post-harvest characteristics is °Brix, which represents the amount of soluble solids and serves as an indicator of sugar content and, consequently, sweetness of the product (Mamede et al. 2014, Machado Filho et al. 2018). Therefore, for fresh consumption, the search is for genotypes that have a high

°Brix (Machado Filho et al. 2018). Another important post-harvest characteristic is pH, where a pH close to neutral is preferred because it maintains sweetness and is unfavorable for the growth of microorganisms (Silveira et al. 2021). Under tropical conditions, characterized by high humidity and high temperature, the product's respiration is accelerated, which intensifies weight loss and increases the importance of this trait (Mamede et al. 2009). Therefore, genotypes with the lowest pH values (provided they are not excessively acidic) and the lowest weight loss rates are preferred.

In this context, the topcross method, based on crossing strains with a tester, allows for the classification of the most promising strains in a breeding program (Chiquito et al. 2021). The topcross method is particularly useful because it allows for the evaluation of several strains at intermediate levels of inbreeding using a common tester (Chiquito et al. 2021). This strategy allows for the discarding of low-performing genotypes, optimizing time and resources, and making breeding programs more rational and efficient (Chiquito et al. 2021).

The scarcity of green corn and sweet corn genotypes that also prioritize post-harvest characteristics limits the expansion of cultivation (Seledes et al. 2022). Given the growing demand from the canning industry and the increasing requirements for quality, the development of hybrids adapted to the tropical climate and with good post-harvest characteristics through breeding programs becomes essential (Rezende et al. 2019, Seledes et al. 2022).

Thus, this study aimed to identify superior hybrid combinations for post-harvest traits of green corn. The hypothesis of the study is that experimental hybrids exist with performance superior to or similar to that of the test hybrids.

MATERIAL AND METHODS

Corn ears from two experiments, conducted under controlled fertilization, and pest and disease management conditions during the years 2019 (planting in September of 2019) and 2020 (planting in April of 2020) were used. The experiment was conducted in Gurupi (lat 11º 44' 42" S, long 49º 03' 05" W and alt 287 m asl), Tocantins. The region's climate is characterized by a semi-humid seasonal tropical climate, type b1 Aw humid (Figure 1) (Dubreuil et al. 2018). The ears selected for evaluation were uniform and had adequate commercial characteristics, harvested at the R4 phenological stage, when the grains were in the doughy phase. Harvesting was carried out in the morning, while minimal processing and evaluations of the green corn ears were performed the day after harvesting. The weight loss assessment was conducted after 10 days of storage.

Two experiments in different seasons (2019 and 2020) were conducted to evaluate 36 genotypes (Table 1). The design was a randomized block design with three repetitions. The 36 genotypes consisted of 34 experimental hybrids, and 2 commercial maize testers (AG1051 and FT2015). The 34 experimental hybrids were obtained by crossing lines with the testers AG1051 and/or FT2015 (Table 1). AG1051 (Agroceres®) is a double hybrid and widely used in human food as green corn and its derivatives (pamonha) (Pinho et al. 2008, Castro et al. 2013). Since AG1051 has a high starch concentration and sweetness is determined by mutant and recessive genes, the grains resulting from crossing with AG1051 will necessarily be rich in starch. FT2015 (Feltrin®) is a single hybrid of sweet corn (Milagres et al. 2021). Each plot consisted of two ears of corn with suitable commercial characteristics of husked ear weight, length, and ear diameter. The two ears of corn were chosen in order to ensure representativeness of the plot.

The husked ears of corn were placed in polystyrene trays measuring 23.5 cm x 18.2 cm and protected with 10-micron thick plastic film. They were then stored in a refrigeration chamber at a temperature of 16 °C ± 2.0. A temperature of 16 °C allows for the storage of the corn cobs in a controlled atmosphere (Silva et al. 2019), but it is a more challenging environment for weight loss. The traits evaluated were soluble solids content (°Brix)
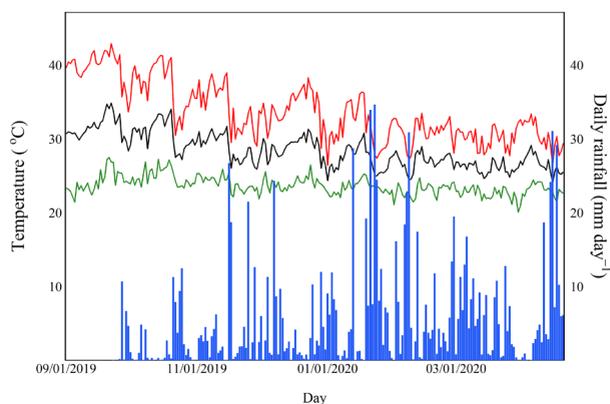

Figure 1. Average temperature (black line), minimum temperature (green line), maximum temperature (red line) and precipitation (blue column) during the experiment in Gurupi, Tocantins, Brazil, 2019/20.

measured with a refractometer before (raw) and after (cooked) cooking, evaluated the day after harvest, and pH measured before (raw) and after (cooked) cooking using a pH meter, evaluated the day after harvest. The cooking process consisted of boiling (in distilled water with °Brix 0.00 and pH 6.80), for 10 minutes in an iron pot, two ears of corn at a time from each plot. 100 grams of raw and cooked sweet corn kernels (in distilled water with °Brix 0.00 and pH 6.80) were ground in a food processor, followed by the determination of °Brix and pH values. The weight loss result was expressed in grams and represents the cumulative weight loss over the 10 days.

Table 1. Genotypes evaluated in experiments in Gurupi, Tocantins, Brazil, 2019/20

AG1051	L13 x AG1051	L3 x FT2015	L5 x AG1051
FT2015	L134 x AG1051	L33 x AG1051	L5 x FT2015
L110 x AG1051	L138 x AG1051	L33 x FT2015	L60 x AG1051
L111 x FT2015	L17 x AG1051	L37 x AG1051	L63 x AG1051
L112 x AG1051	L17 x FT2015	L37 x FT2015	L78 x AG1051
L119 x AG1051	L18 x AG1051	L38 x AG1051	L79 x AG1051
L12 x AG1051	L18 x FT2015	L39 x AG1051	L89 x AG1051
L12 FT2015	L21 x AG1051	L47 x AG1051	L9 x AG1051
L128 x AG1051	L3 x AG1051	L47 x FT2015	L9 x FT2015

Based on the individual analyses of variance for each season, joint analyses were performed. The joint analysis of variance was conducted considering the following statistical model:

$$y_{ijk} = \mu + \omega_{k(i)} + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon ijk, \qquad (1)$$

in which y_{ijk} is the response trait, μ is the effect of the overall mean, $\omega_{k(i)}$ is the effect of the k-th block within the i-th season (k = 1, 2 and 3), α_i is the effect of the i-th season (i = 1, 2), β_j is the effect of the j-th genotype (j = 1, 2, ..., 36), $\alpha\beta_{ij}$ is the effect of the season x genotype interaction and εijk is the effect of random error. The block, season, and genotype effects were considered as fixed effects in the model. When necessary, the means were compared using the Scott-Knott's (1974) test at a 5% probability level. The Scott-Knott test has the advantage of grouping the means into disjoint groups (Scott and Knott 1974). The coefficient of variation was calculated using the expression:

$$\text{CV(\%)} = \frac{MSResidual}{\bar{y}} \; 100\% \qquad (2)$$

in which MSResidual is the mean square of the residual obtained by the analysis of variance, and $\bar{y}$ is the overall mean of the trait. All analyses and graphs were created using the R software (R Core Team 2025).

RESULTS AND DISCUSSION

The average values for °Brix ranged from 7.18 to 6.33 considering raw and cooked grains, respectively (Table 2). These average values for soluble solids are slightly below those found by Mamede et al. (2014) and Chiquito et al. (2021), highlighting the existence of crosses with low °Brix results. The pH showed values close to 7 (Table 2), a result similar to that obtained by Mamede et al. (2014) and Silveira et al. (2021). The coefficient of variation (CV) ranged from 0.23% (pH in raw grain) to 30.13% (°Brix in cooked grain) (Table 2). The values found for the coefficient of variation in the pH characteristics demonstrate good experimental precision and are below those found in the work of Silveira et al. (2021). The coefficient of variation obtained for °Brix in raw and cooked grain is slightly above the values found by Suzukawa et al. (2018) and similar to that found by Machado Filho et al. (2018).

A comparison was made between genotypes within each season and between seasons within each genotype due to the presence of a significant season x genotype interaction for the traits °Brix and pH in raw and cooked grain (Tables 2, 3 and 4). The significant interaction between season and genotype demonstrates the need to recommend hybrid combinations for each season evaluated due to the existing dependence between genotype and season. As the genotype x season interaction was not significant for weight loss, then for this trait only the comparison between genotypes was made (Tables 2 and Table 4). Therefore, for weight loss, there is no need to recommend hybrid combinations for each season, and the behavior of the genotypes can be generalized to both seasons evaluated.

Soluble solids (°Brix)

Considering the °Brix level in raw grains, nine genotypes formed the group with the highest mean in the first season, and six formed the group with the highest mean in the second season (Table 3). Evaluating the effect of genotype on the raw grain °Brix trait, AG1051 (means of 8.00 in 2019 and 11.17 in 2020), L111 x FT2015 (means of 8.00 in 2019 and 11.67 in 2020) and L33 x FT2015 (means of 7.67 in 2019 and 11.75 in 2020) showed good results in both seasons

evaluated (Table 3). In the comparison between the two seasons, the second season showed a higher mean for four genotypes of the top 10 ranking (Table 3).

Considering °Brix in cooked grains, eight genotypes formed a group with the highest mean in the first season and eighteen in the second season (Table 3). The genotypes AG1051 (means of 8.67 in 2019 and 6.90 in 2020), L111 x FT2015 (means of 8.67 in 2019 and 7.50 in 2020), L18 x FT2015 (means of 8.00 in 2019 and 7.33 in 2020), L33 x FT2015 (means

Table 2. Summary of the analysis of variance and descriptive measures of the traits soluble solids content (°Brix) in raw and cooked grain, pH in raw and cooked grain, and weight loss in experimental and commercial hybrids of green corn and sweet corn evaluated in Gurupi, TO, Brazil, in the years 2019 and 2020

SV	df	F value				
		°Brix raw	°Brix cooked	pH raw	pH cooked	Weight loss
Block|season	4	0.51	0.26	0.30	1.33	1.28
Season (S)	1	349.46**	20.93**	22.50**	2269.82**	4.65*
Genotype (G)	35	6.03**	3.22**	2.92**	2.02**	1.58*
S x G	35	3.31**	3.78**	3.10**	2.05**	0.90
Maximum	-	9.83	9.12	7.45	7.29	2.42
Mean	-	7.18	6.33	7.26	7.16	1.93
Minimum	-	5.00	4.83	7.11	7.00	1.49
CV (%)	-	21.99	30.13	0.23	0.24	9.09

** and * are significant at 1% and 5% probability levels, respectively, according to the F-test.

Table 3. Mean ± standard deviation of the mean for °Brix in raw and cooked grains within each season (2019 and 2020). Only the top 10 genotypes are shown. SD represents the standard deviation and n represents the number of repetitions. Means followed by the same lowercase letter in the column do not differ from each other by the Scott-Knott test (p-value > 0.05). Uppercase letters represent the comparison between seasons within each genotype, although not all genotypes are presented in both seasons

°Brix in raw grain			
2019		**2020**	
Genotype	$\bar{y} + \frac{SD}{\sqrt{n}}$	Genotype	$\bar{y} + \frac{SD}{\sqrt{n}}$
L111 x FT2015	8.00±0.00 aB	L9 x FT2015	14.00±0.50 aA
AG1051	8.00±0.00 aB	L78 x AG1051	12.17±2.17 aA
L33 x FT2015	7.67±0.33 aB	L33 x FT2015	11.75±1.01 aA
L38 x AG1051	7.33±0.88 aA	L111 x FT2015	11.67±0.33 aA
L79 x AG1051	7.00±1.00 aA	L119 x AG1051	11.67±0.33 aA
L3 x FT2015	6.67±0.33 aA	AG1051	11.17±0.17 aA
L33 x AG1051	6.33±0.33 aA	L5 x FT2015	10.33±1.92 bA
L47 x AG1051	6.33±0.33 aA	L12 x FT2015	10.33±0.67 bA
L18 x FT2015	6.33±0.67 aB	L60 x AG1051	10.17±0.17 bA
L21 x AG1051	6.00±0.58 bA	L47 x FT2015	9.67±0.33 bA
°Brix in cooked grain			
2019		**2020**	
Genotype	$\bar{y} + \frac{SD}{\sqrt{n}}$	Genotype	$\bar{y} + \frac{SD}{\sqrt{n}}$
L5 x FT2015	10.00±0.00 aA	L33 x AG1051	9.50±0.76 aA
L3 x FT2015	9.67±1.20 aA	L33 x FT2015	9.25±1.30 aA
L33 x FT2015	9.00±0.58 aA	L38 x AG1051	8.83±0.44 aA
L111 x FT2015	8.67±1.33 aA	L47 x AG1051	8.67±0.33 aA
AG1051	8.67±0.33 aA	L134 x AG1051	8.67±0.33 aA
L47 x FT2015	8.00±0.58 aA	L5 x AG1051	7.73±0.82 aA
L18 x FT2015	8.00±1.73 aA	L47 x FT2015	7.70±0.57 aA
L17 x FT2015	7.33±0.67 aA	L21 x AG1051	7.67±0.73 aA
L9 x FT2015	6.00±0.58 bA	L111 x FT2015	7.50±0.76 aA
L79 x AG1051	6.00±0.00 bA	L12 x AG1051	7.50±0.50 aA

of 9.00 in 2019 and 9.25 in 2020), and L47 x FT2015 (means of 8.00 in 2019 and 7.70 in 2020) showed good results in both evaluated seasons (Table 3).

In this study, the tester hybrid AG1051 showed a mean of approximately 10 °Brix for raw grains and 8 °Brix for cooked grains in both seasons, while several hybrids showed similar means in both seasons (Table 3). The tester FT2015 showed an average soluble solids content close to 6 °Brix and was surpassed by several experimental hybrids in both seasons. Thus, several experimental hybrids and diallel hybrids showed promise for increasing the average soluble solids content.

Table 4. Mean ± standard deviation of the mean for pH in raw and cooked grains within each season (2019 and 2020) and weight loss. The seasonal effect is not considered in the weight loss ranking. Only the top 10 genotypes are shown. The means are presented in descending order because pH and weight loss are traits that we wish to reduce. SD represents the standard deviation and n represents the number of repetitions. Means followed by the same lowercase letter in the column do not differ from each other by the Scott-Knott test (p-value > 0.05). Uppercase letters represent the comparison between seasons within each genotype, although not all genotypes are presented in both seasons

pH in raw grain			
2019		**2020**	
Genotype	$\bar{y} + \frac{SD}{\sqrt{n}}$	Genotype	$\bar{y} + \frac{SD}{\sqrt{n}}$
L63 x AG1051	7.07±0.05 aB	L33 x FT2015	6.95±0.14 bB
L39 x AG1051	7.13±0.01 aB	L5 x FT2015	6.97±0.00 bB
L110 x AG1051	7.13±0.14 aA	L17 x FT2015	6.97±0.05 bB
L18 x AG1051	7.17±0.01 aA	L12 x FT2015	7.00±0.11 bB
L12 x AG1051	7.19±0.04 aB	L21 x AG1051	7.00±0.04 bB
L9 x AG1051	7.23±0.05 aA	L9 x FT2015	7.02±0.06 bB
L12 x FT2015	7.23±0.01 aA	L18 x FT2015	7.04±0.09 bB
L112 x AG1051	7.24±0.08 aA	L47 x FT2015	7.07±0.10 bA
L13 x AG1051	7.25±0.04 aA	L13 x AG1051	7.08±0.07 bA
L9 x FT2015	7.26±0.07 aA	L111 x FT2015	7.13±0.03 bA
pH in cooked grain			
2019		**2020**	
Genotype	$\bar{y} + \frac{SD}{\sqrt{n}}$	Genotype	$\bar{y} + \frac{SD}{\sqrt{n}}$
L17 x AG1051	7.35±0.07 bA	L47 x AG1051	6.53±0.06 bB
L111 x FT2015	7.45±0.06 Ba	L63 x AG1051	6.53±0.06 bB
L5 x AG1051	7.45±0.03 bA	AG1051	6.53±0.14 bB
L79 x AG1051	7.46±0.14 bA	L5 x AG1051	6.57±0.03 bB
AG1051	7.48±0.08 bA	L3 x AG1051	6.60±0.05 bB
L3 x AG1051	7.50±0.08 bA	L111 x FT2015	6.63±0.03 bB
L9 x FT2015	7.50±0.01 bA	L3 x FT2015	6.63±0.06 bB
L78 x AG1051	7.51±0.13 bA	L18 x FT2015	6.63±0.03 bB
L89 x AG1051	7.53±0.03 bA	L138 x AG1051	6.63±0.08 bB
L18 x FT2015	7.53±0.03 bA	FT2015	6.63±0.08 bB
Weight loss (in grams)			
	Genotype	$\bar{y} + \frac{SD}{\sqrt{n}}$	
	L33 x FT2015	1.49±0.0031 b	
	L21 x AG1051	1.63±0.0010 b	
	AG1051	1.66±0.0015 b	
	L111 x FT2015	1.66±0.0008 b	
	L38 x AG1051	1.66±0.0012 b	
	L3 x FT2015	1.68±0.0004 b	
	L119 x AG1051	1.75±0.0008 b	
	FT2015	1.75±0.0012 b	
	L39 x AG1051	1.79±0.0014 b	
	L47 x AG1051	1.80±0.0010 b	

Despite the promising performance of the experimental hybrids compared to commercial hybrids, the °Brix values obtained have not yet reached the levels commonly found for sweet corn (Mamede et al. 2014, Perfeito et al. 2017).

pH

Regarding the raw grain pH trait, the objective is to select genotypes with reduced pH, discouraging the proliferation of microorganisms and increasing the product's shelf life, but it should not be an excessively acidic pH (Mamede et al. 2014, Silveira et al. 2021). Mamede et al. (2014) performed a physicochemical analysis of sweet corn grains and obtained a mean pH of 7.1 and a maximum °Brix of 14. The authors indicated that this value is higher for sweet corn because a higher °Brix, combined with a pH close to neutrality, enhances the flavor of the sweet corn, resulting in greater palatability and accessibility to the consumer public. Therefore, pH values close to 7.00 are preferred because they combine neutrality and do not provide a favorable environment for microorganisms.

Considering both seasons, there was no statistical difference between the genotype means for raw grain pH in the top 10 ranking (Table 4). Three genotypes (L12 x FT2015, L9 x FT2015 and L13 x AG1051) were selected in the top 10 ranking for both seasons when considering raw grain pH (Table 4). When comparing the seasons within each genotype, the second season showed the lowest mean in seven genotypes of the top 10 ranking (Table 4).

Considering pH in cooked grain, a group of five genotypes (L5 x AG1051, AG1051, L3 x AG1051, L111 x FT2015 and L18 x FT2015) had the lowest means in both seasons (Table 4). The cross L111 x FT2015 stands out, showing the lowest average pH in raw grain (mean of 7.21) and cooked grain (mean of 7.04) (Table 4), in addition to higher values of soluble solids in both raw grain (mean of 9.83) and cooked grain (mean of 8.08) (Table 3). Again, there was a large discrepancy in the results obtained between seasons, with the second season showing the lowest pH in cooked grain for all genotypes in the top 10 ranking (Table 4). These pH values are higher than those obtained by Lima et al. (2015) in the evaluation of raw baby corn and are also higher than the result obtained by Silva et al. (2019) in the evaluation of baby corn.

Weight loss

Regarding weight loss, the season x genotype interaction was not significant, and therefore no further analysis of the interaction was performed. The main factor responsible for weight loss during storage of sweet corn and green corn is transpiration, which is directly related to the product's respiration (Mamede et al. 2015). Weight losses above 7% are sufficient to cause a sharp decline in product quality. For green corn cultivars, the observed weight loss occurs at a percentage lower than the maximum value (7%) allowed for retail marketing, regardless of the type of tester involved in the crosses (Szymanek et al. 2015, Calvo-Brenes and O'hare 2020). Weight loss is attributed to respiration and transpiration, which reduce water in the tissues, influenced by temperature and humidity, and can be optimized. Sweet corn retains sugar for longer because water is lost slowly and conversion to starch is delayed (Laughnan 1953, Huelsen 1954).

In the study of the genotype effect, eighteen crosses showed lower means for this weight loss (Table 4). Among these genotypes, the L111 x FT2015 cross stands out, with one of the lowest means for weight loss (mean of 1.66 g), in addition to good results for °Brix and pH (Tables 3 and 4). The weight loss results are more promising than those presented by Mamede et al. (2015), who found weight losses below 3.41% in three cultivars of minimally processed sweet corn stored under a passive modified atmosphere for nine days.

CONCLUSIONS

It is concluded that there are promising crosses for the evaluated post-harvest traits. The crosses L111 x FT2015 and L33 x FT2015 showed high °Brix values in raw (means of 9.83 and 9.70, respectively) and cooked (means of 8.08 and 9.12, respectively) grains, low pH values in raw (means of 7.21 and 7.11, respectively) and cooked (means of 7.04 and 7.28, respectively) grains, and low weight loss (means of 1.65 g and 1.49, respectively). These results demonstrate the good performance of FT2015 as a parent of good genes for post-harvest traits. Therefore, these results reinforce the feasibility of obtaining promising crosses for tropical conditions and with good post-harvest characteristics.

CREDIT STATEMENT

Conceptualization: Lopes DAPS, Nascimento IRN, Faria MV; Methodology: Lopes DAPS, Costa NMEPL, Nascimento IRN, Faria MV; Formal analysis: Lopes DAPS, Nascimento IRN, Costa NMEPL; Investigation: Lopes DAPS, Casais LKN, Ferreira Júnior OJ; Data curation: Lopes DAPS, Costa NMEPL, Faria MV; Writing – original draft: Lopes DAPS, Costa NMEPL, Casais LKN, Nascimento IRN, Faria MV; Writing – review and editing: Lopes DAPS, Costa NMEPL, Casais LKN, Ferreira Júnior OJ, Nascimento IRN, Faria MV; Visualization: Lopes DAPS, Costa NMEPL, Faria MV; Supervision: Nascimento IRN, Faria MV; Project administration: Nascimento IRN, Faria MV; Validation: Nascimento IRN, Costa NMEPL, Faria MV; Resources: Nascimento IRN, Faria MV.

DATA AVAILABILITY

The datasets generated and/or analyzed in this study, as well as the supplementary Tables and Figures, are available from the corresponding author upon reasonable request.

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