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Earliness and productive efficiency in tropical black bean genotypes (*Phaseolus vulgaris* L.) under terminal drought

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ABSTRACT

Objective: To determine the effect of earliness on grain yield of tropical black bean genotypes under terminal drought and to select those with lower susceptibility and higher productive efficiency than the cultivar Negro Jamapa.

Design/methodology/approach: Fifteen genotypes were evaluated using a randomized complete block design with three replications in two trials: one under full irrigation and another in which irrigation was suspended at the onset of flowering. Days to physiological maturity and grain yield were quantified. Analyses of variance were performed for each moisture regime, means were compared using the Least Significant Difference test ($\alpha=0.05$), and correlation analysis was conducted. Drought response was evaluated using the drought susceptibility index (DSI) and the relative efficiency index (REI).

Results: Verdín was the earliest genotype, reaching maturity at 72.3 and 68.0 days under full irrigation and drought stress, respectively. Papaloapan/SEN-46-7-10, CIAT-103-25, Jamapa Plus/XRAV-187-3-4-4, Papaloapan/SEN-46-2-6, and Rubí exhibited the lowest susceptibility to terminal drought (DSI$<$0.90), whereas Verdín, CIAT-103-25, and Jamapa Plus/XRAV-187-3-4-4 showed the highest productive efficiency (REI$>$1.28), surpassing Negro Jamapa. Grain yield was negatively correlated with days to maturity under both full irrigation ($r=-0.719$**) and drought stress ($r=-0.557$*).

Study Limitations/Implications: The selected genotypes constitute elite breeding materials; multi-environment evaluation is recommended.

Findings/conclusions: Earliness, as a drought escape mechanism, contributed significantly to productive efficiency under both moisture regimes. Five genotypes with the lowest susceptibility to terminal drought were selected, of which CIAT-103-25, Jamapa Plus/XRAV-187-3-4-4, and Verdín exhibited higher productive efficiency than Negro Jamapa.

Keywords: *Phaseolus vulgaris* L., drought resistance, drought escape, grain yield, tropical agriculture.

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INTRODUCTION

In the humid tropical region of southeastern Mexico, terminal drought is the main environmental factor limiting common bean yield during the fall-winter growing season, when production depends on the last rains of the rainy season and on the residual moisture

stored in the soil profile (Tosquy-Valle *et al.*, 2018). Terminal drought periods have become more frequent and severe due to climate change (McClean *et al.*, 2011; Chaves-Barrantes *et al.*, 2018). This results in significant reductions in essential yield components, including pods per plant, seeds per pod, and seed weight (Nuñez-Barrios *et al.*, 2005; Tosquy-Valle *et al.*, 2014), which ultimately leads to low grain production (Ghassemi-Golezani & Mardfar, 2008; Rosales *et al.*, 2012). Depending on its frequency, duration, and magnitude, terminal drought during the reproductive phase can reduce grain yield by more than 60% and, in extreme cases, cause total crop loss (López-Salinas *et al.*, 2011).

The use of drought-resistant varieties represents an effective strategy to mitigate yield losses caused by water deficit. Drought resistance in plants involves a series of adaptive strategies, which are commonly classified into three main mechanisms: escape, avoidance, and tolerance (Fang & Xiong, 2015; Bandurska, 2022). Drought escape involves completing the life cycle before the onset of severe stress, mainly through earliness or phenological adjustment (Kooyers, 2015). Drought avoidance refers to the ability of plants to maintain a favorable water status under stress through morphophysiological adaptations such as deep root development, reduction of leaf area, and efficient stomatal closure (Blum, 2011). By contrast, true drought tolerance is defined as the capacity of plants to endure cellular dehydration through mechanisms such as osmotic adjustment, synthesis of protective proteins, and membrane stabilization (Blum, 2017).

Although substantial progress has been made in identifying genotypes of tropical black bean with resistance to terminal drought (Tosquy-Valle *et al.*, 2014, 2016), further characterization is necessary to determine more precisely the effect of earliness on grain yield and productive efficiency under water-limited conditions. This information is essential to support breeding programs in the development of new varieties better adapted to terminal drought in tropical environments.

To select genotypes with resistance to water stress, conventional common bean breeding programs typically use the irrigation-drought methodology (Rosales-Serna *et al.*, 2000), which involves monitoring soil moisture availability throughout the crop cycle to determine the level of stress reached (Hillel, 1980) and to quantify the yield response of each genotype under contrasting moisture conditions (Tosquy-Valle *et al.*, 2018). In addition, various selection indices are used to identify materials with high productive efficiency under both well-watered and terminal drought conditions, characterized by minimal yield reduction when transitioning from optimal irrigation to water deficit (Fischer & Maurer, 1978).

Currently, the Common Bean Program of the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) in southeastern Mexico has developed improved varieties and advanced black bean lines. Some of these genotypes have been selected for their high yield potential and adaptation to tropical environments (Tosquy-Valle *et al.*, 2019), while others exhibit resistance to economically important diseases such as rust [*Uromyces appendiculatus* var. *appendiculatus* (Pers.) Unger], anthracnose [*Colletotrichum lindemuthianum* (Sacc. & Magnus) Lams. Scrib.], bean common mosaic virus (BCMV), and bean golden yellow mosaic virus (BGYMV) (Anaya-López *et al.*, 2018; Garrido-Ramírez *et al.*, 2020), all of which are frequently present in the main bean-producing areas of the region.

Therefore, the objective of this study was to determine the effect of earliness on grain yield in tropical black bean genotypes under terminal drought conditions and to select those with lower susceptibility and higher productive efficiency than the widely cultivated cultivar Negro Jamapa.

MATERIALS AND METHODS

Location and genetic material

Genotypes were evaluated in two field trials established during the winter-spring cropping cycle of 2024 on land located in La Colonia Ejidal, Cotaxtla, Veracruz, Mexico (18° 54' 53.39" N, 96° 13' 14.74" W; 22 m a.s.l.).

Both trials included 15 genotypes: ten advanced breeding lines from the INIFAP National Common Bean Program (five derived from the cross Papaloapan/SEN-46, three from Negro Citlali/XRAV-187-3, and two from Jamapa Plus/XRAV-187-3), line CIAT-103-25 from the International Center for Tropical Agriculture (CIAT, Cali, Colombia), and four improved cultivars developed by INIFAP for tropical areas of southeastern Mexico: Verdín, Rubí, Rincón Grande, and Negro Jamapa as the regional check (Tosquy-Valle *et al.*, 2016; 2025; Ibarra-Pérez *et al.*, 2022).

Trial establishment and irrigation treatments

Both trials were planted on January 26, 2024, at a density of 250,000 plants ha^{-1}, using a randomized complete block design with three replications. Each plot consisted of three 5-m-long rows spaced 0.80 m apart; the central row was considered the useful plot. One trial was maintained under full irrigation throughout the crop cycle. A total of seven irrigations were applied, the first at pre-planting and subsequent applications at intervals of 11 to 15 days, depending on soil moisture conditions. The total irrigation depth applied was approximately 350 mm. In the second trial, only four irrigations were applied, with a total irrigation depth of approximately 200 mm. Irrigation was suspended 42 days after planting, when most genotypes had initiated flowering, in order to induce terminal drought conditions.

Soil moisture determination

In both trials, soil samples were collected at depths of 0-15 and 15-30 cm every 10 days, from planting until crop maturity, to determine moisture content using the gravimetric method (Caicedo-Rosero *et al.*, 2021). Additional soil samples were collected from the 0-30 cm layer to determine permanent wilting point (PWP) and field capacity (FC), allowing the estimation of available soil moisture under both moisture regimes, where 0% corresponded to PWP and 100% to FC (Walters, 2021).

Available soil moisture values were plotted to evaluate their dynamics before and after flowering under both moisture conditions. Terminal drought was considered to occur when available soil moisture fell below 45% (Allen *et al.*, 2006).

Agronomic management

Fertilization, weed control, pest management, and harvest were carried out in accordance with the recommendations of López-Salinas *et al.* (2017) for common bean production in Veracruz. Throughout the crop cycle, no diseases occurred that affected plant development or grain yield in either the fully irrigated or terminal drought trial.

Variables evaluated and statistical analysis

The variables evaluated were: days to physiological maturity, recorded from planting until 50% of the plants of each genotype exhibited yellow-colored pods, and grain yield (kg ha^{-1}), estimated from harvested and cleaned grain from each plot and adjusted to 14% moisture content.

Analyses of variance were performed separately for each moisture condition, and mean comparisons were conducted using the Least Significant Difference (LSD) test ($\alpha=0.05$). In addition, correlation analyses were carried out among the variables evaluated under each moisture condition (Olivares, 1994).

Assessment of drought impact

The effect of drought on the mean yield of each genotype was estimated using the drought susceptibility index (DSI; Fischer & Maurer, 1978) and the relative efficiency index (REI), both widely used in drought-resistance studies (Bennani *et al.*, 2017; Basavaraj *et al.*, 2025). The following variables were used for index calculation: Ysi = mean yield of genotype i under stress, Yni = mean yield of genotype i under non-stress conditions, Ys = mean yield of all genotypes under stress, and Yn = mean yield of all genotypes under non-stress conditions.

DSI was calculated as $DSIi=(1-Ysi/Yni)/DII$, where the drought intensity index was obtained as $DII=1-(Ys/Yn)$. DSI is a function of yield reduction caused by drought; a value of 1 indicates medium susceptibility, values greater than 1 indicate susceptible genotypes, and values close to zero indicate lower drought susceptibility (Fischer & Maurer, 1978).

REI was calculated as $REIi=(Ysi/Ys)\times(Yni/Yn)$. This index allows classification of genotypes on the basis of their performance under both moisture conditions; higher values indicate greater productive efficiency and better relative performance (Basavaraj *et al.*, 2025).

RESULTS AND DISCUSSION

Soil moisture and stress conditions

From planting to the flowering stage, both trials showed similar patterns in soil moisture content, with an average of 96% available water. During this period, soil water depletion did not exceed 45%, the threshold at which common bean begins to experience stress (Allen *et al.*, 2006). Upon suspending irrigation in the terminal drought trial, available moisture declined gradually as the crop progressed toward physiological maturity (Figure 1).

At physiological maturity in this trial, moisture content averaged 26.4%, indicating that plants were subjected to water stress during most of the reproductive phase. This did not occur in the irrigated trial, where available moisture remained above the critical threshold throughout the entire cycle, averaging 88%.

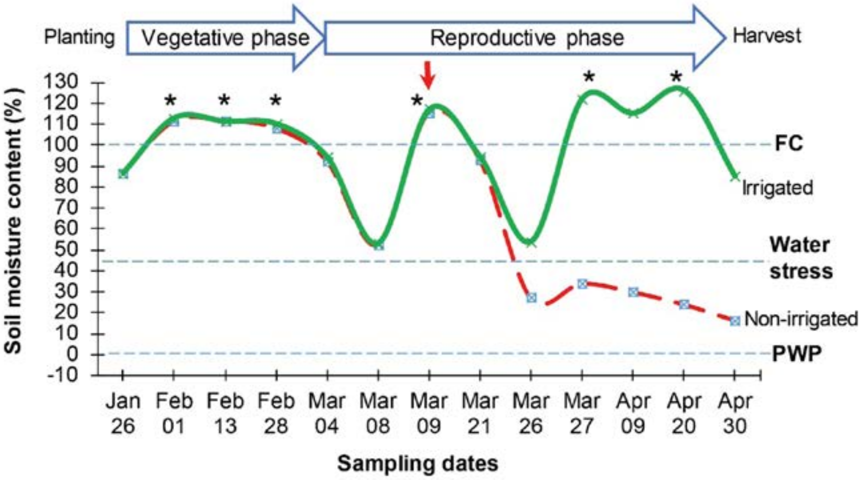

Figure 1. Available moisture in the topsoil layer (0-30 cm) during common bean development in the irrigated and terminal drought trials established at La Colonia Ejidal, Cotaxtla, Veracruz, during the winter-spring 2024 cycle. Blue dotted lines show the percentage of soil moisture at field capacity (FC), under water stress, and at permanent wilting point (PWP). Asterisks indicate irrigation dates, and the red arrow indicates irrigation suspension in the drought trial.

Earliness and grain yield

In both trials, statistical significance was detected among treatments (P≤0.01 or 0.05) for both variables quantified (Table 1), indicating that genotypes differed both in the timing of physiological maturity and in their productive capacity under irrigated and terminal drought conditions.

Under both moisture conditions, the cultivar Verdín was the earliest to reach physiological maturity, with timing statistically similar to the cultivar Rubí and the lines Papaloapan/SEN-46-3-2 and Negro Citlali/XRAV-187-3-1-8 under full irrigation, and significantly shorter than the rest of the genotypes under terminal drought (Table 2). Terminal drought stress reduced days to maturity by an average of 6.47% across all genotypes, equivalent to 5.0 days; the cultivars Verdín and Rubí, along with five other lines, showed reduction percentages below the overall average, whereas the cultivar Rincón Grande and the line Papaloapan/SEN-46-7-7 were the most affected for this

Table 1. Mean squares and statistical significance of variables quantified in trials conducted under full irrigation and terminal drought during the crop cycle at La Colonia Ejidal, Cotaxtla, Veracruz. Winter-spring cycle of 2024.

SV	DF	Full irrigation		Terminal drought	
		DPM[†]	GY[‡]	DPM[†]	GY[‡]
Treatments	14	26.25 **	188926.28**	8.58 **	133609.42 *
Blocks	2	0.47	32704.00	4.86	41350.00
Error	28	2.30	51611.14	1.39	59156.00
Total	44				
CV (%)		1.96	15.88	1.63	21.60

SV: Source of variation. DF: Degrees of freedom. [†]DPM: Days to physiological maturity. [‡]GY: Grain yield. *Significant at P≤0.05; **Significant at P≤0.01.

Table 2. Effect of terminal drought stress on days to physiological maturity of black bean genotypes evaluated under full irrigation throughout the crop cycle and with irrigation suspension at flowering initiation. La Colonia Ejidal, Cotaxtla, Veracruz, Mexico. Winter-spring cycle of 2024.

Genotype	**Physiological maturity (days)**		
	Full irrigation	**Terminal drought**	**Reduction (%)[†]**
Papaloapan/SEN-46-2-6	77.67cde	73.33ab	5.59
Papaloapan/SEN-46-3-2	74.67fgh	73.33ab	1.79
Papaloapan/SEN-46-7-7	82.33a	73.67a	10.52
Papaloapan/SEN-46-7-10	79.00bcd	72.67abcd	8.01
Papaloapan/SEN-46-7-12	80.67ab	74.00a	8.27
Negro Citlali/XRAV-187-3-1-5	75.67efg	73.33ab	3.09
Negro Citlali/XRAV-187-3-1-6	76.00efg	73.67a	3.07
Negro Citlali/XRAV-187-3-1-8	74.33fgh	70.00e	5.82
Rincón Grande	80.00abc	71.33cde	10.84
Jamapa Plus/XRAV-187-3-4-1	80.67ab	73.67a	8.68
Jamapa Plus/XRAV-187-3-4-4	76.00efg	71.33cde	6.14
CIAT-103-25	79.33bc	73.00abc	7.98
Negro Jamapa (RC)	76.67def	71.00de	7.39
Verdín	72.33h	68.00f	5.99
Rubí	73.67gh	71.67bcde	2.71
Mean[††]	77.27	72.27	6.47
LSD (0.05)	2.54	1.97	
Correlation (r) with GY[‡]	−0.719**	−0.557*	

[†] Percentage reduction due to terminal drought stress. [††] Mean days to physiological maturity under full irrigation and terminal drought. [‡] Correlation coefficient with grain yield. RC: regional check. Means followed by different letters within a column are significantly different according to LSD (α=0.05).

trait (Table 2). This phenomenon occurs because water stress prematurely induces leaf senescence to accelerate nutrient remobilization toward reproductive structures (Labastida *et al.*, 2023).

Generally, common bean genotypes that perform well under drought conditions also perform well without moisture stress (Szilagyi, 2003; Beebe *et al.*, 2008). This premise held true in this study, as most genotypes that excelled in yield under irrigated conditions also performed well under terminal drought. The cultivar Verdín was the most productive under both moisture conditions, followed by the lines CIAT-103-25 and Jamapa Plus/XRAV-187-3-4-4, whereas the lines Papaloapan/SEN-46-7-12 and Papaloapan/SEN-46-7-7 yielded the lowest under both moisture regimes (Table 3). The high productivity of Verdín in environments with and without terminal drought has been documented in other evaluation studies of black bean genotypes under residual moisture conditions in Veracruz and Chiapas (Tosquy-Valle *et al.*, 2018).

Under both irrigated and terminal drought conditions, days to physiological maturity were negatively and significantly correlated with grain yield (r=−0.719** and −0.557*). This correlation suggests that earliness may have functioned as a drought-escape mechanism, allowing completion of the reproductive cycle before severe water

Table 3. Effect of terminal drought stress on grain yield of black bean genotypes evaluated under full irrigation throughout the crop cycle and with irrigation suspension at flowering initiation, and estimated drought susceptibility (DSI) and relative efficiency (REI) indices. La Colonia Ejidal, Cotaxtla, Veracruz, Mexico. Winter-spring cycle of 2024.

Genotype	Grain yield (kg ha^{-1})			DSI	REI
	Full irrigation	Terminal drought	Reduction (%)†		
Papaloapan/SEN-46-2-6	1480.00abc	1198.33ab	19.03	0.89	1.10
Papaloapan/SEN-46-3-2	1581.67ab	1215.00ab	23.18	1.09	1.19
Papaloapan/SEN-46-7-7	1033.33de	768.33cd	25.64	1.20	0.49
Papaloapan/SEN-46-7-10	1106.67cde	1000.00bcd	9.64	0.45	0.69
Papaloapan/SEN-46-7-12	838.33e	645.00d	23.06	1.08	0.34
Negro Citlali/XRAV-187-3-1-5	1538.33ab	1211.67ab	21.23	1.00	1.16
Negro Citlali/XRAV-187-3-1-6	1486.67ab	1088.33abc	26.79	1.26	1.00
Negro Citlali/XRAV-187-3-1-8	1570.00ab	1260.00ab	19.74	0.93	1.23
Rincón Grande	1430.00abc	1093.33abc	23.54	1.10	0.97
Jamapa Plus/XRAV-187-3-4-1	1450.00abc	1040.00abcd	28.28	1.33	0.94
Jamapa Plus/XRAV-187-3-4-4	1601.67ab	1300.00ab	18.83	0.88	1.29
CIAT-103-25	1630.00ab	1343.33ab	17.59	0.83	1.36
Negro Jamapa (RC)	1380.00bcd	1020.00abcd	26.09	1.22	0.87
Verdín	1781.67a	1418.33a	20.39	0.96	1.57
Rubí	1546.67ab	1286.67ab	16.81	0.79	1.23
Mean††	1430.33a	1125.89b	21.28		
LSD (0.05)	379.89	406.71			

†Percentage reduction due to terminal drought stress. ††Mean grain yield under full irrigation and terminal drought. DSI: Drought susceptibility index. REI: Relative efficiency index. RC: regional check. Means followed by different letters within a column are significantly different according to LSD (α=0.05).

deficits (Beebe *et al.*, 2008; Zilio *et al.*, 2013), rather than as true tolerance based on physiological mechanisms such as osmotic adjustment or deeper root systems (Polania *et al.*, 2016).

The early maturity of Verdín and Rubí represents an adaptive advantage under terminal drought by allowing plants to complete their cycle before water-deficit periods that generally occur at the end of the reproductive phase (Acosta-Díaz *et al.*, 2004). In addition to reducing risks of yield loss from the occurrence of terminal drought, early genotypes allow producers to obtain greater bean production in less time, with or without terminal water stress (Tosquy-Valle *et al.*, 2018), possibly through greater efficiency in the partitioning of dry matter to the grain (Rao *et al.*, 2016). This escape strategy has been extensively documented in wheat, where high yield potential has also been observed due to the development of both shallow and deep roots, representing plasticity in response to drought combined with early flowering (Ehdaie *et al.*, 2012; Shavrukov *et al.*, 2017). In this study, morphophysiological traits and root characteristics were not evaluated; therefore, the specific contribution of each mechanism to the observed response requires additional investigation.

Terminal drought susceptibility and productive efficiency

During the trials, no rainfall occurred that modified the terminal drought condition. The drought intensity index (DII) was 0.21, equivalent to an average grain yield reduction of 304.4 kg ha^{-1} compared to the irrigated condition. This value corresponds to moderate water stress and is comparable to that reported by Wasae (2021) during pod filling (DII=0.25) and Darkwa *et al.* (2016) for terminal drought in Ethiopia (DII=0.30), who also classified these levels as moderate stress.

Although this level is lower than that considered severe (DII>0.60; Ramírez-Vallejo & Kelly, 1998), it is representative of the range of terminal drought intensities occurring in the humid tropics of southeastern Mexico. For instance, López-Salinas *et al.* (2011) reported a DII of 0.62 under severe drought conditions in Veracruz, reflecting the variability in stress intensity that can manifest in the region. This variability depends on factors such as the duration of periods without rainfall and residual soil moisture, characteristics of a region with high vulnerability to drought (Ortega-Gaucin *et al.*, 2018). The moderate stress level evaluated is relevant for identifying genotypes with a favorable response to terminal drought that commonly occurs in bean plantings in the southeastern region and allowed differentiation of genotype responses, with yield reductions ranging from 9.64% to 28.28% (Table 3).

The lines Papaloapan/SEN-46-7-10, CIAT-103-25, Jamapa Plus/XRAV-187-3-4-4, Papaloapan/SEN-46-2-6, and the cultivar Rubí showed the lowest susceptibility to terminal water stress, obtaining drought susceptibility index (DSI) values closest to zero. Meanwhile, the lines Jamapa Plus/XRAV-187-3-4-1, Negro Citlali/XRAV-187-3-1-6, Papaloapan/SEN-46-7-7, and the cultivar Negro Jamapa were the most susceptible, with DSI values exceeding 1.0 (Table 3), indicating that they exhibited the highest percentages of grain yield reduction due to terminal drought (Fischer & Maurer, 1978). It is important to note that genotypes with low DSI values are not necessarily the most productive, as occurred in this study, where the line Papaloapan/SEN-46-7-10, which showed the lowest drought susceptibility (DSI=0.45), did not exhibit significantly outstanding grain yield under either full irrigation or terminal drought (Table 3). A similar situation was reported by Tosquy-Valle *et al.* (2014) with other opaque black bean genotypes of the Mesoamerican race from CIAT and the University of Puerto Rico.

Among the genotypes showing the lowest terminal drought susceptibility, the lines CIAT-103-25 and Jamapa Plus/XRAV-187-3-4-4, together with the cultivar Verdín, obtained the highest relative efficiency index (REI) values, indicating high grain yield under both moisture conditions, whereas the lines Papaloapan/SEN-46-7-12, Papaloapan/SEN-46-7-7, and Papaloapan/SEN-46-7-10 showed the lowest productive efficiency, with REI values well below 1.0 (Table 3). The ideal scenario is to have bean genotypes that exhibit low yield reduction under terminal water stress and high productive efficiency under both full irrigation and terminal drought.

Selected genotypes require multi-environment validation across diverse locations and cycles in the humid tropics to confirm their stability. Future research should include characterization of morphophysiological traits (root system, pod harvest index, water-use efficiency) and molecular analyses to elucidate possible specific tolerance mechanisms (Wu *et al.*, 2024).

In practical terms, Verdín is commercially available (Tosquy-Valle *et al.*, 2016), whereas CIAT-103-25 and Jamapa Plus/XRAV-187-3-4-4 require additional validation cycles before becoming available as cultivars or can be used as parents in breeding programs for terminal drought resistance. The earliness of these materials offers additional advantages: lower production costs, the possibility of relay cropping, and reduced exposure to late-cycle pests.

CONCLUSIONS

Earliness functions as an effective escape mechanism to terminal drought in tropical black bean, explaining the differences in productive efficiency among genotypes. Three elite materials were selected that combine earliness, low drought susceptibility, and high productive efficiency under both full irrigation and terminal drought conditions: the cultivar Verdín (commercially available) and the lines CIAT-103-25 and Jamapa Plus/XRAV-187-3-4-4, which represent superior alternatives to Negro Jamapa in the humid tropics. These findings confirm that selection for a short crop cycle is a practical and effective strategy for developing cultivars adapted to terminal drought. The characterization of complementary physiological mechanisms would enable optimization of future breeding strategies.

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