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Millet survival submitted to associated stress using generalized gamma and Burr XII distribution

Sobrevivência de milheto subimetido a estresse associado usando as distribuições gama generalizada e Burr XII

Supervivencia del mijo sometida a estrés asociado utilizando las distribuciones gamma generalizadas y Burr XII

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Abstract

Water and saline stresses are the main factors affecting agricultural production. Millet is tolerant to these abiotic stresses and cultivated in regions with scarcity of rain and used for the production of grains and pastures. The knowledge of the lifetime of forage plants provides very useful information on cultivation and management of populations. The objective was to evaluate the lifetime of millet under conditions of water and saline stress using survival analysis. The experiment was carried in 48 millet plants submitted the water and saline deficit, for 4 cycles of 105 days. To estimate the lifetime of the millet, we used the survival functions of the probability distributions: exponential, Weibull, Gumbel, log-normal, Gompertz, logistics, Gamma, generalized Gamma, Burr XII and Birnbaum-Saunders and the Kaplan-Meier estimator. The lifetime of 64.6% of the plants was less than 105 days. Using the Kaplan-Meier estimator, 50% of plants survive up to 65th day, using the generalized Gamma and Burr XII survival function this rate occurs on the 75th day. The generalized Gamma and Burr XII survival function are alternatives to estimate the lifetime of millet submitted to conditions of water and saline stress.

Keywords: Lifetime; Saline stress; Survival function; Water deficit.

Resumo

O estresse hídrico e salino são fatores que afetam a produção agrícola. O milheto é tolerante a esses fatores de estresse e cultivado em regiões com escassez de chuva e utilizado na produção de grãos e pastagens. O conhecimento do tempo de vida das plantas forrageiras fornece informações muito úteis sobre o cultivo e manejo de populações. O objetivo foi avaliar o tempo de vida do milheto sob condições de estresse hídrico e salino usando análise de sobrevivência. O experimento foi realizado em 48 plantas de milheto submetidas a déficit hídrico e salino, em 4 ciclos de 105 dias. Para estimar o tempo de vida do milheto, foram utilizadas as funções de sobrevivência das distribuições de probabilidade: exponencial, Weibull, Gumbel, log-normal, Gompertz, logística, Gamma, Gamma generalizado, Burr XII e Birnbaum-Saunders e o estimador de Kaplan-Meier. O tempo de vida de 64,6% das plantas foi inferior a 105 dias. Usando o estimador Kaplan-Meier, 50% das plantas sobrevivem até o

65º dia, usando a função de sobrevivência generalizada Gamma e Burr XII essa taxa ocorre no 75º dia. A função de sobrevivência Gamma generalizada e Burr XII são alternativas para estimar o tempo de vida do milheto submetido a condições de estresse hídrico e salino.
Palavras-chave: Déficit hídrico; Estresse salino; Função de sobrevivência; Tempo de vida.

Resumen

El estrés hídrico y salino son factores que afectan la producción agrícola. El mijo es tolerante a estos factores de estrés y se cultiva en regiones con poca lluvia y se utiliza en la producción de cereales y pastos.. El conocimiento de la vida útil de las plantas forrajeras proporciona información muy útil sobre el cultivo y manejo de poblaciones. El objetivo fue evaluar la vida útil del mijo en condiciones de estrés hídrico y salino mediante análisis de supervivencia. El experimento se llevó a cabo en 48 plantas de mijo sometidas a déficit hídrico y salino, en 4 ciclos de 105 días. Para estimar la vida útil del mijo se utilizaron las funciones de supervivencia de las distribuciones de probabilidad: exponencial, Weibull, Gumbel, log-normal, Gompertz, logística, Gamma, Gamma generalizada, Burr XII y Birnbaum-Saunders y el estimador de Kaplan. -Meier. La vida útil del 64,6% de las plantas fue inferior a 105 días. Usando el estimador de Kaplan-Meier, 50% de las plantas sobreviven hasta el día 65, usando la función de supervivencia generalizada Gamma y Burr XII, esta tasa ocurre en el día 75. La función de supervivencia generalizada Gamma y Burr XII son alternativas para estimar la vida útil del mijo sometido a condiciones de estrés hídrico y salino.
Palabras clave: Déficit hídrico; Estrés salino; Función de supervivencia; Tiempo de vida.

1. Introduction

Water and saline stresses are the main factors affecting agricultural production in semiarid regions (Yahmed et al., 2016; El-Mageed et al., 2018). Water stress causes changes in the anatomy, physiology and biochemistry of plants, affecting all its stages of development (Balardin et al., 2011; Scalon et al., 2011).

The use of groundwater irrigation can be a viable strategy to agricultural production, however, groundwater in most semiarid regions presents a high concentration of salts, and its use can contribute to the increase of salinized areas. Thus, the accumulation of salts in soil negatively affects the growth of crops, reducing the productivity of forage plants in agricultural areas (Lucena et al., 2019a and 2019b).

Under stress conditions, the use of species that are more resilient to environmental changes is necessary to ensure the forage supply. Millet (*Pennisetum glaucum*) present C4 metabolism, is tolerant to water deficit, high temperature and salinity (Ullah et al., 2017; Nelson et al., 2018; Singh et al., 2015), and used for grain production and pasture in semiarid regions (Ghatak et al., 2016).

The mentioned aspects lead to the study of millet lifetime under stress conditions. Knowledge of the lifetime of forage plants provides very useful information on cultivation and management of natural populations, and has great biological importance, because they enable the viability of cultivating a species by evaluation of the growth rate.

In survival analysis, the response variable is in most cases the time until the occurrence of a certain event. This time is called failure time and can be the time until the death of the individual (plant) under evaluation or any other event of interest (Mazucheli et al., 2018).

A characteristic resulting from these studies of lifetine is the presence of incomplete or partial observations. These observations, called censures, can occur for a variety of reasons, amongst them the death of a plant in the course of the study and the non-occurrence of the event of interest until the end of the experiment.

The non-negative random variable, T, usually continuous, representing the failure time or lifetime, is generally specified in survival analysis by its survival function or failure rate (risk) function (Colosimo & Giolo, 2006). The survival function can be obtained through non-parametric estimators, being largely through the Kaplan-Meier estimator.

No studies have been found in the literature that report the association of water and saline stresses in millet, especially on the lifetime of plants. The objective of this work was to evaluate the lifetime of millet under conditions of water and saline stress using survival analysis.

2. Methodology

Research had the character of a quantitative study, characterized as experimental research, carried out through techniques of execution and analysis of tests, numerical evaluation and data processing using statistical techniques (Pereira et al., 2018). The research was carried in period of January, 2019 to May, 2020 out at the Forage Crop Sector of the Federal Rural University of Pernambuco (Serra Talhada County Campus), in the semiarid region of Pernambuco State, northeastern Brazil (07° 56’ 15” S, 38° 18’ 45” E, at an elevation of 429 meters). According to the Köppen classification, the climate is BSwh' type, called semiarid, hot and dry, with summer-autumn rains.

The soil used in the experiment (Typical Haplic Cambisol Ta Eutrophic), was collected from the 0-20 cm layer, and then crushed, homogenized and sifted (2.0 mm). The after chemical analysis revealed the following attributes: pH (water) = 7.20; P (extractor Mehlich I) = 40 mg dm^{-3}; K^+ = 0.45; Ca^{2+} = 5.3; Mg^{2+} = 1.10; Al^{3+} = 0,0 cmolc dm^{-3}.

The experiment was carried in 48 Millet plants submitted to water deficit (25% of crop evapotranspiration) and salt stress of 4.0 $dS.m^{-1}$, with four cycles of 105 days. The millet cultivar used in this experiment was IPA Bulk 1BF. The lifetime until the death of the 48 plants or 105 days after emergence (DAE) (end of the experiment) was recorded. Daily evaluations were carried out during the experimental period.

Survival time (T) of millet under water and salt stress conditions was estimated using the survival functions of the distributions: exponential, Weibull, Gumbel, log-normal, Gompertz, logistic, gamma, generalized gamma, Burr XII and Birnbaum-Saunders (Table 1) and by Kaplan-Meier estimator.

Table 1. Probability density and survival function for estimating millet lifetime.

Distribuitions	Density function	Survival function
Exponential	$f(t) = \frac{1}{\alpha}\exp\{-(t/\alpha)\}$ $t \geq 0$ and $\alpha > 0$	$S(t) = \exp\{-(t/\alpha)\}$
Weibull	$f(t) = \frac{\gamma}{\alpha^\gamma} t^{\gamma-1}\exp\left\{-(t/\alpha)^\gamma\right\}$ $t \geq 0, \quad \alpha$ and $\gamma > 0$	$S(t) = \exp\left\{-(t/\alpha)^\gamma\right\}$
Gumbel	$f(t) = \frac{1}{\gamma}\exp\left\{\left(\frac{t-\alpha}{\gamma}\right) - \exp\left(\frac{t-\alpha}{\gamma}\right)\right\}$ $t \geq 0, \quad \alpha$ and $\gamma > 0$	$S(t) = \exp\left\{-\exp\left(\frac{t-\alpha}{\gamma}\right)\right\}$
Log-normal	$f(t) = \frac{1}{\sqrt{2\pi}\, t\gamma}\exp\left\{-\frac{1}{2}\left(\frac{(\log(t)-\alpha)}{\gamma}\right)^2\right\}$	$S(t) = \Phi\left(\frac{-\log(t)+\alpha}{\gamma}\right)$ $\Phi(*)$ is the cumulative distribution

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	$t > 0, \quad \alpha \text{ and } \gamma > 0$	function standard normal
Gompertz	$f(t) = \gamma \exp^{\alpha t} \exp\left\{\frac{-\gamma}{\alpha(\exp^{\alpha t} - 1)}\right\}$ $t > 0, \alpha > 0 \text{ and } \gamma > 0$	$S(t) = \exp\left\{\frac{-\gamma}{\alpha(\exp^{\alpha t} - 1)}\right\}$
Logistic	$f(t) = \frac{\exp\left(\frac{t-\alpha}{\gamma}\right)}{\gamma\left\{1 + \exp\left(\frac{t-\alpha}{\gamma}\right)\right\}^2}$ $t > 0, -\infty < \alpha < \infty \text{ and } \gamma > 0$	$S(t) = \frac{1}{1 + \exp\left(\frac{t-\alpha}{\gamma}\right)}$
Gamma	$f(t) = \frac{1}{\Gamma(\phi)\alpha^{\phi}} t^{\phi-1} \exp\left\{-\left(\frac{t}{\alpha}\right)\right\}$ $t > 0, \quad \phi \text{ and } \alpha > 0$	$S(t) = \frac{\Gamma(\phi,(\alpha t))}{\Gamma(\phi)}$ $\Gamma(\phi,(\alpha t)) = \int_{(\alpha t)}^{\infty} x^{\phi-1} \exp(-x)\,dx$
Generalized gamma	$f(t) = \frac{\gamma}{\Gamma(\phi)\alpha^{\gamma\phi}} t^{\gamma\phi-1} \exp\left\{-\left(\frac{t}{\alpha}\right)^{\gamma}\right\}$ $t > 0, \quad \phi, \alpha \text{ and } \gamma > 0$	$S(t) = \frac{\Gamma(\phi,(\alpha t)^{\gamma})}{\Gamma(\phi)}$ $\Gamma(\phi,(\alpha t)^{\gamma}) = \int_{(\alpha t)^{\gamma}}^{\infty} x^{\phi-1} \exp(-x)\,dx$
Burr XII	$f(t) = \frac{\gamma \alpha t^{\alpha-1}}{\theta^{\alpha}} \left[1 + \left(\frac{t}{\theta}\right)^{\alpha}\right]^{-(\gamma+1)}$ $t > 0, \quad \alpha, \theta \text{ and } \gamma > 0$	$S(t) = \left[1 + \left(\frac{t}{\theta}\right)^{\alpha}\right]^{-\gamma}$
Birnbaum-Saunders	$f(t) = \frac{1}{2\sqrt{2\pi}}\left(\frac{\alpha}{t\sqrt{t}} + \frac{\gamma}{\sqrt{t}}\right) \exp\left\{-\frac{1}{2}\left(\frac{\alpha}{\sqrt{t}} - \gamma\sqrt{t}\right)^2\right\}$ $t > 0, \quad \alpha \text{ and } \gamma > 0$	$S(t) = \Phi\left(\frac{\alpha}{\sqrt{t}} - \gamma\sqrt{t}\right)$

Source: The authors.

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The Kaplan-Meier estimator is an adaptation of the empirical survival function and defined by:

$$S(t) = \prod_{j:t_j<t}\left(\frac{n_j - d_j}{n_j}\right) = \prod_{j:t_j<t}\left(1 - \frac{d_j}{n_j}\right)$$

where, $t_1 < t_2 < \cdots < t_k$, k distinct times and ordered failure; d_j number of failures in t_j, j=1,2,...,k and n_j is the number of plants at risk in t_j.

The following metrics were used to evaluate goodness-of-fit of the survival functions: Akaike information criterion (AIC), Bayesian information criterion (BIC), sum of squares of the difference between the Kaplan-Meier survival function and the survival function estimated by the distribution (RMS) and proposed the metric called R^2_{prop}.

$$AIC = -2L(x;\hat{\theta}) + 2p;$$

$$BIC = -2L(x;\hat{\theta}) + p\log(n);$$

$$R^2_{prop} = \left(1 - \frac{\sum_{i=1}^{n}(S_i - \hat{S}_i)^2}{\sum_{i=1}^{n}(S_i - \bar{S})^2}\right);$$

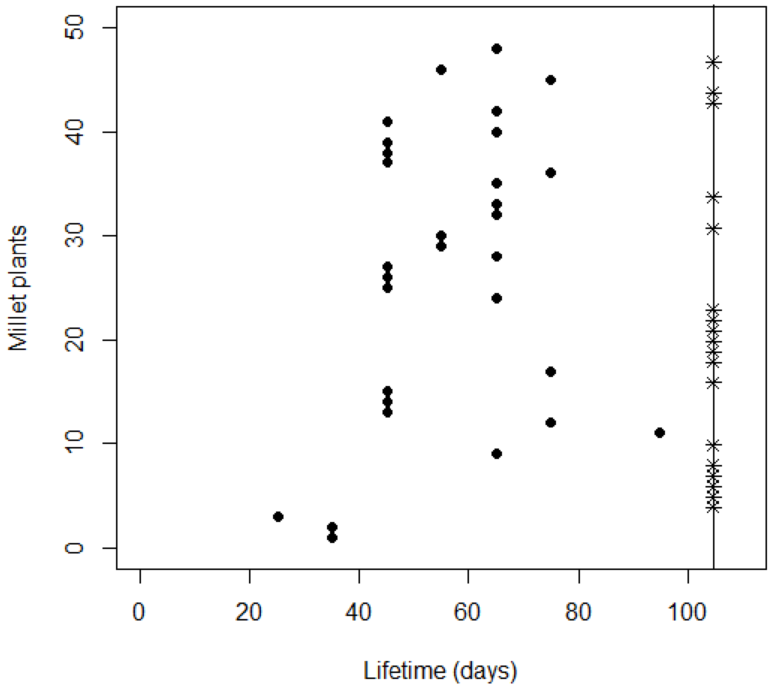
$$RMS = \frac{\sum_{i=1}^{n}(S_i - \hat{S}_i)^2}{n - p}$$

where, $L(x;\hat{\theta})$ is the maximum likelihood, n is number of plants, p is number of parameters; S_i is the value of the i-th survival estimated at time T by the Kaplan-Meier estimator; $\hat{S}_i$ is the i-th survival value estimated by distribution in time T; $\bar{S}$ is the mean of the values of the survival function of the Kaplan-Meier estimator. All analyzes were performed using survival, flexsurv and fitdistrplus packages of the R-project software version 2.13.1 for Windows.

3. Results and Discussion

In Figure 1 observed that of the 48 plants evaluated, (2.1%) died at the beginning and another (2.1%) at the end of the experiment, while the majority 29 (60.4%) of the plants present lifetime between 45 and 75 days, and 17 (35.4%) were censored, as their lifetime exceeded the end of the experiment (105 DAE).

Figure 1. Lifetime of millet plants (*- censure and • uncensured).



Source: The authors.

The results presented corroborate with Lucena et al. (2020), which verified that 31.4% of millet plants die when exposed to water availability of 25% ETc and 42.9% of plants die when exposed to 4 dS/m of salinity.

Table 2 shows the estimate of the survival function of the Kaplan-Meier estimator and their respective confidence intervals. Note that after 65 days the survival rate was 47.9%, while at 105 DAE the rate was 35.4%. These results suggest that out to each 100 millet plants submitted to water and saline stress, 35 plants survive for more than 105 days.

Table 2. Survival rate estimation of millet plants by the Kaplan-Meier estimator.

Lifetime (days)	Plants at risk	Dead plants	S(t)	Lower limit 95%	Upper limit 95%
25	48	1	0.979	0.940	1.000
35	47	2	0.938	0.871	1.000
45	45	10	0.729	0.614	0.886
55	35	3	0.667	0.546	0.814
65	32	9	0.479	0.357	0.644
75	23	4	0.396	0.279	0.561
95	19	1	0.375	0.260	0.540
105	18	1	0.354	0.242	0.519

Source: The authors.

The probability of millet plants surviving water stress of 25%ETc and 4 dS/m of salinity is 0.51%, while that the plants submitted only to water stress this rate is of 25.58% (Lucena et al., 2020).

High concentrations of soluble salts in the soil solution, mainly NaCl, and other ions, such as Mg^{2+}, HCO^{3-} and SO_4^{2-}, cause inhibition of plant growth, due to the decrease in the water potential of the soil solution at a level below the necessary for the absorption of water and and essential elements by the root cells, reducing the growth and development of the plant, which can result in death (Soares et al., 2015).

The excess of salts in the soil causes a series of changes in its properties, which will reduce the availability of water for plants due to the decline in their osmotic potential, decreasing the availability of water and nutrientes (Alves et al., 2011). In addition, the accumulation of specific ions can cause toxicity at the cellular level, causing cellular plasmolysis and death (Souza et al., 2011).

Water stress triggers a series of physiological changes, such as stomata closure, reducing the entry of CO_2 into the mesophile, reducing the raw material for the photosynthetic process, which compromises the plant growth and plant survival (Tardin et al., 2013). The water deficit promotes less cell differentiation and cells number, compromising the expansion of plant vegetables tissues (Tardieu et al., 2011).

Millet, grass of group C4, present a CO_2 concentration mechanism in the cells of the vascular sheath, which favors the activity of ribulose 1.5 bisphosphate carboxylase (RubisCO), preventing the occurrence of photorespiration in these plants, resulting, maintenance of photosynthetic activity at normal levels, same when plants are submitted to abiotic stresses, with water and saline.

Table 3 shows the estimated survival functions and their respective goodness-of-fit criteria. The generalized gamma and Burr XII distribution presented the best evaluation criteria (largest R^2_{prop} and lowest RMS, AIC and BIC), while the worst performance was verified by the Gumbel distribution (low R^2_{prop} and high RMS, AIC and BIC).

Table 3. Estimated survival function of the evaluateddistributions and goodness-of-fit criteria.

	Survival function	Goodness-of-fit criteria			
Distributions	S(t)	R^2_{prop}	RMS	AIC	BIC
Exponential	$S(t) = \exp\left\{-\left(t/_{115.48}\right)\right\}$	0.763	0.0022	360.40	364.14
Weibull	$S(t) = \exp\left\{-\left(t/_{97.83}\right)^{2.12}\right\}$	0.818	0.0017	345.00	350.61
Gumbel	$S(t) = \exp\left\{-\exp\left(\frac{t-98.97}{34.24}\right)\right\}$	0.722	0.0026	361.40	367.01
Log-normal	$S(t) = \Phi\left(\frac{-\log(t)+4.37}{0.56}\right)$	0.855	0.0013	337.60	343.21

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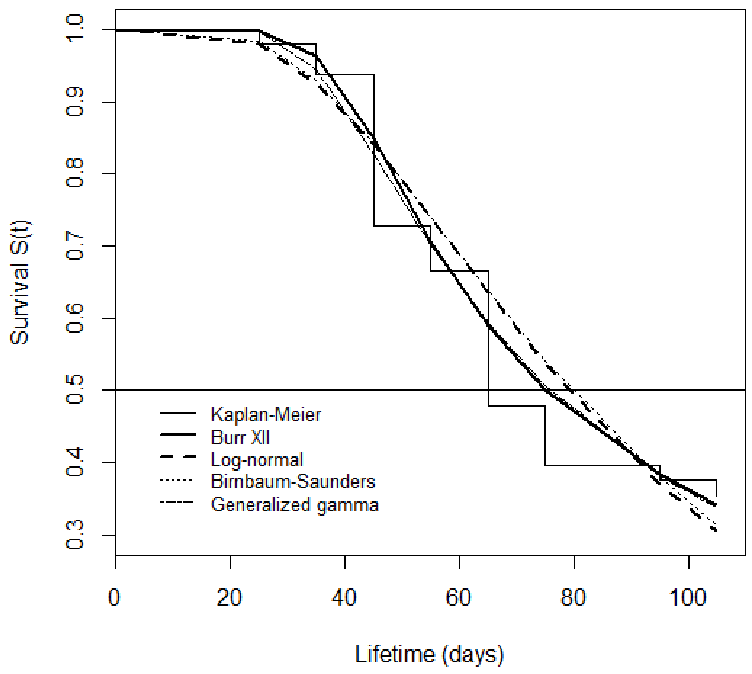
Gompertz	$S(t) = \exp\left\{\frac{-0.0034}{0.0188(\exp^{0.0188t} - 1)}\right\}$	0.813	0.0017	353.01	358.63
Logistic	$S(t) = \frac{1}{1 + \exp\left(\frac{t - 80.39}{23.93}\right)}$	0.802	0.0018	353.80	359.41
Gamma	$S(t) = \frac{\Gamma(0.0437, (3.842t))}{\Gamma(0.0437)}$	0.825	0.0016	341.15	346.76
Generalized gamma	$S(t) = \frac{\Gamma(-1.446, (4.031t)^{0.5218})}{\Gamma(-1.446)}$	0.917	0.0008	332.38	339.86
Burr XII	$S(t) = \left[1 + \left(\frac{t}{40.992}\right)^{7.958}\right]^{-0.144}$	0.909	0.0008	330.81	336.43
Birnbaum-Saunders	$S(t) == \Phi\left(\frac{15.527}{\sqrt{t}} - 0.195\sqrt{t}\right)$	0.850	0.0014	334.96	338.71

AIC-Akaike information criterion; BIC- Bayesian information criterion, sum of squares of the difference between the Kaplan-Meier and survival function estimated by the distribution; R^2_{prop}- proposed determination coefficient. Source: The authors.

Log-normal, Generalized gamma, Burr XII and Birnbaum-Saunders distributions presented the best goodness-of-fit criteria, opted in demonstrate the next results using these four distributions.

Figure 2 shows that the generalized gamma and Burr XII distribution presented survival values closer to the Kaplan-Meier estimator, when comparing the log-normal and Birnbaum-Saunders distributions, indicating a better adequacy of the generalized gamma and Burr XII distributions to estimate the lifetime of millet plants submitted to water and salt stress. 50% of the plants survive up to 65th day according to Kaplan-Meier estimator, already using the survival functions of log-normal, generalized Gamma, Burr XII and Birnbaum-Saunders this mortality rate is at 79th, 75th, 75th and 80th day, respectively.

Figure 2. Estimation of millet survival as a function of the Kaplan-Meier, log-normal, generalized gamma, Burr XII and Birnbaum-Saunders estimators.



Source: The authors.

In this research, about half of the millet plants survived up to 65 days and more than a third of the plants completed the entire phenological cycle (Table 2 and Figure 2). The duration of the vegetative growth stage (FC 1) in millet genotypes producing green biomass, such as the cultivar IPA-BULK 1BF is around 31 days (Costa & Priesnitz, 2014). In this stage (FC 1), basal tillering starts at 21 DAE while the panicle formation stage range from 47 to 61 days, already stage of growth and filling of the grains varied from 74 to 84 days (Costa et al., 2005). Panicle viewing occurred approximately at 53 days and the emergence of 50% of the stigmas in the panicle occurs before 65 days, in this research.

These results suggest millet tolerance to water deficit and salt stress. Millet tolerance to water stress may be associated with some antioxidant enzymes that can contribute to mitigate the effect of water stress by eliminating reactive oxygen species (EROs) (Lakshmi et al., 2017), and also, to the accumulation of compatible osmosolutes (proline, free amino acids and soluble sugar) that contribute to the millet making an osmotic adjustment (reducing the cellular water potential), facilitating water absorption by the plant even under water deficit (Marviya & Vakharia, 2016).

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4. Conclusion

Millet plants present a median survival time of 75 days when submitted to water and salt stresses. About 30% of millet plants submitted to water and saline stress survive more than 105 days of planting. The generalized gamma and Burr XII survival function are alternatives to estimate the lifetime of millet submitted to conditions of water and salt stress.

To improve the results found, new studies can be used with use of other levels of salinity and water deficit.

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