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Descriptions of okra seed longevity loss behavior using nonlinear regression models

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All relevant data are within the paper and its Supporting Information files.

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The authors declare no competing interests.

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Abstract: Seeds longevity loss is an inevitable problem of seed storage. Applications of nonlinear regression models to describe and predict the aging damages to seed germination would be reliable and helpful for understanding the relationship between seed quality and storage condition. In this study, various nonlinear models, including logistic, Hill, Weibull, Sigmoid, Gompertz and Probit, were applied on seed germination data, obtained from the accelerated aging test of three Iranian okra landraces. Results revealed that the Weibull 4 parameter and Probit 4 parameter functions failed to describe cumulative germination of Ahwaz ecotype in contrast to sigmoid models. The best three parameters sigmoid model to describe germination data of Isfahan ecotype was Hill 3p (AICc=26.89) while there was a failure to fit germination data using Weibull 4p and Probit 4p. Mashhad germination and vigor was well described using Hill 3p (AICc=33.72 and 32.22). It is suggested that the use of the Hill, Gompertz and Weibull parameters provided more information of viability and vigor loss of okra seeds during deterioration conditions.

1. Introduction

Okra is a crop belonging to Malvaceae family, largely cultivated in Africa and Asia (Düzyaman, 2005; Sorapong, 2012). It is mainly planted for its fresh, tender and tasty pods as food purposes alongside high generic medical or industrial potential applications (Dhankhar and Singh, 2009). Recent researches revealed that okra seed oil has a great potential use as industrial products and liquid biofuels (Anwar *et al.,* 2010; Moosavi *et al.,* 2018).

Good seed quality assures rapid, uniform seed germination and healthy seedling establishment.

Seed germination as the complex physiologically active process is initiated with water uptake by dry seeds and completed by radicle protrusion from the seed coat (Bewley and Black, 1994; McDonald and Kwong, 2005).

Germination characteristics of okra seeds depend at least partly on the duration, temperature and relative humidity of storage condition. Seeds from different geographical locations commonly react differently to germination conditions (Campbell and Sorensen, 1979). Okra is a crop of warm and humid climate and when it comes to seed production, one of the main concerns would be storage damages to see due to storage conditions (George, 2009). Understanding the pattern of seed quality loss under various storage conditions would be very useful for okra seed producers to estimate their seed loss and find solutions for better seed storage condition.

The conventional method of seed germination data analysis depends on the single-value indices or descriptive statistics such as mean, variance, final germination, mean germination time to represent the results of experimental treatment (Shafii *et al.,* 1991). However, such indices retain no information on either the initiation or rate of germination (Brown and Mayer, 1988; McNair *et al.,* 2012). Moreover, there is no room to put information of lag, speed, and extent phase of germination into the single value data. Another concern of statistics in seed germination is the skewness of germination frequency (Soltani *et al.,* 2016). Therefore, cumulative germination will not only provide ambiguous information about seed germination but also it will make much easier to understand and amenable to statistical analysis (Brown and Mayer, 1988).

Regression analysis studies the relationship between dependent variable y and one or more explanatory or independent variables x_i. Basic model is:

$$Y_i = h\,(x_i\,(1), x_i\,(2), \ldots, x_i(n); \theta_1, \theta_2, \ldots, \theta_{pi}) + E_i\,.$$

Where h is an appropriate function that depends on the explanatory variables and parameters.

Application of nonlinear model in cumulative data analysis is a powerful tool to predict and understand the changes in cumulative germination data (Yin *et al.,* 1995; Aparecida Guedes *et al.,* 2014). The logistic model is a nonlinear regression method, which developed for the sigmoid models. It is symmetric about the inflection point but its application to fit germination data needs special care due to the skewed nature of such data (Shafii *et al.,* 1991). In contrast to logistic, Gompertz is asymmetric sigmoidal function. The Gompertz model was first introduced to fit the relationship between increasing death rate and age by the Mr. Benjamin Gompertz and now it is one of the most useful sigmoid models fitted to different data types including growth data (Gompertz, 1825; Tjørve and Tjørve, 2017). The Weibull function has widely been used by seed researchers to explain germination data (Scott *et al.,* 1984; Dumur *et al.,* 1990; Akbari *et al.,* 2016). This regression model works well with small sample data and provides reasonable, simple and useful failure graph and analysis (Abernethy, 2006). The four-parameter Hill function was useful to explain seed germination variations among different seed lots of coniferous by incorporating germination rate, germination onset and cumulative germination data (El-Kassaby *et al.,* 2008). Probit model analysis has been widely applied to seed longevity experiments to estimate the probabilities of germination at each level of treatment (Probert *et al.,* 2009; Gazola *et al.,* 2015).

Large amounts of naturally existing plants produce seed populations with a different degree of germinability (Meyer and Kitchen, 1994; Gesch *et al.,* 2016). Prediction of germination behavior of such germplasm will help us to provide a better genetic pool to breed better crops.

The aim is also to compare different methods of nonlinear regression models for the description of okra seed germination behavior after exposure to the accelerated aging condition.

2. Materials and Methods

Seed materials

The okra seeds were purchased in dry state form local seed stores of Ahwaz, Isfahan and Mashhad. Seeds were then cleaned from the white pappus and sent immediately to seed technology laboratory of the department of plat production and genetics. All seed germination measurements were performed based on the ISTA rules for seed testing (ISTA, 2013).

Accelerated aging test

For the accelerated aging test, 200 mL of distilled water were added to each plastic box (20*15*10 cm) and 200 seeds were placed on a wired mesh tray (19*14*10 cm) inside the box. To avoid the direct content of seed with water, they were placed in the middle part of the tray. Seeds were aged at 40°C and 99% humidity for 24, 48, 72 and 96 h using one box for each aging/time combination (Demir *et al.*, 2004; Souza *et al.,* 2017). Seeds were disinfected before standard germination test using 3% solution of NaOCl (Sauer and Burroughs, 1986).

Germination test

To test the germination of Okra seeds, 50 seeds were disinfected with 3% sodium hypochlorite for 5 minutes, then cultured by sandwiching between two layered filter papers. The counting of germinated seeds was done regularly after every 24 h and the appearance of 2 mm or more of radicle was considered as germination. Germination test was ended after 14 days when the number of germinated seeds was equal in two sequential counting. The seedling size was measured on the last day of the germination test. Final germination percentage (FGP) was calculated using the following formula (Sumithra *et al.,* 2006):

$$\text{FGP (\%)} = \frac{\text{Number of total geminated seeds}}{\text{Total number of seeds tested}} \times 100$$

Seedling vigor

Seedlings vigor was determined when the number of germinated seeds at the two subsequent counts remained constant (day 14th). All seedlings that had completed morphological parts without lesions or defects, were selected and computed as vigorous seedlings and average seedling length and weight of 10 seedlings were measured for calculating seedling vigor index (SVI) by a modified formula of (Abdul-Baki and Anderson, 1973; Williamson and Richardson, 1988):

$$\text{SVI} = \frac{\text{FGP (\%) x means of seedling length (cm)}}{100}$$

Statistics

The experimental design was a factorial experiment fitted into the randomized complete design with three replications. Treatments were three Okra ecotypes and five durations (0, 24, 48, 72 and 96 h) of accelerated aging conditions arranged as the first and second factor, respectively. All acquired experimental data were subjected to fit with non-linear regression models to evaluate model parameters and their performance of data explanations. Models applied were:

i) Sigmoid 3 parameter: $Y=\frac{a}{1+e^{-\left(\frac{x-x0}{b}\right)}}$ and Sigmomoid 4 parameter: $Y=y_0\frac{a}{1+e^{-\left(\frac{x-x0}{b}\right)}}$

ii) Standard Logistic 3 parameter: $Y=\frac{a}{1+\left(\frac{x}{x0}\right)^b}$ and Logistic 4 parameter: $Y=y_0\frac{a}{1+\left(\frac{x}{x0}\right)^b}$

iii) Gompertz 3 parameter: $Y=ae^{-e^{-\left(\frac{x-x0}{b}\right)}}$ and Gompertz 4 parameter: $Y=y_0+ae^{-e^{-\left(\frac{x-x0}{b}\right)}}$

iv) Hill 3 parameter: $Y=\frac{ax^b}{c^b+x^b}$ and Hill 4 parameter: $Y=y_0+\frac{ax^b}{c^b+x^b}$

Where *a* is Y_{Max} or *upper asymptote*, *b* was a *slope*, x_0 *Critical point* or the *x* that reached 50% of Y_{Max} and y_0 is a lower *asymptote.*

Variable "y" corresponds to the germination percentage and "x" to the time of accelerated aging, respectively.

Also, other non-linear regression models included:

vi) Weibull 4 parameter:

$$Y= a\left[1-e^{-\left[\frac{x-x0+bln\,2^{\frac{1}{2}}}{b}\right]^c}\right]$$

vii) Probit 4 parameter:

$$Y= y_0+ (a-y_0) \times \text{normal distribution} \left(\frac{(x-x0)}{b}\right)$$

Where *a* is Y_{Max} or *upper asymptote*, *b* is the *slope*, x_0 is the c*ritical point* or *the x* that reached 50% of Y_{Max} and y_0 is a *lower asymptote.*

Sigma plot v. 11 was used for calculating the type of regression equation. R^2, AICc, and RMSE was applied to determine the best estimates of the parameters. R^2 was calculated using the following formula:

$$R^2= SSR/SST$$

Where SSR denotes the sum of squares (SS) for regression ($\sum_{i=1}^{n}$ L-$\bar{L}$) and SST the total SS ($\sum_{i=1}^{n}$ Li-$\bar{L}$). *Li* is the *observed value* and $\bar{L}$ is the *corresponding estimated value*. In addition, root mean square error (RMSE) calculated using following the formulae:

$$RMSE =\sqrt{(1/n)}\sum (Y_{obs}-Y_{pred})^2$$

Where Y_{obs} denotes *observed* value, Y_{pred} *predicted* value, and *n* is the *number of samples*.

To identify the best model for estimating, the Akaike Information Criterion corrected (AICc) was used. This statistic incorporates the amount of reduction of RSS and the model complexity (Butler and King, 2004; Kamkar *et al.,* 2012).

$$AICc=n \ln + (RSS/N) + 2K [2K (K-1)]/(N-K-1)$$

Where *n* is *number of data points*, and *K* is the *number of parameters* in the model.

3. Results and Discussion

The data subjected to model data analysis were from an experiment to study seed longevity loss during accelerated aging conditions. Main investigated traits were cumulative seed germination and seedling vigor. Results of fitted parameters with both three and four parameters nonlinear regression models are presented in Table 1. Among investigated ecotypes,

Table 1 - Comparative indices of models performance to describe cumulative germination data of three okra ecotypes (Ahwaz, Isfahan and Mashhad) under deterioration conditions

Model		Normal			24 h			48 h			96 h			192 h		
		Ahwaz	Isfahan	Mashhad	Ahwaz	Isfahan	Mashhad	Ahwaz	Isfahan	Mashhad	Ahwaz	Isfahan	Mashhad	Ahwaz	Isfahan	Mashhad
Sigmoid 3P	R^2	0.998	0.996	0.994	1.00	0.997	0.998	0.999	0.992	0.961	0.989	0.978	0.968	1.00	0.983	0.982
	RMSE	1.74	2.70	3.31	0.31	1.98	1.38	0.49	3.25	7.03	4.74	6.45	6.90	0.14	4.01	1.42
	AICc	25.29	29.08	30.85	10.55	26.39	23.28	14.41	30.70	37.40	33.97	36.64	37.23	3.38	32.52	23.52
Logistic 3P	R^2	0.996	0.999	0.997	0.999	0.992	0.999	0.997	0.994	0.994	0.988	0.972	0.964	0.999	0.993	0.983
	RMSE	2.93	1.54	2.20	0.43	3.61	0.52	2.11	2.76	2.76	4.79	6.55	7.31	0.23	2.46	1.41
	AICc	29.80	24.24	27.30	13.20	31.60	14.78	26.96	29.26	29.29	34.07	36.77	37.73	8.00	28.29	23.48
Gompertz 3P	R^2	0.993	0.999	0.998	0.999	0.996	1.00	0.996	0.996	0.978	0.988	0.978	0.966	1.00	0.992	0.984
	RMSE	3.75	0.97	1.94	0.50	2.63	0.12	2.48	2.06	5.20	4.81	6.57	7.12	0.21	2.70	1.40
	AICc	31.94	20.20	26.22	14.53	28.58	2.53	28.34	26.73	34.7	34.09	36.81	37.50	7.31	29.10	23.37
Hill 3P	R^2	0.996	0.990	0.997	0.999	0.992	0.999	0.997	0.994	0.994	0.988	0.978	0.964	0.999	0.993	0.983
	RMSE	2.93	1.54	2.20	0.43	3.61	0.52	2.11	2.76	2.46	4.79	6.55	7.31	0.23	2.46	1.41
	AICc	29.80	24.24	27.32	13.20	31.60	14.78	26.96	29.26	29.29	34.07	36.77	37.73	8.00	28.29	23.48
Sigmoid 4P	R^2	0.998	0.997	0.996	1.00	0.998	0.999	0.999	0.992	0.961	0.993	0.987	0.968	1.00	0.987	0.982
	RMSE	1.83	2.65	3.10	0.27	1.81	1.35	0.53	3.51	7.60	3.90	5.44	7.42	0.126	3.66	1.53
	AICc	30.54	33.76	35.12	14.20	30.45	27.93	19.86	36.20	42.90	37.12	40.0	42.69	7.32	80.49	29.02
Logistic 4P	R^2	0.997	0.999	0.997	1.00	0.992	0.999	0.998	0.994	0.994	0.993	0.987	0.969	0.999	0.994	0.983
	RMSE	2.84	1.60	2.35	0.35	3.90	0.56	1.69	2.98	2.98	3.88	5.41	7.34	0.25	2.52	1.52
	AICc	34.35	29.39	32.72	16.23	37.10	20.28	29.85	34.76	34.79	37.07	39.95	42.60	13.50	33.32	28.97
Gompertz 4P	R^2	0.996	0.999	0.998	0.999	0.996	1.00	0.998	0.997	0.978	0.993	0.987	0.968	1.00	0.992	0.983
	RMSE	3.11	1.04	2.089	0.38	2.83	0.136	1.91	2.14	5.61	3.88	5.41	7.48	0.235	2.80	1.511
	AICc	35.18	25.66	31.68	17.06	34.34	7.99	30.91	31.9	40.27	37.07	39.95	42.76	12.73	34.24	28.86
Hill 4P	R^2	0.997	0.999	0.997	1.00	0.992	0.999	0.998	0.994	0.994	0.993	0.987	0.969	0.999	0.994	0.983
	RMSE	2.84	1.60	2.35	0.35	3.90	0.56	1.69	2.98	2.98	3.88	5.41	7.34	0.25	2.52	1.52
	AICc	34.35	29.39	32.72	16.23	37.10	20.28	29.85	53.3	34.79	37.07	39.95	42.60	13.50	33.32	28.97
Weibull 4P	R_2	0.999	0.999	0.998	0.999	0.999	1.00	0.999	0.998	0.995	0.989	0.980	0.966	1.00	0.996	0.985
	RMSE	0.40	0.67	1.77	0.54	1.20	0.133	0.47	1.67	2.60	4.93	6.76	7.70	0.002	2.002	1.53
	AICc	17.48	21.92	30.25	20.02	26.89	7.77	18.87	29.78	33.6	39.14	41.89	43.01	0.001	31.31	28.19
Probit 4P	R_2	0.998	0.997	0.996	0.999	0.999	0.998	0.999	0.998	0.994	0.993	0.986	0.967	1.00	0.985	0.982
	RMSE	1.71	2.51	3.03	0.44	1.23	1.83	0.77	1.38	2.77	3.94	5.49	7.57	0.017	3.85	1.53
	AICc	59.03	66.74	70.49	32.08	52.53	60.3	43.04	54.77	68.69	75.70	82.35	88.75	0.00	75.27	56.9

Mashhad ecotype was more susceptible to longevity loss, especially at higher aging stress durations (Fig. 1, A_1-A_5). Among four parameter models, Weibull and Probit functions were produced the best curve fit as illustrated in figure 2 (E_1-E_5; F_1-F_5).

Our results revealed that at most aging treatments, the best-fitted data obtained from three parameter nonlinear regression models (Fig. 3).

The differences in parameter estimates among aging treatments had biological significance. The maximum germination, estimated by the parameter *a* (asymptotic part of the model), decreased as aging duration increased meaning that aging damages decrease the proportion of seeds which are able to survive and complete germination by radicle protrusion. The estimates of parameter *b*, which is the rate of seed germination were also reduced due to the increase in aging durations (Fig. 3). Deterioration damages due to oxidative stress caused by aging resulted in a reduction of seed germination properties and aged seeds germinated slower than no aged seeds (Anderson and Baker, 1983; Goel *et al.,* 2003; Balešević-Tubić *et al.,* 2007; Parmoon *et al.,* 2015).

Under no aging conditions, there was a significant difference in the estimated parameter for all three okra ecotypes. Using sigmoid 3p, Weibull 4p models parameter a, was well predicted and as shown in figure 3 it was very close to actual observed value (dash red line). Our results revealed that only Gompertz model did not provide precise estimation for Parameter x_0 (the time required for 50% of viable seeds to germinate) while other 3 parameter models performed well. Parameter X_0 in Ahwaz and Isfahan ecotypes well fitted using 4p Weibull and Hill while in Mashhad ecotype probit model was closer to the observed value.

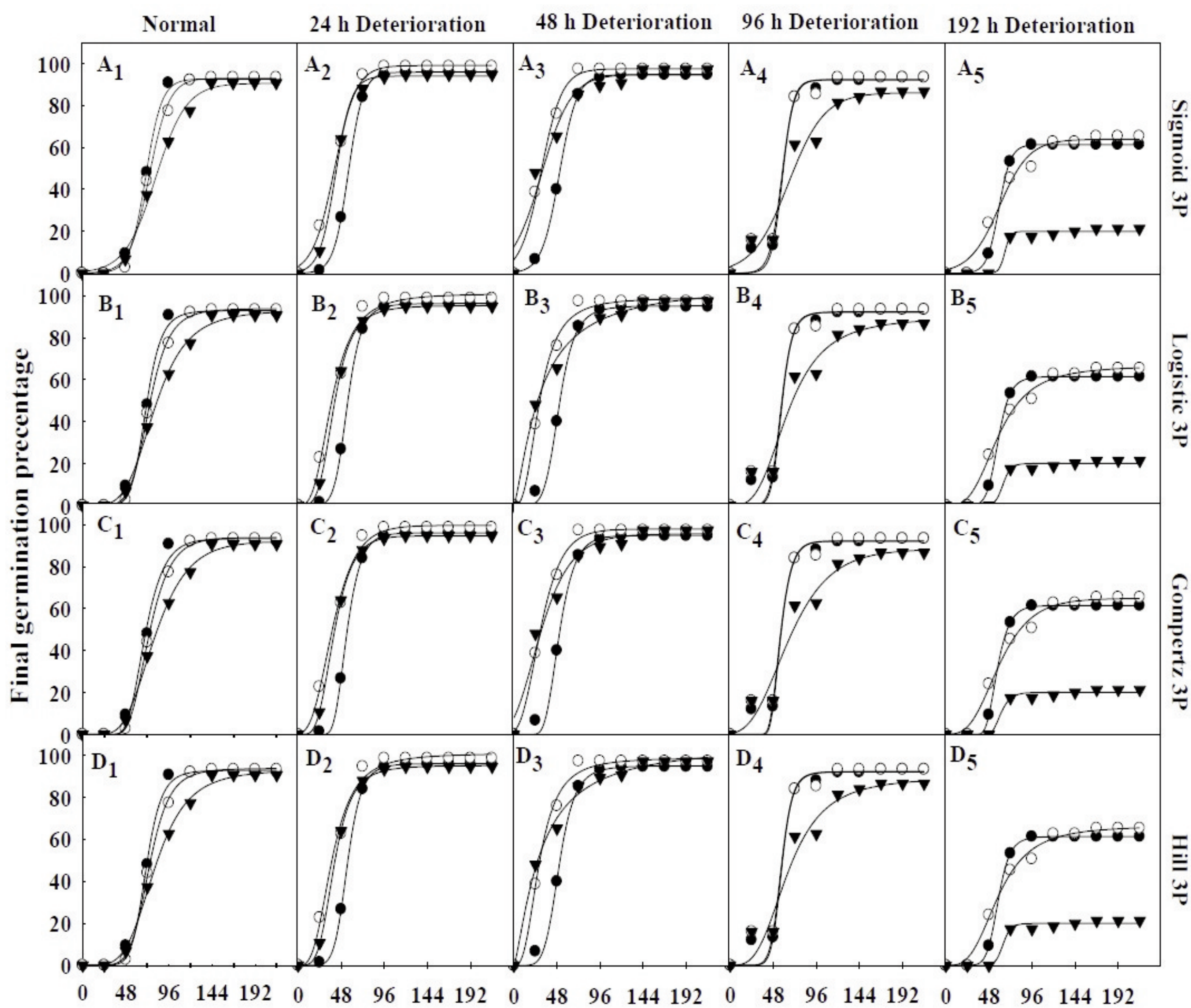

Fig. 1 - Model fit function 3 parameter of germination ecotypes okra (*Abelmoschus esculentus* L.) under deterioration condition. ● Ahwaz, ○ Isfahan and ▲ Mashhad ecotypes.

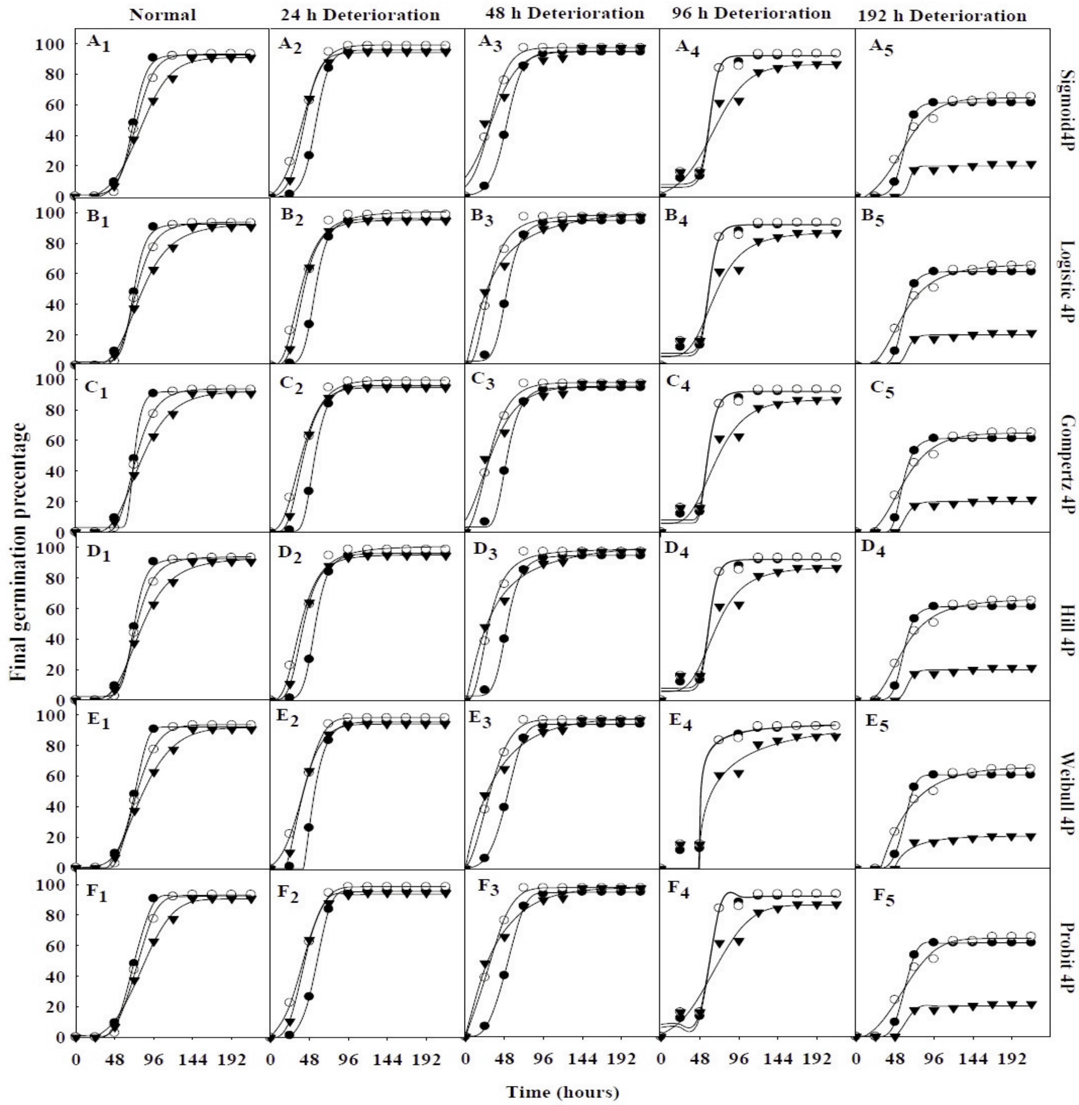

Fig. 2 - Model fit function 4 parameter of germination ecotypes okra (*Abelmoschus esculentus* L.) under deterioration condition. ● Ahwaz, ○ Isfahan and ▲ Mashhad ecotypes.

Accelerated aging (deterioration) after 24h, resulted in a reduction of X_0 value compared to no aged seeds (normal condition). Results revealed that an increase in deterioration treatments led to a decrease in observed maximum germination and predicted parameter.

Model output for parameter a (the maximum germination) of Ahwaz ecotype using sigmoid 3p model was less than the observed value. The result of the Weibull 4p function showed that the predicted parameter a, was the same as the maximum value of observed germination. There was no difference in estimated parameter a (asymptote), for Isfahan ecotype using Gompertz 3p and Weibull 4p. Model performance to predict germination of okra ecotypes under deterioration conditions varied among regression models (Table 1). For instance, at no aged treatment (normal condition), the best model to predict cumulative germination of Ahwaz ecotype were Weibull 4p and Sigmoid 3p with AICc values of 17.48 and 25.29 respectively. Results showed that, at the 96 h of accelerated aging conditions, the best fit and the lowest AICc values were obtained from three parameter growth models. In the case of Mashhad ecotype, the Gompertz 3p provided the best model fit to estimate germination loss at both no aged and severe aging treatments with the AICc values of 23.37 and 26.22, respectively. Application of regression models will result in various measures of the asymptotic point of Cumulative seed germination curves (Aparecida Guedes *et al.,* 2014). To compare the model performance of parameter estimation, AICc was a well discriminant index (Hurvich and Tsai, 1989; Spiess and Neumeyer, 2010). The lower AICc, the better parameter estimation of the model is expected (Sandvik, 2008).

Under 48 and 96 hours of deterioration, the estimated parameter a using Sigmoid 4p, Logistic 4p and Hill 4p, was less than the maximum observed germination. Our results showed that the sigmoid 3p model predicts lower values for actual maximum germination, while Sigmoid 4p and Logistic 4p estimated higher values especially in Isfahan ecotype seeds.

Weibull was the best model to show the alteration of the parameter *b* (rate of increase in seed germination), at different deterioration durations. Aging reduced the value of parameter b, which mean that deterioration because the reduction of seed germination rate of seed lot compared to no aged (normal condition) seeds (Fig. 3).

Results of experiments suggested that the Weibull model was the best among all of four parameter models for cumulative germinating data of Ahwaz and Mashhad ecotypes while Gompertz 4 parameter performed well for the fitting of Isfahan data.

The Study of the germination data of deterioration seeds after 24 hours showed that the best three parameter model to fitted data of Ahwaz and Isfahan ecotypes was Sigmoid 3p (AICc= 10.55 and 26.39) while Gompertz exhibited the best fit for Mashhad ecotype (AICc= 2.53) (Table 1). Germination data of deterioration seeds for 48 hours were best-fitted using Sigmoid 3p, Gompertz 3p and Hill 3p in Ahwaz, Isfahan and Mashhad ecotypes respectively. Among four parameter models, the best fit data was Weibull 4p for all ecotypes. Results of fitting cumulative ger-

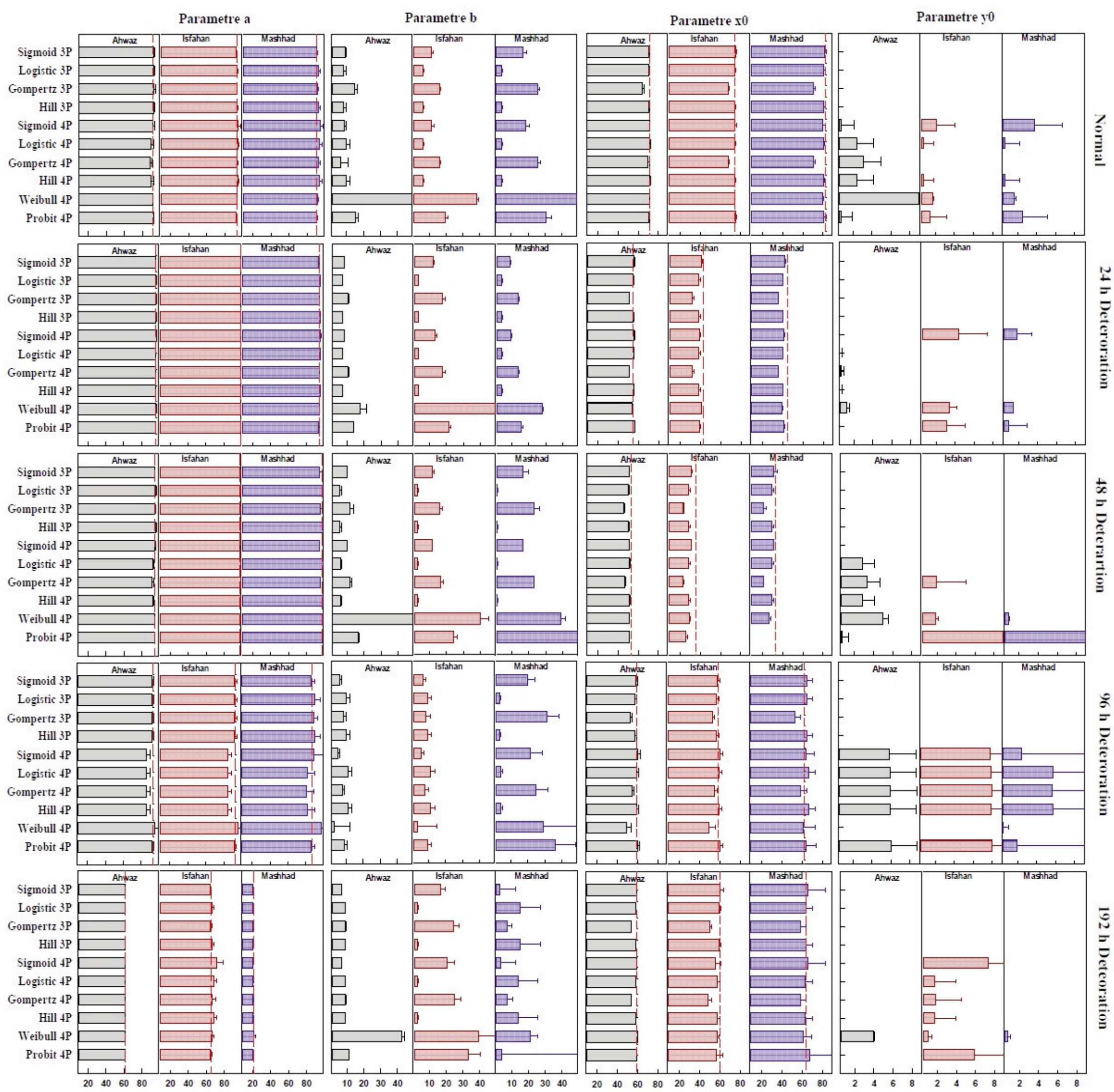

Fig. 3 - Estimate parameter of fit models germination ecotypes okra (*Abelmoschus esculentus* L.) under deterioration condition. Dash red line indicated observed parameter value. Parameter a= Asymptote (theoretical maximum for y); parameter b=rate of increase; X0= time required to completion of germination in 50% of seed population or D50; Y0= initial seed germination.

mination data of deterioration seeds for 96 hours showed that the sigmoid 3p model was the best model to describe data. Among four parameter models, Gompertz and Hill both performed well to describe germination data of Ahwaz and Isfahan ecotypes having similar AICc, while Mashhad ecotype was well-fitted using Logistic 4p and Hill 4p.

The study performed at the 192 hours of deterioration showed that the sigmoid 3p was the best-fit model for Ahwaz, Isfahan while for the Mashhad ecotype Gompertz was the best model (Table 1). It is concluded that the Weibull 4p was the best-fit model to describe germination data of okra seeds.

Seed vigor is an important index of seed quality and any change in this trait resulted in a reduction of seedling emergence. Among all three parameter models, Hill 3p well-illustrated changes of seed germination and vigor loss for Mashhad ecotype (Fig. 4). Model comparisons to describe germination and vigor of okra ecotypes during deterioration conditions revealed that Weibull 4p and Probit 4p functions failed to describe cumulative germination of Ahwaz ecotype in contrast to sigmoid models. The best 3p model to describe germination data of Isfahan ecotype was Hill 3p (AICc=26.89) while there was a failure to fit germination data using Weibull 4p and Probit 4p. Mashhad germination and vigor was well described using Hill 3p (AICc=33.72 and 32.22) (Table 2). Non-linear model fit to germination of vigor data of okra ecotypes showed that in almost all treatments decline of seed vigor initiated earlier than germination loss. However, predictions of vigor loss with an increase in deterioration treatments was not well described by four parameter models (Fig. 5). Application of logistic and Weibull functions to describe the germination and vigor of alfalfa seeds

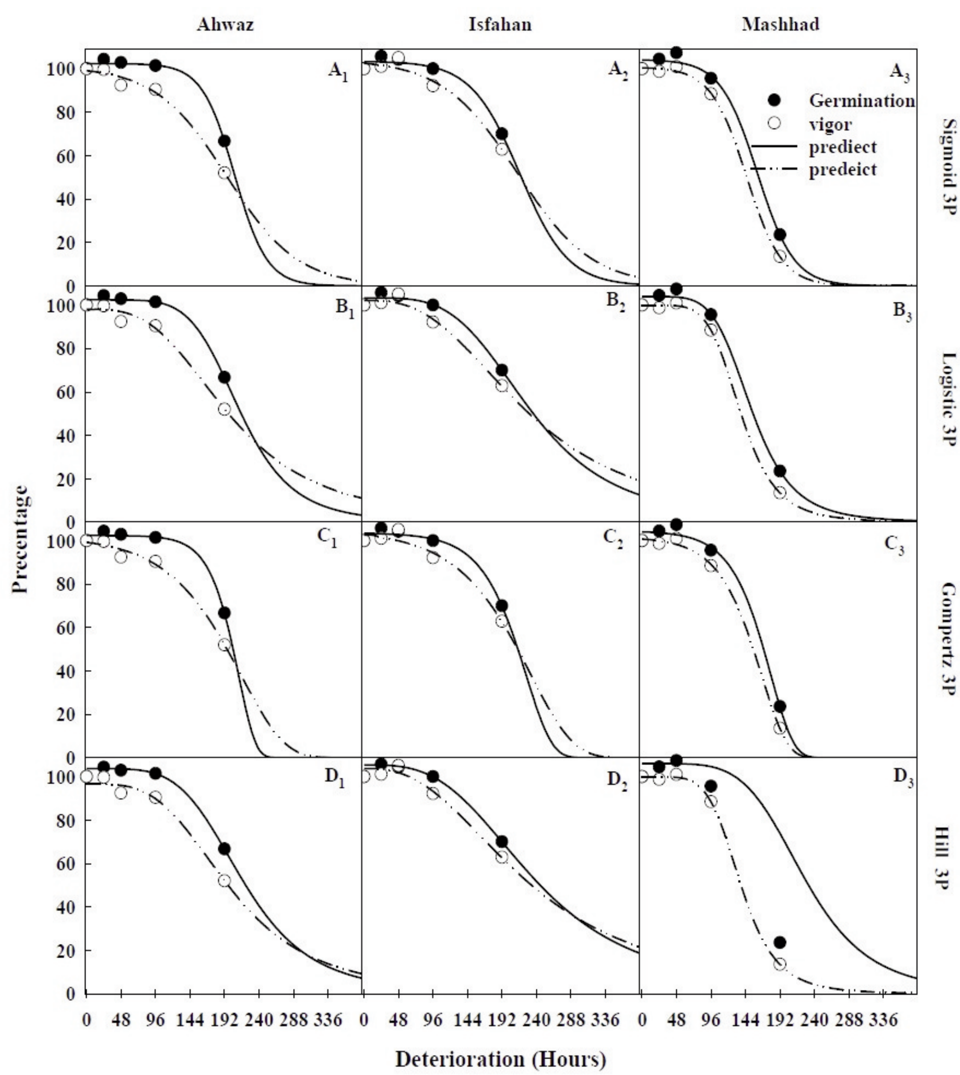

Fig. 4 - Model fit function 3 parameter of process deterioration germination and vigor ecotypes okra (*Abelmoschus esculentus* L.). Points are the percentage of improvements in seed properties compared with control treatment (no aged seeds) (● germination percentage, ○ seedling vigor) and lines are predicted values.

Table 2 - Comparative indices of models performance to describe seed germination and vigor of okra ecotypes

Model		Ahwaz		Isfahan		Mashhad	
		Germination	Vigor	Germination	Vigor	Germination	Vigor
Sigmoid 3P	R^2	0.990	0.987	0.976	0.968	0.992	0.998
	RMSE	2.23	3.11	3.18	4.29	4.28	1.79
	AICc	35.33	37.05	37.17	38.72	38.72	34.17
Logistic 3P	R^2	0.990	0.981	0.979	0.977	0.9942	0.999
	RMSE	2.21	3.80	3.02	3.59	3.80	1.23
	AICc	35.28	38.10	36.89	37.80	38.10	32.22
Gompertz 3P	R^2	0.990	0.988	0.976	0.967	0.991	0.998
	RMSE	2.23	30.046	3.20	4.37	4.49	2.18
	AICc	35.33	36.87	37.20	38.82	38.96	35.20
Hill 3P	R^2	0.991	0.984	0.999	0.984	0.998	0.999
	RMSE	0.68	3.34	0.44	2.97	1.64	1.23
	AICc	29.12	37.34	26.89	36.81	33.72	32.22
Sigmoid 4P	R^2	0.990	0.989	0.979	0.987	0.994	0.999
	RMSE	3.13	4.11	4.20	3.79	5.23	1.56
	AICc	25.74	30.17	30.36	28.77	33.78	14.92
Logistic 4P	R^2	0.990	0.985	0.979	0.987	0.994	0.999
	RMSE	3.13	4.87	4.20	3.79	5.23	1.56
	AICc	25.74	32.68	30.36	28.77	33.78	14.92
Gompertz 4P	R^2	0.990	0.977	0.979	0.987	0.994	0.999
	RMSE	3.13	6.04	4.20	3.70	5.23	1.56
	AICc	25.74	36.04	30.36	28.77	33.73	14.92
Hill 4P	R^2	0.998	0.981	0.999	0.992	0.999	0.999
	RMSE	1.02	5.09	0.49	2.84	2.07	1.55
	AICc	8.28	33.35	0.00	24.25	19.35	14.85
Weibull 4P	R^2	-	-	0.00	0.00	0.00	-
	RMSE	31.9	191.41	29.51	34.16	70.6	75.3
	AICc	62.05	90.05	60.82	63.11	74.46	75.48
Probit 4P	R^2	0.731	0.938	-	0.987	0.993	0.963
	RMSE	16.53	9.86	29.51	3.79	5.65	14.49
	AICc	51.76	43.68	60.82	27.77	35.02	49.7

showed that the Weibull parameter was more informative than the logistic (Bahler *et al.,* 1989). Among ecotypes, Mashhad ecotype vigor and germination data were fitted more uniformly to four parameter models. The Hill 4p was not capable of fitting germination data of the Isfahan ecotype. We found that none of the four-parameter models is suitable to describe seedling vigor loss of okra seeds due to accelerated aging condition. At high levels of aging treatments, seed germination was declined to zero and so there is no lower limit to produce Y_0 parameter, and like the results, model equations could not predict satisfied result (Fig. 6). Interestingly, results showed that aging condition did not exceed to deteriorative level before 24 hours and instead it might improve seed germination by providing after-ripening requirements.

4. Conclusions

In this study, we test the moments and indices of seed germination using growth models with three to four parameter. This method of data description provides sufficient information about the dispersion of germination rate in time and extent of germination due to aging conditions. The Hill and Weibull models were capable of good predictions across cumulative germination and seedling vigor data of three okra ecotypes. We recommend non-linear regression

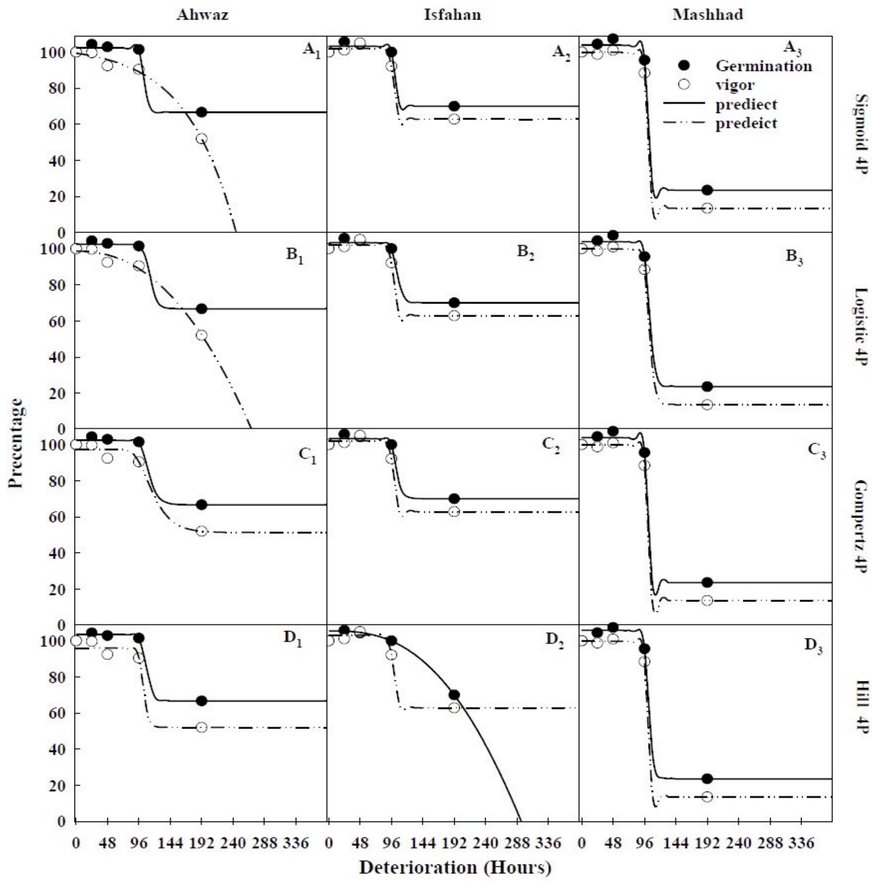

Fig. 5 - Model fit function 4 parameter of process deterioration germination and vigor ecotypes okra (*Abelmoschus esculentus* L.). Points are the percentage of improvements in seed properties compared with control treatment (no aged seeds) (● germination percentage, ○ seedling vigor) and lines are predicted values.

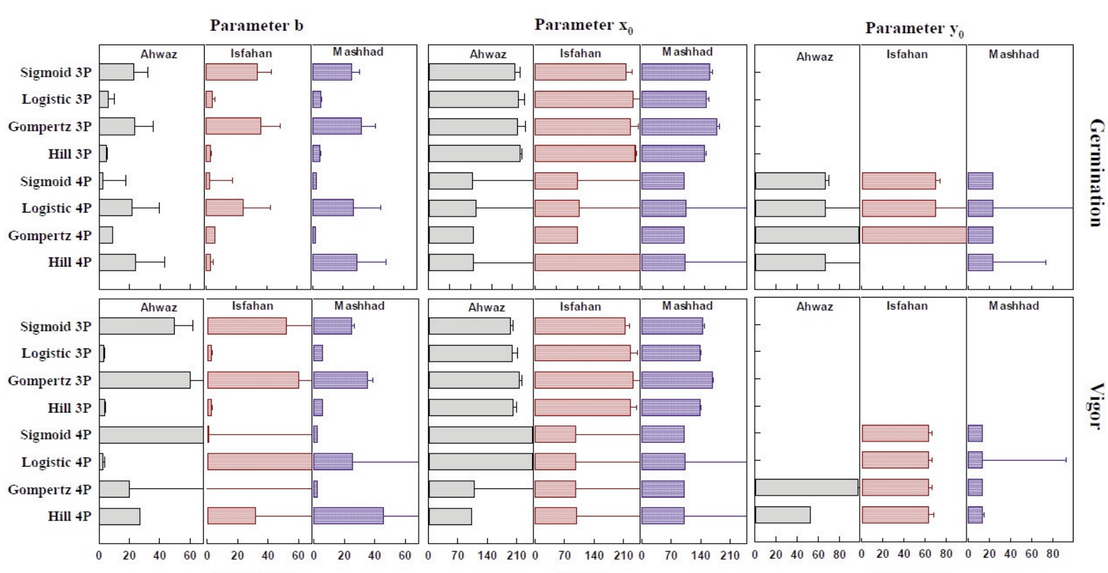

Fig. 6 - Estimate parameter of fit models process deterioration germination and vigor ecotypes okra (*Abelmoschus esculentus* L.). In these models germination and vigor were considered as 100%, and parameter a, for all models was 100%.

models as an unambiguous and strong approach to predict okra seed germination and longevity loss during aging conditions.

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