



Modelling germination curves of magneto-primed sorghum (*Sorghum bicolor*) seeds using Logistic and Gompertz models

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ABSTRACT

The traditional analysis of germination percentages tends to be quite limited, providing minimal information. Thus, a regression model based on the time to germination can be the most effective approach to describing germination behaviour. In this study, the effects of magneto-priming on sorghum [*Sorghum bicolor* (L.) Moench] seed germination were analysed and compared using Logistic and Gompertz models (LM and GM), respectively. Sorghum seeds were primed with a static magnetic field for four distinct durations (0, 1, 3, and 5 h). Germination data, gathered over a 10 days period for all magneto-priming exposures, then LM and GM growth curves were utilised to model seed germination. The experiment relied on two key metrics: the coefficient of determination (R^2) and the mean square error (MSE) to determine the best fitting growth curve. After the appropriate growth curve was selected, both statistical values and graphical plots were used to compare the model outputs and their parameter estimates. The results showed that the GM fit better than the LM model in describing the germination process of sorghum in the magneto priming test, as it yielded the lowest MSE and highest R^2 values. These findings suggest that the GM model can represent the best shape of sorghum germination curves under magneto-primed conditions.

Keywords: Cumulative germination percentage, Curve-fitting, Germination rate, Magnetic field, Primed seed, Seed priming durations

Seed priming methods, such as physical priming, are well-known pre-sowing techniques that are considered to be effective in improving seed germination and plant growth. Several physical agents, such as magnetic fields, microwaves, infrared light, and ultrasonic waves, have been successfully used as priming techniques. Based on magnetic fields, magneto-priming is one of the most extensively researched physical pre-sowing seed treatments. Prior research, including in maize (Himoud *et al.* 2022), soybean (Joshi-Paneri *et al.* 2023), wheat (Rathod and Anand 2015) and in cucumber (Bhardwaj *et al.* 2012), documented improvements in the germination parameters of magnetically treated seed. Traditional methods are most frequently used to characterise the germination kinetics of seeds induced with a magnetic field before sowing. The time course of germination may not be adequately described by conventional techniques for analysing seed germination data, such as germination indices and coefficients of velocity, making the results unclear and insufficient. Germination behaviour over time can be best described using regression models. A suitable fitted curve preserves

the essential information regarding germination initiation. The procedure of fitting a curve involves adjusting the free parameters of the function until it approaches the true curve of the assay more closely than any other parameter combination. Although choosing the right curve seems crucial, criteria based on forecasting errors are typically used to choose between the two models. As with other statistical analyses, it is crucial to present the statistical findings of the nonlinear estimation.

Mathematical curves are frequently used to model cumulative germination proportions. The germination process, time, and speed of germination of stimulated seeds can be modeled using a non-linear, suitable description of seed germination (Shafii *et al.* 1991). Several models have been proposed to analyse and describe seed germination curves, such as Logistic, Gompertz, Hill, and Richards functions (Hsu *et al.* 1984, Hara 1999, El-Kassaby *et al.* 2008, Sousa *et al.* 2014, Rymuza and Radzka 2021).

The Gompertz and Logistic models (GM and LM) were chosen as the most popular and straightforward models for growth curve analysis. Additionally, these models help to explain the growth mechanisms that go into plant development and seed germination. The comparison between the GM and LM is necessary due to their divergent assumptions regarding growth symmetry. Comparing the

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both previous models ensures that the biological variations caused by the treatments of magnetic field are modeled with the highest statistical accuracy rather than assumed to be symmetrical (Lazim S K and Ramadhan 2020). Insufficient study has been done to assess the variations between models and their corresponding parameters using statistical criteria in order to explain the impacts of magneto-priming procedures. The current study shifting the focus from static germination metrics to dynamic growth modeling, it introduces a rigorous comparative modeling framework that pinpoints the exact shifts in germination kinetics especially for sorghum [*Sorghum bicolor* (L.) Moench] for a deeper understanding of the germination rate over time.

Therefore, this study was planned to test the hypothesis that the non-linear dynamic kinetic shifts in sorghum seed germination, induced by magnetic stimulation, could be represented by an asymmetric growth function due to the underlying biological acceleration of metabolic stimuli. To move beyond the fixed germination parameters of previous studies, a comparative framework between the LM and GM was developed. The selection of the optimal prediction curve was assessed using the coefficient of determination (R^2) and the mean squared error (MSE). Thus, the study was aimed to provide a mathematical representation that reflects the actual physiological phases of cumulative germination under four different magnetic stimulation periods.

MATERIALS AND METHODS

Experimental design: The experiment was conducted in September 2024 at the Agricultural College of Basrah University, Basrah, Iraq. The experiment was conducted using a completely randomised design (CRD) replicated thrice having four treatments. Fifty healthy sorghum seeds were soaked in distilled water at 25°C and later seeds were dried to their original moisture content (~12%) in the open forced air at 25±2°C. The seeds were then primed with a magnetic field of 125 mT. For the control group, seeds underwent the identical soaking and drying procedures but were not exposed to the magnetic field. The seed priming durations were 0, 1, 3, and 5 h, labelled NP, MP₁, MP₂, and MP₃, respectively. Subsequently, all seeds that were treated were moved to filter paper-wetted 100 mm diameter Petri cups with 12 mL of distilled water on the same day in a lab setting. Deionized water was added at intervals to keep the paper moist when necessary. Germinated counts were recorded every 12 h for 10 days. The test was deemed finished when there were no more variations in the number of germinated seeds after two consecutive counts. Out of 50 seeds, radicle of at least 1 mm in length were considered germinated.

The mathematical model: For each treatment, the germination percentage of the seeds (G%) was calculated every 12 h as the ratio of the cumulative number of germinated seeds to the total number of seeds. The effect of magneto priming on sorghum seed germination can be determined by studying germination kinetics after prior primed stimulation. The germination kinetic curves obtained

are described by fitting two classical three-parameter growth functions (logistic and Gompertz). The mean cumulative percentage was fitted to a nonlinear regression model, as follows:

$$\text{Logistic model (LM): } y(t) = a/(1 + b \times \exp(-c \times t)) \quad (1)$$

$$\text{Gompertz model (GM): } y(t) = a \times \exp(-c \times t) \quad (2)$$

Where $y(t)$, Predicted cumulative percentage of germination to time t . Additionally, both models had three parameters, a , b , and c , calculated from the model using Excel programmeme. Where a , denotes the asymptote or theoretical maximum value for Y ; b , is the location variable associated with the model's initial value, One parameter that influences the curve's growth rate is c , where the natural logarithm's base is denoted by e . Besides to the theoretic start amount of germination, inflection points, and maximum germination rate, the growth germination rate equation was computed using the next equation (Torres and Frutos 1989, Gregorczyk 1991):

$$\text{Germination rate: } (dy/dt)_{LM} = c/a.y(t).(a-y(t)); (dy/dt)_{GM} = y(t).b.c. \exp(-ct)$$

$$\text{Theoretical initial value of growth: } (y_0)_{LM} = a/(1+b), (y_0)_{GM} = ae^{-b}$$

The coordinates of the function's inflection point are: The duration required to determine the LM and GM curves' inflection points: $(t_i)_{LM} = \ln b/c, (t_i)_{GM} = \ln b/c.(y_{ti})_{LM}$, and $(y_{ti})_{GM}$, denotes the germination percentage of seeds in t_i of LM and GM curves at which growth has reached to 0.5. a and 0.368. a , respectively.

Maximum germination rate: The maximum germination rate (MGR) occurs where the rate of change in the germination rate is 0, i.e. its value is: $(MGR)_{LM} = a.c/4$, $(MGR)_{GM} = ac/e = 0.368 ac$.

The computed mean values were used to plot germinating kinetics curves. The LM and GM curves for the germinating kinetics curves were fitted using equation (1) and (2), respectively.

Statistical analysis: All parameters were subjected to analysis of variance. The two models' goodness-of-fit was statistically compared using the mean square error (MSE) and coefficient of determination (R^2). The regression's analysis of variance that have R^2 values greater than 99% suggests a well-fitting model with a lower MSE. Germination parameters (a , b , and c) between treatments for each replicate were generated by fitting the LG and GM curves. Means were compared using the least significant difference (LSD) test at a level of 0.05. All analyses were performed using the commercial programmeme SPSS 20 on a personal computer. The coefficient of determination (R^2) was determined with the help of the following equation:

$$R^2 = 1 - \frac{SSE}{SST}$$

$$SSE, \text{ Sum of squared errors} = \sum_{i=1}^n (y_o - y_p)^2$$

Where y_o is the germination growth of observed values,

y_p is the value predicted by the estimation model, and n is the number of observations.

$$\text{Total Sum of Squares (SST)} = \text{SSR} + \text{SSE},$$

$$\text{Regression Sum of Squares (SSR)} = \sum_{i=1}^n (y_p - \bar{y})^2,$$

Where y_p the values predicted by the estimation model and $\bar{y}$, Mean value. Additionally, the mean square error (MSE) is determined with the help of the equation:

$$\text{MSE} = \frac{\text{SSE}}{n}$$

RESULTS AND DISCUSSION

The effect of magnetic fields on seeds can be ascertained by examining the germination kinetics following magneto-primed stimulation. The germination percentages (GP) and germination timeframes were visually depicted following the germination kinetics curves. Variance analysis results of magneto-priming treatments with GP showed statistically significant differences in sorghum seeds (Fig. 1). All treatments with magneto-priming significantly improved seed germination compared with the control unprimed seeds (Fig. 1). The lowest GP was 76.66% in the control unprimed seeds, and the highest significant value of GP was 100% after 3 h of exposure (MP_2). All treatments resulted in significantly higher germination values than those of the control. Similar enhancement by previous work on magneto-priming treatments of various crops seeds has been found on germination percentage for maize (Shine *et al.* 2017, Lazim and Ramadhan 2023), soybean (Joshi-Paneri *et al.* 2023), cucumber (Bhardwaj *et al.* 2012), and other cereals (Martinez *et al.* 2017). Several authors have suggested that biochemical mechanisms, such as antioxidant enzymes, might occur after magneto-priming, which aids in early germination. The alignment of our experimental data with the GM model, rather than the LM model, provides a deeper understanding of the biological dynamics underlying magnetically stimulated sorghum seeds. This mathematical feature reflects a specific physiological configuration, where the germination acceleration phase is nonlinear and responsive to early-applied metabolic stimuli.

The GM model generally better represents the asymmetry in germination curves because growth inherently encounters initial physiological resistance before reaching exponential acceleration (Tipton J L 1984, Yin *et al.* 2003). These mathematical results are consistent with the biological observations reported by Shine *et al.* (2017) and Kataria *et al.* (2015). While these studies identified the involvement of reactive oxygen species (ROS), the activation of antioxidant enzymes, and the rate of action of amylase and hydrolytic proteases, the success of the present model quantifies the temporal dynamics of these biochemical transformations. Similar kinetic models have shown that physical treatments change the internal energy of seeds, which accelerate the transition from water absorption to active root emergence (Bukhari *et al.* 2019, Abdel Latef *et al.* 2020, He *et al.* 2025). The initial latency phase followed by the rapid,

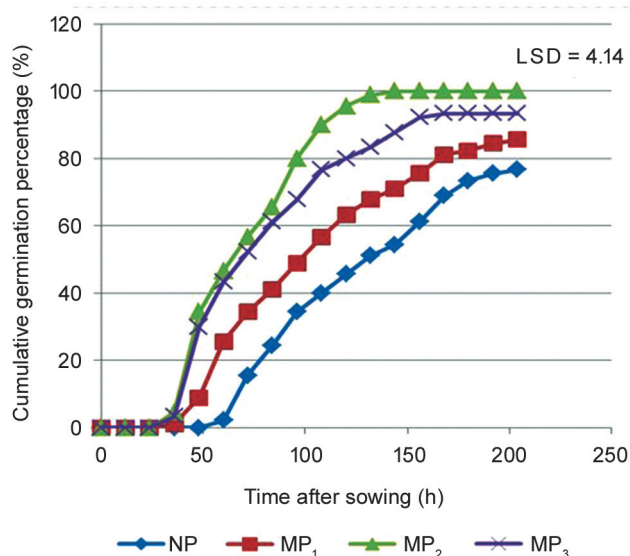


Fig. 1 Cumulative germination percentage of sorghum seeds, as affected by magneto-priming for 0 h (NP) as control; 1 h (MP_1); 3 h (MP_2); and 5 h (MP_3).

asymmetric acceleration, represented by the GM curve, can be explained by the sudden surge in protease and amylase activity triggered by the magnetic field. This enzymatic activation accelerates starch degradation in the endosperm, providing the immediate energy needed to cross the germination threshold more quickly than unstimulated seeds (Ozdinc and Yalcin 2025, He *et al.* 2025). Therefore, the GM model successfully bridges the gap between the mechanisms of magnetic stimulation at the cellular level and germination kinetics at the macro level.

Analysis of variance showed a significant difference between all treatments, $p < 0.05$. Each point is the mean of 3 replicates of 50 seeds.

Experimental data of sorghum seeds at different values of magnetic field can be tested by fitting curve techniques. Plotting curves depending on data from experiments involved minimizing the square sum of the deviations between the mathematical model and the actual data. Both Gompertz and logistic equations use three arbitrary constants to describe growth phenomena empirically, which correspond essentially to upper asymptotes and origin times. In this study, germination kinetic curves obtained are described by fitting two classical three-parameter growth functions. According to the fitting curves of the LG and GM functions, the germination equations and their germination rates are presented in Table 1.

The results of estimating variables a , b , and c for the LM and GM functions are displayed in Table 2. The Gompertz model's estimated parameter correlations typically exhibited significantly superior performance compared to those of the Logistic model. The GM produced the lowest coefficients c (germination rate parameter) and b (shape parameter), as well as the greatest theoretically asymptotic result (parameter a) when compared to the LM. Because variable (a) differed considerably from the others, the 3 h of magneto-priming

Table 1 Germination model functions and germination rate equations for magneto-primed sorghum seeds

Germination rate equation	Function	Treatments	Models
$dy/dt = 5.03 \times 10^{-3} \times y(t) \times [79.56 - y(t)]$	$y(t) = 79.56/[1 + 5.75 \times \text{Exp}(-0.40t)]$	NP	Logistic
$dy/dt = 5.49 \times 10^{-3} \times y(t) \times [83.76 - y(t)]$	$y(t) = 83.76/[1 + 7.34 \times \text{Exp}(-0.46t)]$	MP ₁	
$dy/dt = 6.01 \times 10^{-3} \times y(t) \times [101.53 - y(t)]$	$y(t) = 101.53/[1 + 4.98 \times \text{Exp}(-0.61t)]$	MP ₂	
$dy/dt = 0.90 \times 10^{-3} \times y(t) \times [91.49 - y(t)]$	$y(t) = 91.49/[1 + 4.37 \times \text{Exp}(-0.54t)]$	MP ₃	
$dy/dt = 0.58y(t) \times \text{Exp}(-0.26t)$	$y(t) = 85.07 \times \text{Exp}[-2.24.\text{Exp}(-0.26t)]$	NP	Gompertz
$dy/dt = 0.78y(t) \times \text{Exp}(-0.30t)$	$y(t) = 87.44 \times \text{Exp}[-2.60.\text{Exp}(-0.30t)]$	MP ₁	
$dy/dt = 0.86y(t) \times \text{Exp}(-0.42t)$	$y(t) = 104.65 \times \text{Exp}[-2.06.\text{Exp}(-0.42t)]$	MP ₂	
$dy/dt = 0.76y(t) \times \text{Exp}(-0.39t)$	$y(t) = 93.68 \times \text{Exp}[-1.95.\text{Exp}(-0.39t)]$	MP ₃	

Values were mean $\pm$ standard error. NP, MP₁, MP₂, and MP₃, Seed magneto-priming at exposure times of 0 (control), 1, 3, and 5 h, respectively.

resulted in a greater percentage of germination than the other treatments. In addition to determining the maximum slope of the curve (Ln**b**/c), the parameter **b** has biological implications for values of **x** above zero. The greater the value of **b**, the larger the interval across which the curve asymptotically stays close to the **x**-axis for an equal value of **c**. Because the **x**-axis represents time, the association is significant; high **b** values indicate a longer delay at the start of germinating (Souza *et al.* 2013).

The curve-fitting programme of the LM and GM functions calculates the important derived quantities. These consist of the anticipated starting germination value, the maximum germination rate, and the percentage germination at the inflection point (Table 3). According to GM function analysis, the MP₂ and MP₃ treatments reduced the inflection time by 1.72 days compared to the NP treatment. Conversely, these treatments increased MGR by 16.17% and 13.44% per day, respectively. Whereas, in the LM function, MP₂ and MP₃ demonstrated the highest seed germination, occurring between 2.63 and 2.73 days, respectively, with corresponding daily germination rates of 15.46% and 12.35% (Table 3). Gompertz inflection time was earlier for the germination of seeds derived from

MP₂ and MP₃ than seeds germination derived from NP, indicating that the former emerged more rapidly than the latter. According to the results in Table 3, the highest percent germinating seeds in the inflection time of GM function occurred in MP₂ and MP₃ approximately on the 2nd and 3rd days of the trial, with predicted initial values of 13.19% and 13.34%, respectively. Also, as it can be seen from Table 3, the inflection time of LM function had the highest values of percentage germinating seeds on the 3rd and 4th days of the trial in MP₂ and MP₃, with predicted initial values of 16.945 and 16.84%, respectively. The maximum germination rate happened at the point of inflection in both models, which showed homogeneity in germination time. The higher Gompertz MGR and predicted initial value of germination for the MP₂ and MP₃ than for the NP indicated that increased priming exposure time resulted in more uniformity at the time of germination emergence. The influence of a static magnetic field on germination of sorghum seeds showed improved germination than the control, according to the experimental results compared to the fitted values produced by the GM.

The statistical evaluation of the curves fitted by the two models is shown in Table 4. The mean square error

Table 2 Estimated parameters and their standard deviations for the logistic and Gompertz models describing sorghum primed seed germination.

LSD	Magneto-primed				Models	Parameters
	MP ₃	MP ₂	MP ₁	NP		
Primed=3.10	91.49 $\pm$ 12.70	101.53 $\pm$ 1.89	83.76 $\pm$ 4.62	79.56 $\pm$ 19.52	LM	a
Model=4.39	93.68 $\pm$ 15.34	104.65 $\pm$ 3.11	87.44 $\pm$ 14.25	85.07 $\pm$ 31.47	GM	
Primed=0.46	4.37 $\pm$ 0.14	4.98 $\pm$ 0.46	7.34 $\pm$ 1.24	5.75 $\pm$ 0.39	LM	b
Model=0.66	1.95 $\pm$ 0.001	2.06 $\pm$ 0.02	2.60 $\pm$ 0.03	2.24 $\pm$ 0.02	GM	
Primed=0.03	0.54 $\pm$ 0.002	0.61 $\pm$ 0.001	0.46 $\pm$ 0.001	0.40 $\pm$ 0.002	LM	c
Model=0.04	0.39 $\pm$ 0.001	0.42 $\pm$ 0.001	0.30 $\pm$ 0.001	0.26 $\pm$ 0.001	GM	

Values were mean $\pm$ standard deviations (SD). NP, MP₁, MP₂, and MP₃, Seed magneto-priming at exposure times of 0 (control), 1, 3, and 5 h, respectively. a, b, and c, models parameters.

Table 3 Estimated derived quantities for the logistic and Gompertz models describing sorghum-primed seed germination

Parameters	Gompertz				Logistic			
	Magneto-primed				Magneto-primed			
	MP ₃	MP ₂	MP ₁	NP	MP ₃	MP ₂	MP ₁	NP
y ₀ (%)	13.19	13.34	6.06	8.88	16.94	16.84	9.65	11.65
t _i (day)	1.72	1.72	3.17	3.13	2.65	2.63	4.34	4.30
yt _i (%)	34.47	38.51	32.18	31.30	45.75	50.77	41.88	39.78
MGR (% – dau ⁻¹)	13.44	16.17	9.65	8.14	12.35	15.46	9.63	7.96

NP, MP₁, MP₂, and MP₃, Seed magneto-priming at exposure times of 0 (control), 1, 3, and 5 h, respectively; t_i, Time inflection point; y₀, Per cent of germinating seeds in time t_i; MGR, Maximum germination rate; y₀, Predicted initial value of germination.

(MSE) and coefficient of determination (R²) were analysed in order to statistically compare the goodness-of-fit for both models. According to these hypotheses, the GM had the lowest MSE values and the highest R² for every treatment, followed by the LM. Based on the GM function, the R² and MSE values for the four seed priming are shown in Table 4 ranging from 0.997 to 0.998 and 5.751-11.037, respectively. Because the GM has a lower MSE value and coefficients of determination that are near to one, it thus more accurately depicts the germination process of sorghum in magneto-priming treatments.

To the best of our knowledge, there are no previous studies on sorghum seeds treated with magneto-priming that compare curves fitted by the LM and GM models. However, some studies have proposed mathematical models to describe seed germination curves in magneto-primed seeds. For instance, the Gompertz curve equation was successfully used by Muszyński *et al.* (2009) to study the effect of alternating magnetic fields on the germination of wheat. The logistic curve of the Malthus-Verhulst equation was effectively used by Mounang *et al.* (2020) to investigate the electromagnetic radiation effect on the germination of bean seeds. Additionally, Mahajan and Pandey (2011) successfully utilised the Malthus-Verhulst logistic equation to the germination of black gram seeds using magnetic fields. On the other hand, several authors have examined some mathematical models successfully to describe seed germination curves under different physical seed treatments. In this regard, Muszyński and Gladyszewska (2008) found that the Gompertz curve suited actual data on laser-irradiated

seeds of radish quite well. Bahler *et al.* (1989) used logistic and Weibull functions for the germination curve of alfalfa seeds and found that the Weibull growth function was more sensitive to temperature for predicting cumulative germination. Similar successful results have been recorded for Richards' function when soybean and bean seeds were treated with cold plasma by Ling *et al.* (2014) and Bormashenko *et al.* (2015), respectively.

Data were obtained from a laboratory experiment to select a mathematical model to describe the effects of magneto-priming on sorghum germination. A comparison between the LM and GM germination kinetics curve parameters may permit an accurate determination of the magnetic field effects on sorghum seeds. The GM outperformed the LM in magnetic priming tests, exhibiting the lowest MSE and the highest R² for each treatment. Significant consistency among the observed and expected results determined from the GM function regressions was obtained using the magneto-primed tests for curve fitting approach. The Gompertz model can be directly applied to priming optimisation by analysing parameters. By comparing these parameters across different priming treatments, seed technologists can mathematically identify the optimal priming magnetic field duration that minimises the mean germination time and maximises uniformity. In conclusion, the GM was found to be the most suitable model under magneto-primed conditions for fitting sorghum germination growth data in this study. We suggest scaling up the magneto-priming technology for other commercial seed processing and testing the effect of long term storage on primed seeds.

Table 4 Comparison of the statistics for the two models that forecast the cumulative germination of magneto-primed sorghum seeds.

Magneto-primed	Gompertz				Logistic			
	MSE	R ²	SSR	SSE	MSE	R ²	SSR	SSE
NP	6.214	0.997	38066.46	105.648	10.168	0.995	37742.16	172.858
MP ₁	5.751	0.998	58619	97.772	12.406	0.996	58124.53	210.917
MP ₂	11.361	0.998	96478.42	193.150	15.918	0.996	66596.87	270.619
MP ₃	11.037	0.998	93631.86	187.639	18.216	0.995	68571.57	309.674

NP, MP₁, MP₂, and MP₃, Seed magneto-priming at exposure times of 0 (control), 1, 3, and 5 h, respectively; SSE, Sum of squared errors; SSR, Regression Sum of Squares; R², Coefficient of determination; MSE, Mean square error.

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