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Reformulation of Malthus-Verhulst equation for black gram seeds pretreated with magnetic field

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A b s t r a c t. The effect of magnetic field on germination of black gram (*Cicer arietinum* L.) seeds is presented. Experiment were performed in the magnetic field of 0.060, 0.116, 0.168 and 0.2T. The germination behaviour of black gram seeds strongly depends on the strength of applied magnetic field. The germination kinetics of seeds stimulated with a magnetic field before sowing is most often described using the Malthus-Verhulst equation. This equation is reformulated and verified experimentally for any (initial) number of seeds germinated at initial time. The double differential equation related to germination rate used by other authors is also corrected. When magnetic field is applied, data shows that there is linear decrease in mean germination time and maximum time (when germination rate is maximum).

K e y w o r d s: magnetic field, black gram, presowing treatment, germination rate, germination time

INTRODUCTION

The germination, growth, yield and quality of crops are determined by the properties of seed material. It can be improved by presowing treatment which involves various physical factors such as the electric field, magnetic field, laser radiation and microwave radiation (Aladjadjiyan, 2007). The presowing stimulation of seeds with variable magnetic field may involve specially designed electromagnets. Pietruszewski and Kania (2010) investigated the influence of magnetic field on wheat seeds and concluded that presowing magnetic stimulation of the seeds results in acceleration of the process of germination. Novitsky *et al*. (2001) noted an increase in leaf size as well as higher protein and chlorophyll levels in onion seeds with application of 0.5 mT magnetic field. Exposure of maize seeds to a 150 mT magnetic field stimulated shoot development and led to an increase in germination, fresh mass and shoot length of maize plants (Aladjadjiyan, 2002). Carbonell *et al*. (2000) noted higher rice seed germination rates under the influence of 150 and 200 mT magnetic fields. Martinez *et al*. (2000) reported higher yields of barley subjected to a magnetic field with the intensity of 125mT with exposure time of 24 h. Atak *et al*. (2003) subjected soybean seeds to constant magnetic fields of 2.9-4.6 mT and noted accelerated root growth as well as an increase in the chlorophyll levels. The effect of a weak magnetic field with the intensity of 20 mT increased the mass and height of sunflower plants and enhanced wheat germination rates (Fischer *et al*., 2004). Ratushnyak *et al*. (2008) demonstrated that high frequency magnetic fields of 30-60 GHz with exposure time of 5-15 min stimulated the growth of microflora in pine seeds.

In order to measure the germination process several methods and mathematical expressions have been proposed (Anjum and Bajwa, 2005; Ranal and Santana, 2006), but still there is no satisfactory mathematical expression which could incorporate distinct characteristics of same germination process. Time of germination of the faster seeds (t_0) has been expressed by some authors (Ranal and Santana, 2006; Quintanilla *et al*., 2000). The behaviour of the majority of seeds is neglected by the use of t_0 so it is not preferred. Similarly the last germination time that expresses the time of germination of the slower seeds is also not preferred because of the same reason. To solve this inconvenience, authors (Salehzade *et al*., 2009) used the time for 50% of germination ($t_{1/2}$) and the mean germination time ($\bar{t}$). In 19th century Haberlandt proposed (Ranal and Santana, 2006) the mean germination time as:

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$$\bar{t} = \frac{\sum_{i=1}^{k} n_i t_i}{\sum_{i=1}^{k} n_i}, \quad (1)$$

where: t_i is the time from the start of the experiment to the *i*th observation (day or hour), n_i is number of seeds germinated corresponding to the *i*th observation, and t_k is the last time of germination corresponding to *k*th observation. The idea of the coefficient of velocity (*CV*) was introduced by Kotowski in 20th centuary ((Ranal and Santana, 2006). The formula for the coefficient of velocity is (Sikder *et al.*, 2009),

$$CV = 100(n_1 + n_2 + ... + n_x) / (n_1 t_1 + n_2 t_2 + ... + n_x t_x), \quad (2)$$

where: n_1, n_2,..., n_x are number of seedlings counted on the first day, second day, and so on until the last day (x) and t_1, t_2,..., t_x are number of days between sowing and the first collection , second collection and so on. Accordingly the mean germination rate is defined as:

$$CV/100 = 1/\bar{t}. \quad (3)$$

The germination kinetics of seeds stimulated with a magnetic or electric field before sowing is most often described using the Malthus-Verhulst equation (Pietruszewski, 2001, 2002; Pietruszewski and Kania, 2010):

$$N_g(t) = N_k / [1 + (N_k - 1)\exp\{-\alpha N_k (t - t_0)\}], \quad (4)$$

where: $N_g(t)$ is number of seeds that germinated within time t, N_k is final number of germinated seeds, α is germination rate coefficient, t_0 is time required for the first seed to germinate.

The use of this function is limited as experimentally it is very difficult to find the time when very first seed germinates. Otherwise we can easily find the starting time t_0 when a few number of seeds N_i germinate. So Malthus-Verhulst equation is reformulated as:

$$N_g(t) = N_k N_i / [N_i + (N_k - N_i)\exp\{-\alpha N_k (t - t_0)\}]. \quad (5)$$

This equation is true for any number N_i of germinated seeds at $t = t_0$.

Now the number of seeds in dormant state N with in time t is formulated using above Eq. (5) as:

$$N(t) = (N_k (N_k - N_i)\exp(-\alpha N_k (t - t_0)))/ (N_i + (N_k - N_i)(\exp(-\alpha N_k (t - t_0))). \quad (6)$$

This equation is also true for number of seeds N_i germinated at time $t = t_0$.

For germination rate, differentiating Eq. (5) with respect to time we get:

$$v_k = dN_g(t)/dt = N_g(t)\alpha[N_k - N_g(t)], \quad (7)$$

where v_k is germination rate.

The expression for v_k is same as can be obtained from Eq. (4) by differentiating it with respect to time.

Pietruszewski (2002) and Pietruszewski and Kania (2010) differentiated Eq. (7) with respect to time and found equation:

$$d^2 N_g(t)/dt^2 = N_g(t)\alpha[N_k - N_g(t)][N_k - 2N_g(t)]. \quad (8)$$

There is a mistake in Eq. (8), here it is corrected as:

$$d^2 N_g(t)/dt^2 = N_g(t)\alpha^2[N_k - N_g(t)][N_k - 2N_g(t)]. \quad (9)$$

It is to be noted that Eq. (8) and (9) can be derived using Eq. (4) or (5). The results of Eq. (8) and (9) are independent of N_i.

Pietruszewski (2001) obtained the time (maximum time) when germinated rate is maximum, by letting Eq. (8) equals to zero and using Eq. (4) as:

$$t_{max} = (\ln(N_k - 1)/\alpha N_k) + t_0. \quad (10)$$

The problem for this equation is again the same as it is valid only if at t_0 time when only one seed is germinated. The above equation is reformulated for this condition as well as for any number N_i of seeds germinated at $t = t_0$ time as:

$$t_{max} = (\ln((N_k - N_i)/N_i)/\alpha N_k) + t_0. \quad (11)$$

MATERIALS AND METHODS

A magnetic field generator was fabricated to provide variable horizontal magnetic field strength up to 750 mT. The gap between pole pieces was variable (5 to 10 cm) with two way knobbed wheel screw adjusting system. The flat faced pole pieces were cylindrical in shape with 7.5 cm in diameter. There was two coils, each coil was wound on non magnetic format and had resistance of about 3 Ω. The number of turns per coil was 850. The power supply was designed to provide constant current to electromagnet. The current requirement up to 3.5 A/coil (total of 7 A) was met by DC power supply (0-45V/0-7.5A) with a continuously variable output current used for the electromagnet. A digital Gauss meter monitored the field strength produced in the pole gap. The probe was made of indium arsenide crystal and encapsulated to a non-magnetic thin cylindrical sheet which could measure up to 2T.

Black-gram seeds were exposed to the magnetic field of 60-200 mT in steps of 50 mT for 1 h for all field strengths in a cylindrical-shaped sample holder of 42 cm^3 capacity, made of a non-magnetic thin transparent plastic sheet. Four replications each with 30 seeds were taken in the plastic container at a volume between the poles of the electromagnet having uniform magnetic field and exposed for one hour. The required strength of the magnetic field was obtained by increasing the total current in step of 1.5 A in the coils of the electromagnet. From center to end of the poles, the variation in the magnetic field was 0.8% in all around outward direction. All treatments in the experiments were run simultaneously along with controls under similar conditions.

Five replications of black gram seeds (four treated and one untreated), were taken in 5 transparent plastic boxes with lid of dimension $20 \times 13 \times 4$ cm^3 with a sponge sheet of 2 cm thickness. Sponge sheets in each box were damped with water. All the seeds were planted on same day, ensuring that all the external variables are same for each class of seed during experiment. Average room temperature and average relative humidity was 26°C and 80% respectively during observations. Water was added to the sponge as and when necessary. When germination started number of germinated seeds were counted after certain time interval. A seed was considered to be germinated when radical came out with more than 2 mm long. If the mean germination time, $\bar{t}$, is calculated according to Eq. (1), the mean germination rate, v_g, is:

$$v_g = 1/\bar{t}\,, \tag{12}$$

$t_{\max}$ is calculated using our reformulated formula:

$$t_{\max} = (\ln((N_k - N_i)/N_i)/\alpha N_k) + t_0. \tag{13}$$

RESULT AND DISCUSSION

The germination kinetics curves are graphical variation between germination capacity (%) and time of germination for various values of magnetic field (Fig. 1). Experimental data of black gram seeds for different values of magnetic field fitted well in reformulated Malthus-Verhulst equation $N_g(t) = N_k N_i / [N_i + (N_k - N_i) \exp\{-\alpha N_k(t - t_o)\}]$. In each data field a trend curve is shown. The trend curve shows that germination grows logarithmically. It was found that the value of α for a range of magnetic field by best fitting of Malthus-Verhulst equation with the experimental data (Table 1). The effect of magnetic field on germination time and germination rate is shown in Fig. 2. The starting time of germination considerably reduced to approximately half than control with magnetic field. This is remarkable achievement of magnetic field. There is also enhancement of germination rate with magnetic field as germination curves are becoming steeper with increasing magnetic field. Germination rate is also calculated using summation method (Eq. (12)) (Table 1) and plotted Fig. 3. Germination rate is approximately a linear function of applied magnetic field. Similar enhancement of various crops seeds exposed to magnetic fields has also been reported by many workers (Aladjadjiyan, 2007; Fischer *et al.*, 2004; Florez *et al.*, 2007; Vashisth and Nagarajan, 2010). We have used reformulated Malthus-Verhulst equation (Eq. (13)) for finding the time when germination rate is maximum, that is $t_{\max}$. These

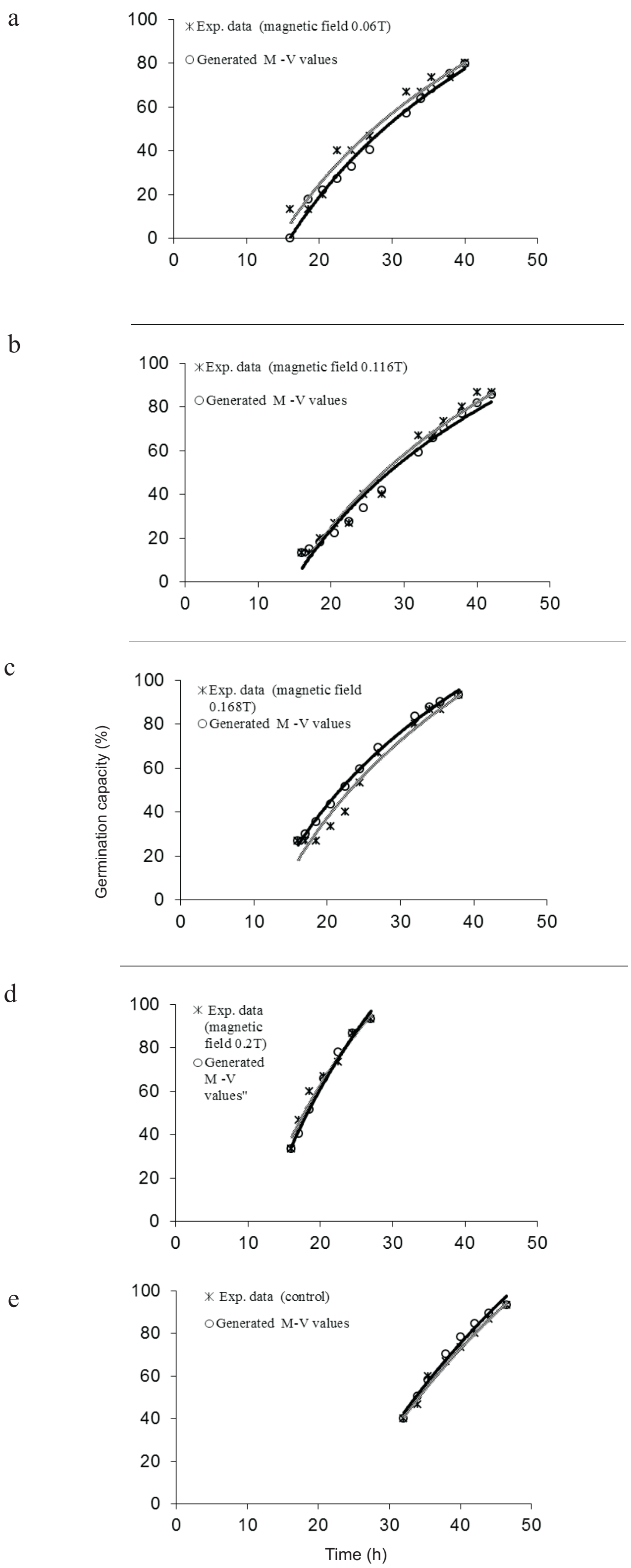

Fig. 1. Variation in germination capacity with time of germination at: a – 0.06T, b – 0.116 T, c – 0.168 T, d – 0.2 T, e – control group; reformulated M-V function showing logarithmic trend with R^2 equals to: 0.9897, 0.9762, 0.9964, 0.99, 0.9839; respectively.

T a b l e 1. Various seed germination parameters

Applied magnetic field	α (h^{-1})	t_0 (h)	t_{mean} (h)	t_{max} (h)	$v_{g\ mean}$ (h^{-1})
Control	0.0140	32.00	36.25	33.93	0.02759
0.060 T	0.0090	16.00	26.54	29.86	0.03768
0.116T	0.0093	16.00	27.81	29.37	0.03596
0.168 T	0.0110	16.00	24.71	22.13	0.04047
0.200T	0.2000	16.00	19.28	18.31	0.05187

α – germination rate coefficient, t_0 – time required for initial number (N_i) seeds to germinate, t_{mean} – mean germination time, t_{max} – time when germination rate is maximum, $v_{g\ mean}$ – mean germination rate.

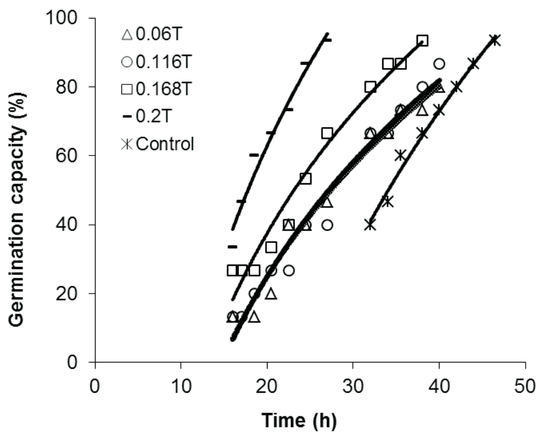

Fig. 2. Variation in germination capacity with time of germination for different strength of applied magnetic field.

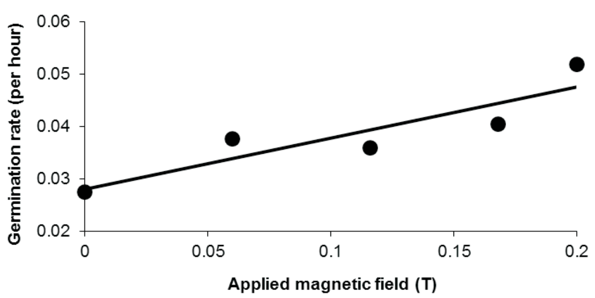

Fig. 3. Variation in mean germination rate with applied magnetic field.

values are shown in Table1. With increasing magnetic field there is linear decrease in t_{max} and t_{mean} ($\bar{t}$) shown in Fig. 4. The mean time ($\bar{t}$) is calculated using Eq. (1). The data shows that the trend of t_{max} is same as that of t_{mean}.

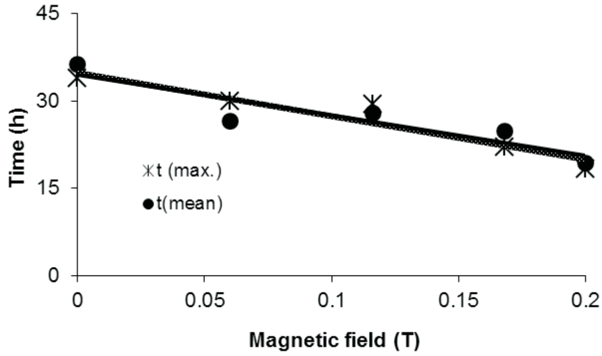

Fig. 4. Variation in mean germination time ($\bar{t}$) and t_{max} with applied magnetic field.

CONCLUSIONS

1. Reformulated Malthus-Verhulst equations for germination capacity and maximum time for maximum germination rate are in best coincidence with germination data of black gram seeds which have been pretreated under magnetic field.

2. There is linear increase in germination rate with applied magnetic field and good improvement of germination time with magnetic field treatment is obtained.

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