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A Comparison of Seed Germination Calculation Formulae and the Associated Interpretation of Resulting Data

M.A. KADER

Abstract: Much experimentation concerns itself with the level and rapidity of germination, yet analyzing and interpreting results can be a difficult task due to the vague nature of some seed germination data. This paper examines a number of data analysis methods adopted in seed germination and emergence tests. What constitutes a good result in one experiment may not be the same in another and this depends, to a large extent, on the data analysis method used. A review of these methods reveals the different interpretations that can be drawn from applying different formulae. Not just the final germination percentage, its mean time or spread, but also the 'high' and 'low' germination events have an impact on the parameters calculated. This paper shows that the Germination Index (GI) is the analysis method that best describes the germination percentage/speed relationship. Germination percentage and mean time alone are not sufficient in representing a seed lot in terms of its germination activity in a given time frame.

Keywords: germination data, data validity, germination speed, emergence rate

INTRODUCTION

The term germination in the seeds of higher plants (Angiosperms) refers to the protrusion of a root or shoot from the seed coat, while emergence is the visible penetration of the shoot above the soil surface (Hadas and Russo 1974, Hadas 1976, Benech Arnold et al. 1991).

In order that a seed can germinate, it must be placed in environmental conditions favourable to this process (Craufurd et al. 1996). Among the conditions required is an adequate supply of water, a suitable temperature range and, for some seeds, light (Collis-George and Williams 1968, Levitt 1980, Long and Woodward 1998). The result is measured in terms of the extent to which seeds have germinated (the final germination percentage attained) and the speed with which the germination process has ended. Frequently, though, other parameters represent significant factors from agronomic, planning or physiological perspectives (Jones and Sanders 1987, Esechie 1994, Kader et al. 1998, Kader 1998, Kader et al., 1999, Kader, 2005).

The length of time elapsed between the first seed to germinate and the last, the variation in germination speed and the timing that the majority of seeds germinate all have impacts on diverse cultural operations like fertilising, harvesting and field maturity of crops (Roberts 1981, Washitani and Saeki 1986, Kader and Jutzi 2001). 'High' (the time at which the majority of seeds germinate) and 'low' (the time at which the minority of seeds germinate) (Kader et al. 1998) germination events are also important indicators of seed vigour and stress resistance (Kader and Jutzi 2002). These data, from an experimental standpoint, also have a significant impact on statistical analyses (Bland and Altman 1995, Legendre and Legendre 1998, Johnson 1999).

A large proportion of experiments relating seed germination to time and rate calculations face difficulty in interpreting and analysing results (Finch-Savage et al. 1998, Trudgill et al. 2000, Grundy et al. 2000). The methods used to evaluate seed germination and emergence are analytical or graphical (Scott et al. 1984), but germination data have several characteristics that distinguish them from other data frequently collected in plant research. Germination is considered to be a qualitative developmental response of an individual seed that occurs at a point in time, but individual seeds within a treatment respond within different times (Harper and Benton 1966, Orchard 1977, Scott et al. 1984, Kader 1998). This leads to a situation where the final germination percentage alone is not sufficient for reporting results due to the lack of ability to compare two sets of data (one lot of seed may have germinated well before the other, but both attained the same final germination percentage). This has been indicated as a set back in previous work relating seed treatments to the germination pattern of seed lots (Timson 1965, Todd and Webster 1965, Harris and Wilson 1970, Thompson, 1974) leading to the development of a number of germination measurement techniques (Heydecker 1966, Scott et al. 1984, Carberry and Campbell 1989).

This review compares various methods of analysing, representing and interpreting germination data. It draws comparisons between the various methods and identifies the most widely encompassing method correlating final germination with time.

MATERIALS AND METHODS

A review of seed germination analysis methods in the literature was conducted and revealed the methods shown in Table 1 as the major parameters used in germination studies. These germination calculation methods fall broadly into the following 3 categories.

1. Data analysis formulae interpreting the final germination percentage attained
2. Data analysis formulae interpreting the time taken to achieve seed lot germination
3. Data analysis formulae correlating 1 and 2

The various methods were compared for accuracy and representation using the germination data of Kader et al. (1998, 1999) and Kader and Jutzi (2001, 2002), as well as hypothetical germination data (see details below), illustrating time-based differences in the 3 different categories below.

1. Accuracy of representation of germination percentage/time correlations
2. Accuracy of representation of time spread of germination
3. Accuracy of representation of the uniformity of seed lot germination

The problem comes from observations from field, laboratory and growth chamber experiments conducted between 1993 and 2002 involving monocotyledons (*Sorghum bicolour* and *Pennisetum glaucum* L. R. Br) and dicotyledons (*Acacia farnesiana* and *Acacia saligna*). These two groups represent both hypogeal and epigeal germination in a field crop and tree species, respectively (ISTA 1993). Hypothetical data was employed where necessary (detailed in each scenario – see Tables 2 to 9 below). The parameters used to compare the germination data for representation and accuracy were as follows.

1. Final Germination Percentage (FGP)
2. Mean Germination Time (MGT)
3. Germination Index (GI)
4. Coefficient of Velocity of Germination (CVG)
5. Germination Rate Index (GRI)
6. First Day of Germination (FDG)
7. Last Day of Germination (LDG)
8. Time Spread of Germination (TSG)

The details, measurement units and calculation methods of each parameter are shown in Table 1, with a base germination period of 10 days being used and applied to 4 seed lots.

RESULTS AND DISCUSSION

The results of Tables 2–9 reveal a wide variation between germination data based on the time spread of germination as well as its final percentage. FGP only reflects the final percentage of germination attained and provides no picture of the speed or uniformity of germination. Table 2 shows that the 4 seed lots tested all attained an FGP of 95%, but had varying time spreads of germination.

MGT is an accurate measure of the time taken for a lot to germinate, but does not correlate this well with the time spread or uniformity of germination. It focusses instead on the day when most germination events occurred. As seen from Table 3, seed lots started germination on the same day and attained the same FGP, but had varying MGT values. Table 4, on the other hand, shows the same TSG value for the 4 seed lots, a different FGP, yet the same MGT. This means that seed lots can germinate across a different spread and attain a different final germination percentage, yet have the same mean germination time.

GRI calculations merely show the percentage of germination per day, so the higher the percentage and the shorter the duration, the higher the GRI. This parameter lacks any correlation with the 'high' and 'low' germination days as it spreads the percentage evenly across the time spread. Table 4, shows seed lots with a CVG of 50, but GRI values ranging from 18.4 to 50.0.

CVG does not focus on the final percentage of germination, but places emphasis on the time required for reaching it. The details of time (first day, last day and time spread) are not taken into account as the time is averaged. Table 5 shows seed lots with the same FDG, LDG and TSG, but different CVG values. This means that time-based measurements, not correlated with the FGP, are not a very useful representation of the overall seed germination activity. Starting germination and ending it at the same time is not sufficient enough to produce a uniform CVG and is therefore misleading.

First day, last day and time spread of germination are good measures of when the first germination event started, when the last event occurred and the time between the two, but, again, lacks any correlation to the final germination attained. Tables 6, 7 and 8 highlight this. Whether the TSG is 1 or 7 days, and regardless of the FGP, seed lots could still start germination and end it on similar days (i.e., same FDG and same LDG values).

The GI appears to be the most comprehensive measurement parameter combining both germination percentage and speed (spread, duration and 'high/low' events). It magnifies the variation among seed lots in this regard with an easily compared numerical measurement. As an example, in Table 3, seed lots all attained an FGP of 95% over 3 days. The lot with 31.6% over 3 days had an MGT of 1.9 days and that with 47.5% over 2 days had an MGT of 1.5 days. This is a difference of merely 0.4 days despite the fact that on each occasion the second seed lot germinated 15.9% more. The GI, on the other hand emphasises this difference more clearly where the GI for the 3-day time spread is 853.2 and that for the 2-day time spread is 905.5, a difference of 52.3 units.

In conclusion, the use of germination data analysis methods is prone to mis-interpretation if germination percentage, speed, spread and concentration are not taken into account in one measurement. In the context of the parameters tested in this investigation, it appears that the GI is the most accurate in this regard. An alternative would be to use a number of parameters when reporting germination trial results and place these in one single formula. This will be addressed in a subsequent paper.

Germination Parameter	Symbol	Unit	Formula for Calculation	Description of Formula	Notes & Reference
Final Germination Percentage	FGP	%	FGP=Final no. of seeds germinated in a seed lot $\times$ 100		The higher the FGP value, the greater the germination of a seed population. Scott et al. (1984)
Mean Germination Time	MGT	day	$\text{MGT}=\sum f\cdot x/\sum f$	f=Seeds germinated on day x	The lower the MGT, the faster a population of seeds has germinated. Orchard (1977)
First Day of Germination	FDG	day	FDG=Day on which the first germination event occurred		Lower FDG values indicate a faster initiation of germination. Kader (1998)
Last Day of Germination	LDG	day	LDG=Day on which the last germination event occurred		Lower LDG values indicate a faster ending of germination. Kader (1998)
Coefficient of Velocity of Germination	CVG	—	$\text{CVG}=\text{N}_1+N_2+\cdots+N_x/100\times N_1T_1+\cdots+N_xT_x$	N=No. of seeds germinated each day, T=No. of days from seeding corresponding to N	The CVG gives an indication of the rapidity of germination. It increases when the number of germinated seeds increases and the time required for germination decreases. Theoretically, the highest CVG possible is 100. This would occur if all seeds germinated on the first day. Jones and Sanders (1987)
Germination Rate Index	GRI	(%/day)	GRI=G1/1 + G2/2 $+\cdots+$ Gx/x	G1=Germination percentage $\times$ 100 at the first day after sowing, G2=Germination percentage $\times$ 100 at the second day after sowing	The GRI reflects the percentage of germination on each day of the germination period. Higher GRI values indicate higher and faster germination. Esechi (1994) after modification.

Table 1. Description of various parameters used to study seed germination. Continued on next page . . .

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Germination Parameter	Symbol	Unit	Formula for Calculation	Description of Formula	Notes & Reference
Germination Index	GI	—	GI=(10×n1) + (9×n2) + ⋯ + (1×n10)	n1, n2 … n10 = No. of germinated seeds on the first, second and subsequent days until the 10th day; 10, 9 … and 1 are weights given to the number of germinated seeds on the first, second and subsequent days, respectively	In the GI, maximum weight is given to the seeds germinated on the first day and less to those germinated later on. The lowest weight would be for seeds germinated on the 10th day. Therefore, the GI emphasizes on both the percentage of germination and its speed. A higher GI value denotes a higher percentage and rate of germination. Bench Arnold et al. (1991)
Time Spread of Germination	TSG	day	TSG=The time in days between the first and last germination events occurring in a seed lot		The higher the TSG value, the greater the difference in germination speed between the ‘fast’ and ‘slow’ germinating members of a seed lot. Kader (1998)

Table 1. Description of various parameters used to study seed germination.

Day	Seed Lot 1	Seed Lot 2	Seed Lot 3	Seed Lot 4
1	0	95	10	0
2	0	0	20	0
3	0	0	65	15
4	15	0	0	35
5	80	0	0	50
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
Parameters				
FGP (%)	95	95	95	95
MGT (day)	4.8	1.0	2.5	4.1
GI	585	950	800	595
CVG	20.8	100.0	38.7	22.7
GRI (%/day)	19.7	95.0	38.0	23.1
FDG (day)	4	1	1	3
LDG (day	5	1	3	5
TSG (day)	1	0	2	2

Table 2. Seed lots with different germination rates.

Day	Seed Lot 1	Seed Lot 2	Seed Lot 3	Seed Lot 4
1	19	23.7	31.6	47.5
2	19	23.7	31.6	47.5
3	19	23.7	31.6	0
4	19	23.7	0	0
5	19	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
Parameters				
FGP (%)	95	95	95	95
MGT (day)	3	2.4	1.9	1.5
GI	760	805.8	853.2	902.5
CVG	13.3	40.0	50.0	66.6
GRI (%/day)	31.6	39.5	50.0	50.0
FDG (day)	1	1	1	1
LDG (day	5	4	3	2
TSG (day)	4	3	2	1

Table 3. The effect of distribution of seed germination on measurement results.

Day	Seed Lot 1	Seed Lot 2	Seed Lot 3	Seed Lot 4
1	31.6	25	18.3	11.6
2	31.6	25	18.3	11.6
3	31.6	25	18.3	11.6
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
Parameters				
FGP (%)	95	75	55	35
MGT (day)	1.9	1.9	1.9	1.9
GI	853.2	675	494.1	313.2
CVG	50.0	50.0	50.0	50.0
GRI (%/day)	50.0	39.4	28.9	18.4
FDG (day)	1	1	1	1
LDG (day	3	3	3	3
TSG (day)	2	2	2	2

Table 4. Germination percentage variations over a 3-day spread.

Day	Seed Lot 1	Seed Lot 2	Seed Lot 3	Seed Lot 4
1	10	70	10	15
2	15	15	70	70
3	70	10	15	10
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
Parameters				
FGP (%)	95	95	95	95
MGT (day)	2.6	1.3	2.0	1.9
GI	795	915	850	860
CVG	31.6	73.0	48.7	51.3
GRI (%/day)	36.5	73.0	47.5	50
FDG (day)	1	1	1	1
LDG (day	3	3	3	3
TSG (day)	2	2	2	2

Table 5. Germination concentration and its impact on germination rates.

Day	Seed Lot 1	Seed Lot 2	Seed Lot 3	Seed Lot 4
1	13.5	19	31.6	95
2	13.5	19	31.6	0
3	13.5	19	31.6	0
4	13.5	19	0	0
5	13.5	19	0	0
6	13.5	0	0	0
7	13.5	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
Parameters				
FGP (%)	95	95	95	95
MGT (day)	3.9	3.0	1.9	1.0
GI	661.5	760	853.2	950
CVG	25.0	33.3	50.0	100.00
GRI (%/day)	24.3	31.6	50.0	95.0
FDG (day)	1	1	1	1
LDG (day	7	5	3	1
TSG (day)	6	4	2	0

Table 6. Time course of germination impacts on measurement data.

Day	Seed Lot 1	Seed Lot 2	Seed Lot 3	Seed Lot 4
1	0	0	0	0
2	0	0	0	31.6
3	0	0	0	31.6
4	0	0	31.6	31.6
5	0	0	31.6	0
6	0	31.6	31.6	0
7	0	31.6	0	0
8	31.6	31.6	0	0
9	31.6	0	0	0
10	31.6	0	0	0
Parameters				
FGP (%)	95	95	95	95
MGT (day)	8.9	6.9	4.9	2.9
GI	189.6	379.2	568.8	758.4
CVG	11.1	14.2	20.0	33.3
GRI (%/day)	10.6	13.7	19.3	32.7
FDG (day)	8	6	4	2
LDG (day	10	8	6	4
TSG (day)	3	3	3	3

Table 7. Early and late germination spread impacts on germination rate.

Day	Seed Lot 1	Seed Lot 2	Seed Lot 3	Seed Lot 4
1	9.5	18.7	27.5	35
2	9.5	18.7	27.5	0
3	9.5	18.7	0	0
4	9.5	18.7	0	0
5	9.5	0	0	0
6	9.5	0	0	0
7	9.5	0	0	0
8	9.5	0	0	0
9	9.5	0	0	0
10	9.5	0	0	0
Parameters				
FGP (%)	95	75	55	35
MGT (day)	5.5	2.4	1.5	1
GI	495.5	635.8	522.5	350
CVG	18.1	40.0	66.6	100
GRI (%/day)	17.2	31.2	36.6	35
FDG (day)	1	1	1	1
LDG (day	10	4	2	1
TSG (day)	9	3	1	0

Table 8. Percentage and spread of germination effects on measurement parameters.

Day	Seed Lot 1	Seed Lot 2	Seed Lot 3	Seed Lot 4
1	0	31.6	0	80
2	0	31.6	0	10
3	0	31.6	0	5
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	31.6	0	80	0
9	31.6	0	10	0
10	31.6	0	5	0
Parameters				
FGP (%)	95	95	95	95
MGT (day)	8.9	1.9	8.2	1.2
GI	189.6	853.2	265	930
CVG	11.1	50.0	12.1	82.6
GRI (%/day)	10.6	50.0	11.5	79.1
FDG (day)	8	1	8	1
LDG (day	10	3	10	3
TSG (day)	2	2	2	2

Table 9. First day of germination, time spread and percentage germination variations.

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M.A. Kader
Director, Consultica Worldwide,
PO Box 3089, Tamarama
NSW 2026 Australia
email: m.kader@consultica.com.au

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