Journal of Seed Science
ISSN 2317-1545
www.abrates.org.br/revista

Journal of Seed Science, v.41, n.4, p.407-415, 2019
http://dx.doi.org/10.1590/2317-1545v41n4214988

Physiological potential of soybean seeds and its relationship to electrical conductivity[1]

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ABSTRACT – Electrical conductivity (EC) stands out among vigor tests because of its capability of detecting damage in seeds in the initial stage, since EC is related to disorganization of the cell membrane. The aim of this paper was to study use of the EC test as an alternative for vigor evaluation in soybean seeds, verifying its relationship to different vigor tests and thus suggesting values and the range of values of electrical conductivity that indicate the performance potential of a seed lot in the field. Eleven seed lots from each of four soybean cultivars were used for this study. The moisture level was determined and the following tests were performed: electrical conductivity, germination, tetrazolium, accelerated aging, first germination count, seedling vigor classification and emergence of seedlings in the field and in sand. The EC test had a significant and negative correlation ($p < 0.01$) with all the tests performed. Linear regression analysis allowed separation of the seed lots into classifications of very high vigor (EC ≤ 70 $\mu S.cm^{-1}.g^{-1}$), high vigor (EC from 71 to 90 $\mu S.cm^{-1}.g^{-1}$), medium vigor (EC from 91 to 110 $\mu S.cm^{-1}.g^{-1}$) and low vigor (EC ≥ 111 $\mu S.cm^{-1}.g^{-1}$).

Index terms: germination, *Glycine max*, leaching of ions, vigor.

Potencial fisiológico de sementes de soja e sua relação com a condutividade elétrica

RESUMO – O teste de condutividade elétrica (CE) é capaz de detectar a deterioração de sementes ainda em sua fase inicial, tendo em vista que está relacionado com a desorganização das membranas celulares. Deste modo, o presente trabalho teve por objetivo o estudo da utilização do teste de CE como alternativa para avaliação de vigor de sementes de soja verificando sua relação com diferentes testes de vigor e, assim, sugerir valores e faixa de valores de condutividade elétrica que indiquem o potencial de desempenho de um lote de sementes em campo. Para tanto, foram utilizados lotes de sementes de soja de quatro cultivares, onze lotes de cada. Foram determinados o teor de água e realizados os testes de condutividade elétrica, germinação, tetrazólio, envelhecimento acelerado, primeira contagem, classificação de vigor de plântulas, emergência da plântula em campo e em areia. O teste de CE apresentou correlação significativa e negativa ($p < 0,01$) para todos os testes avaliados. A análise de regressão linear possibilitou a separação dos lotes de sementes de vigor muito alto (CE ≤ 70 $\mu S.cm^{-1}.g^{-1}$), alto (CE entre 71 a 90 $\mu S.cm^{-1}.g^{-1}$), médio (CE entre 91 a 110 $\mu S.cm^{-1}.g^{-1}$) e baixo (CE ≥ 111 $\mu S.cm^{-1}.g^{-1}$).

Termos para indexação: germinação, *Glycine max*, lixiviação de íons, vigor.

Introduction

The concept of seed quality can be addressed through its main components: physiological quality, genetic quality, quality of seed health and physical quality. However, seed quality is an interaction of these components, which together determine seed attributes (França-Neto, 2009).

Physiological potential gathers information regarding seed germination (viability) and vigor, and thus it includes the set of aptitudes that allows estimation of the theoretical capacity of a seed lot to adequately manifest its vital functions after sowing. Information regarding germination and vigor obtained in the laboratory should allow comparison of seed lots and assess the probability of success in acquiring and using them. After sowing, researchers can ascertain the extent to which the potential identified in the laboratory was

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manifested and the efficiency of the methods used to evaluate this potential (Marcos-Filho, 2011).

The germination test is the official procedure for evaluating the capacity of seeds to produce normal seedlings under favorable field conditions. However, routine interpretation of this test does not reveal the differences in quality and performance among seed lots that might appear in storage or even in the field, and knowledge of these differences would allow an estimate of physiological quality (Carvalho and Nakagawa, 2000; Marcos-Filho, 1999; 2015). Deviations in relation to ideal field conditions are frequent, thus it is necessary to use other procedures to estimate seed physiological potential (Marcos-Filho, 2013; 2015).

Vigor tests have increasingly become a tool of routine use in the seed industry to complement the germination test. Seed production companies and official institutions have included these tests in internal quality control programs to ensure the quality of seeds destined for commercial sale (Vieira et al., 2003).

Vigor testing is very useful in monitoring seed quality beginning at seed maturity because a decline in vigor precedes loss of viability (Dias and Marcos-Filho, 1995). Among vigor tests, electrical conductivity stands out, since it is able to detect the process of seed deterioration in its initial phase and it provides results in 24 h (Vieira and Krzyzanowski, 1999; Marcos-Filho and Vieira, 2009).

The electrical conductivity test is cited by the International Seed Testing Association (ISTA, 2011) as one of the most promising vigor tests since it provides a consistent theoretical basis, objectivity, speed, ease of execution and possibility of being standardized as a routine test due to its reproducibility (Vieira and Krzyzanowski, 1999; Marcos-Filho and Vieira, 2009).

The electrical conductivity test is based on the integrity of cell membranes and, together with the tetrazolium test, it is classified as a biochemical test. Loss of cell membrane integrity is one of the initial manifestations of the process of reduction in seed physiological potential. In the case of orthodox seeds, such as soybean, this disorganization occurs in two situations – through the deterioration process strictly speaking and/or as a result of reduction in seed water content. Thus, the electrical conductivity test is based on the fact that seeds at the time they are placed to soak in water up to reorganization of cell membranes exude sugars, enzymes, nucleotides, fatty acids, organic acids, amino acids, proteins and inorganic compounds, such as phosphates and K^+, Ca^{++}, Na^+ and Mg^{++} ions. During the soaking process, the cell membrane system will be reorganized, and it is thought that the lower the level of seed deterioration, the more quickly and to a greater degree this reorganization will occur. As Bewley et al. (2013) affirms, in deteriorated seeds, this mechanism or speed of reorganization is absent or inefficient, and a larger number of electrolytes is leached (Fessel et al., 2010; Fessel et al., 2006). Thus, with the assistance of a conductivity meter, it is possible to measure the amount of electrolytes leached into the soaking solution. Seed vigor is considered to be inversely proportional to the electrical conductivity reading, i.e., the lower the electrical conductivity of the soaking solution, the greater the seed vigor, because lower electrical conductivity means a lower level of seed deterioration (Vieira and Krzyzanowski, 1999; Marcos-Filho and Vieira, 2009).

Schuab et al. (2006) also performed studies in soybean and found that, among other vigor tests, the electrical conductivity test shows sensitivity to differentiate the physiological potential of the genotypes evaluated. For Vieira et al. (1999), the electrical conductivity test allows estimation of the performance of soybean seed lots in the field with a high degree of accuracy, depending on the climate conditions present.

Studies to determine reference values for the purpose of differentiating the vigor of seed lots by the electrical conductivity test have been performed for some species, such as sunflower (Szemruch et al., 2015) and soybean (Vieira et al., 1999; Vieira et al., 2004; Colete et al., 2004).

The development of studies seeking to identify these reference values is very important because it allows establishment of parameters associated with the vigor level of seed lots, comparison with results obtained in other tests, and, consequently, establishment of standards to be followed in internal quality control programs in seed production companies. For that reason, it is necessary to intensify these studies, always associating these values with the percentage of seedling emergence in the field (Colete et al., 2004; Vieira et al., 2004; Marcos-Filho, 2015).

Therefore, the aim of the present study was to analyze the use of the electrical conductivity test as an alternative for evaluating soybean seed vigor, observing its relationship with different vigor tests and thus suggesting values and a range of values of electrical conductivity that indicate the performance potential of a seed lot in the field.

Material and Methods

The study was conducted in the Physiology Laboratory of the Seed and Grain Technology Center and in the experimental field of the *Empresa Brasileira de Pesquisa Agropecuária* – EMBRAPA Soybean, Londrina, PR (23º28'44.72''S, 50º59'03.24''W). Soybean [*Glycine max* (L.) Merrill] seeds from the 2015/2016 crop season of the cultivars BRS 1001 IPRO, BRS 1007 IPRO, BRS 1010 IPRO and BRS 388 RR were used, each one represented by eleven seed lots coming from seed production companies of the state of Paraná. The seed lots were divided into four replications through a Boerner homogenizer and sample divider.

The seeds were stored in a cool, dry chamber (10 °C, 50-60% RH) throughout the time of the experiment.

First, the seed water content was determined (Table 1) using the laboratory oven method at 105 ± 3 °C for 24 h, according to the Rules for Seed Testing (Brasil, 2009).

The physiological potential of the seed lots of each cultivar was evaluated by the procedures that follow.

Electrical conductivity (EC): evaluated by the bulk method; ten subsamples of fifty seeds per replication per seed lot were used. The seeds were weighed on an analytical balance with 0.01 g precision, immersed in 75 mL of deionized water in plastic cups (200 mL) and kept in a germination chamber at 25 °C for 24 h. After the seed-soaking period, the electrical conductivity of the soaking solutions was determined in a conductivity meter (Digimed DM-32). Evaluation was made in a temperature-controlled environment at 25 ºC without air currents, and the device was connected to a constant electric current. The results obtained were divided by the the mass of fifty seeds and expressed in $\mu S.cm^{-1}.g^{-1}$ of seeds (Marcos-Filho and Vieira, 2009).

Germination (G): conducted in four subsamples of fifty seeds per replication per seed lot. The seeds were distributed in rolls of "Germitest" germination paper moistened with water in the amount of 2.5 times the weight of the dry substrate. The rolls were kept in cabinets within the germination chamber regulated to 25 °C, according to Brasil (2009), except that the evaluations were made on the fifth day after sowing, and the results were expressed in percentage of normal seedlings.

First germination count (FGC): the same procedures as the germination test were used in carrying out this test, however, registering the percentage of normal seedlings larger than 3.75 cm obtained on the third day after sowing, and the results were expressed in percentage of normal seedlings (TeKrony et al., 1987; Nakagawa,1999).

Seedling vigor classification (SVC): performed with four subsamples of fifty seeds per replication, together with the germination test. The normal seedlings that had essential structures that were well-formed and larger than the others were classified as strong (vigorous), whereas those that had some problem in their structure or had injuries (but not characterized as abnormal to the seedling) and were smaller than the previously described seedlings and little developed were classified as weak, as described by Nakagawa (1999). The results were expressed in percentage of "strong" seedlings.

Tetrazolium (TZ): conducted with two subsamples of fifty seeds per replication per seed lot. Initially, the samples were pre-conditioned in moistened germination paper and kept for 16 h in a seed germinator at 25 ºC. At the end of this period, the seeds were transferred to plastic cups (50 mL), immersed in tetrazolium salt solution (0.075%) and kept for 2.5 h in a laboratory oven at 40 ºC. After staining, the seeds were washed in running water and evaluated according to the criteria described by França-Neto et al. (1999). The results were expressed in percentage of viable and vigorous seeds.

Accelerated aging (AA): the seeds were distributed on stainless steel screens in a single layer within a plastic box (11.0 x 11.0 x 3.5 cm), containing 40 mL of water in the bottom, and kept at a temperature of 41 ºC for 24 h (Costa et al., 1984) within an accelerated aging chamber. After aging of the seeds, the germination test was performed on four fifty-seed subsamples, according to the method described above. After the aging period, seed water content was determined (Table 1) by the laboratory oven method (Brasil, 2009).

Table 1. Values of initial water content (IWC) and water content after accelerated aging (WCAA) of eleven soybean seed lots of the cultivars BRS 388 RR, BRS 1010 IPRO, BRS 1001 IPRO and BRS 1007 IPRO.

Cultivar	BRS 388 RR		BRS 1001 IPRO		BRS 1010 IPRO		BRS 1007 IPRO	
Lot	Water content (%)		Water content (%)		Water content (%)		Water content (%)	
	IWC	WCAA	IWC	WCAA	IWC	WCAA	IWC	WCAA
1	10.6	22.4	9.7	21.9	9.8	21.7	9.8	23.1
2	10.2	21.5	9.7	21.6	9.7	21.6	9.5	20.0
3	10.5	21.6	9.4	21.4	10.1	22.1	8.9	21.8
4	10.4	22.0	9.5	22.3	10.3	22.7	8.9	23.2
5	10.2	21.6	9.7	22.1	10.1	22.0	9.1	23.9
6	10.4	21.9	9.5	22.5	10.1	22.0	8.9	22.1
7	10.9	22.6	9.3	21.6	10.1	21.9	8.8	22.8
8	10.4	21.7	9.4	22.6	10.1	18.9	8.6	23.1
9	10.2	21.5	9.1	22.9	10.1	21.6	8.7	23.2
10	10.1	21.7	9.3	22.9	11.0	21.2	8.7	21.5
11	10.1	22.2	9.8	21.7	9.5	20.8	8.4	22.4

Seedling emergence in the field (SEF): conducted at experimental farm of EMBRAPA Soja, Londrina, PR (23º28’44.72”S, 50º59’03.24”W). It was performed with four one-hundred-seed subsamples per replication, per seed lot. Seeds were sown on November 1st, 2016 – they were treated with fungicide and insecticide (Standak®) and distributed in 4-m-length furrows at a depth of 5 cm. The distance between furrows was 30 cm, and seeds were sown in moistened soil. Rainfall (mm) and relative humidity (%) data in reference to the period of conducting the test are shown in Table 2. Emerged seedlings were counted at fifteen days after sowing, and results were expressed in percentage of emerged seedlings.

Seedling emergence in sand (SES): performed with two one-hundred-seed subsamples per replication per seed lot. The test was conducted in a greenhouse, using plastic boxes containing sand as a substrate and performing irrigation whenever necessary. At the end of the test, at twelve days, normal seedlings were counted and the percentage of seedling emergence in sand was determined.

Indications of soybean seed vigor levels considering the results of the electrical conductivity test were defined based on performance of the seed lots observed in the germination and vigor test evaluated. In addition to the results of this study, elaboration of the vigor levels considered reference values of some authors such as Colete et al. (2004) and Vieira et al. (2004), which were used as an indication to separate soybean seed lots into different vigor levels, indicating possible performance in the field, considering climate conditions.

The value of each replication used for statistical analysis was the result of the mean value of ten subsamples for the electrical conductivity test, of two subsamples for the tetrazolium and seedling emergence in sand tests, and four subsamples for the tests of germination, accelerated aging, first germination count, seedling vigor classification and seedling emergence in the field.

A completely randomized experimental design was adopted for the laboratory tests, and randomized complete blocks for the seedling emergence in the field test. Analysis of variance was performed on the data by the F test, using the SASM-Agri software (Canteri, 2001).

To evaluate the correlation strength among the variables, the Pearson linear correlation coefficient (r) was used, and they were classified according to the interpretation of Zou et al. (2003). The correlation coefficients (ρ) were considered significant at 1% probability by the T test.

Simple linear regression analysis was carried out, relating the independent variable, electrical conductivity, to the dependent variables: germination, accelerated aging, first germination count, seedling emergence in the field, tetrazolium viability, tetrazolium vigor, seedling vigor classification and seedling emergence in sand. The F test was used on the equations obtained, testing their significance.

Results and Discussion

Table 3 shows the Pearson linear correlation coefficients (r) among the following variables: electrical conductivity, germination, tetrazolium vigor, tetrazolium viability, accelerated aging, first germination count, seedling vigor classification, seedling emergence in the field and seedling emergence in sand. Results were obtained based on the mean values of 44 lots of soybean seeds.

From Table 3, it can be observed that the electrical conductivity test had significant ($p < 0.01$) and negative correlation with the vigor tests and with the germination test, i.e., in the electrical conductivity test, the seeds that had lower leaching of solutes and, consequently, a lower value of electrical conductivity, are the most vigorous, and this is inversely proportional to the other variables; therefore, the electrical

Table 2. Rainfall and relative humidity observed from October 26th to November 15th, 2016, in Londrina, PR, when conducting the seedling emergence test in the field.

Day/Month	Relative humidity (%)	Rainfall (mm)	Day/Month	Relative humidity (%)	Rainfall (mm)
26/10	94.0	37.2	6/11	76.8	0.2
27/10	83.2	1.6	7/11	81.6	2.3
28/10	65.7	0.0	8/11	75.4	1.6
29/10	67.7	0.0	9/11	67.4	0.8
30/10	75.2	0.0	10/11	68.1	0.0
31/10	78.4	0.0	11/11	82.0	5.5
1/11*	74.8	0.0	12/11	96.4	1.3
2/11	88.3	5.6	13/11	95.9	0.3
3/11	85.7	0.0	14/11	80.4	0.0
4/11	81.5	0.0	15/11	75.4	0.0
5/11	72.8	0.0			

*Sowing in the field.

Table 3. Pearson simple correlation coefficients (r) estimated between the tests of electrical conductivity (EC) and germination (G), tetrazolium vigor (TZVG), tetrazolium viability (TZVB), accelerated aging (AA), first germination count (FGC), seedling vigor classification (SVC), seedling emergence in the field (SEF), and seedling emergence in sand (SES).

	EC	SES	SEF	SVC	FGC	AA	TZVB	TZVG
G	-0.81	0.84	0.83	0.71	0.87	0.92	0.92	0.91
TZVG	-0.84	0.84	0.91	0.69	0.85	0.88	0.89	–
TZVB	-0.65	0.71	0.76	0.64	0.79	0.81	–	–
AA	-0.86	0.90	0.81	0.69	0.84	–	–	–
FGC	-0.78	0.83	0.79	0.57	–	–	–	–
SVC	-0.62	0.63	0.71	–	–	–	–	–
SEF	-0.79	0.83	–	–	–	–	–	–
SES	-0.85	–	–	–	–	–	–	–

Significant at 1% probability by the T test.

conductivity test had negative correlation with the other tests.

The results of the electrical conductivity test showed strong negative correlation with the tests of germination (r = -0.81), tetrazolium vigor (r = -0.84), accelerated aging (r = -0.86), first germination count (r = -0.78), seedling emergence in the field (r = -0.79) and seedling emergence in sand (r = -0.85) (Table 3). Barros and Marcos-Filho (1997), Barbieri et al. (2013), Schuab et al. (2006) and Matera et al. (2019) worked with soybean seeds and also found strong negative correlation between the electrical conductivity test and the tests of germination, accelerated aging and seedling emergence in the field. This is a strong indication that the test can and should be part of programs for quality control of soybean seeds, considering that such programs should always work with more than one procedure, thus assisting in decision making regarding the use of seed lots.

Analysis of the correlation of the electrical conductivity test with the tetrazolium viability tests and the seedling vigor classification test shows that they had moderate negative correlation coefficients of r = -0.65 and r = -0.62, respectively. Moderate correlation between the electrical conductivity test and the tetrazolium vigor and viability tests, the seedling emergence in the field test and seedling emergence in sand test was observed by Schuab et al. (2006). From a practical perspective, this can be understood as a strong indication that more than one test should always be used to evaluate seed vigor, since adding up the results allows more effective and successful decision making.

Table 4 shows the equations calculated from the electrical conductivity test as an independent variable and the tests of germination, accelerated aging, first germination count, seedling emergence in the field, tetrazolium vigor, tetrazolium viability, seedling vigor classification and seedling emergence in sand tests as dependent variables. The F test was significant at 1% for all the equations estimated. The dependent variables had satisfactory coefficients of determination (R^2). The dependent variable of accelerated aging (R^2 = 74%) had the highest coefficient of determination, and the dependent variable of seedling vigor classification (R^2 = 38%) had the lowest coefficient of determination, explaining the mathematical model with less accuracy. Thus, the electrical conductivity variable can be used to predict the values of germination, accelerated aging, first germination count, seedling emergence in the field, tetrazolium vigor and seedling emergence in sand with suitable accuracy.

Through the regression equation of each variable tested is was possible to present in Table 5 the results obtained experimentally and the results estimated by the equations. Comparison of the variables evaluated shows that the equations are fitted in a satisfactory manner because the results estimated generally have the same tendency as the results

Table 4. Regression equations and coefficient of determination (R2) for the germination (G), accelerated aging (AA), first germination count (FGC), seedling emergence in the field (SEF), tetrazolium vigor (TZVG), tetrazolium viability (TZVB), seedling vigor classification (SVC), and seedling emergence in sand (SES) variables as a function of the electrical conductivity test (EC).

Equation $Y = \beta_0 + \beta_1 X$	F test	R^2
G = 113.04 - 0.29 EC	82.71**	0.66
AA = 116.45 - 0.36 EC	120.61**	0.74
FGC = 113.94 - 0.34 EC	64.27**	0.60
SEF = 101.61 - 0.33 EC	68.90**	0.62
TZVG = 115.41 - 0.35 EC	101.63**	0.71
TZVB = 109.22 - 0.21 EC	31.02**	0.42
SVC = 89.56 - 0.36 EC	26.08**	0.38
SES = 111.86 - 0.26 EC	105.28**	0.71

**Significant at 1% probability of error by the F test.

obtained. Matera et al. (2019) worked with soybeans seeds and also found accuracy among the variables evaluated – most prominently for the electrical conductivity and percentage of seedling emergence in the field tests, with accelerated aging as the dependent variable.

Table 5 also shows that the lowest values of leaching

Table 5. Different levels of electrical conductivity and physiological performance of soybean seeds estimated (E) and observed (O) through the simple linear regression equation.

Vigor level		G		AA		FGC		SEF		TZVB		TZVG		SVC		SES	
	EC	E	O	E	O	E	O	E	O	E	O	E	O	E	O	E	O
Very high	50.00	98		99		97		85		99		98		72		99	
	55.00	97		97		95		83		98		96		70		98	
	58.28	96	98	96	97	94	98	82	80	97	99	95	96	69	84	97	96
	59.56	96	95	95	97	94	98	82	78	97	96	95	93	68	46	96	98
	60.09	96	96	95	95	94	98	82	79	96	98	94	96	68	85	96	96
	63.37	95	97	94	97	93	98	81	82	96	97	93	95	67	64	95	97
	63.47	95	96	94	97	93	97	81	78	96	98	93	95	67	72	95	98
	64.03	94	96	94	97	92	98	80	82	96	97	93	88	67	66	95	99
	65.00	94		93		92		80		95		93		66		95	
	70.00	93		92		90		78		94		91		65		94	
High	72.87	92	89	91	86	89	83	77	74	94	89	90	85	64	65	93	87
	74.60	91	93	90	92	89	87	77	76	93	94	89	88	63	62	92	92
	74.67	91	96	90	95	89	91	77	80	93	97	89	92	63	77	92	96
	75.92	91	91	89	89	88	89	76	78	93	94	89	89	63	65	92	92
	76.24	91	87	89	81	88	84	76	72	93	91	89	88	62	48	92	86
	77.48	90	92	89	91	88	73	76	79	93	91	88	85	62	74	92	93
	78.16	90	85	89	79	88	81	76	71	93	87	88	84	62	60	92	88
	80.00	90		88		87		75		92		87		61		91	
	82.83	89	91	87	88	86	83	74	76	92	95	86	91	60	53	90	88
	84.66	88	91	86	93	85	84	74	73	91	92	86	88	59	46	90	91
	85.12	88	91	86	85	85	89	73	76	91	95	86	90	59	60	90	87
	85.97	88	81	86	81	85	79	73	64	91	88	85	82	59	50	89	87
	87.31	88	90	85	82	85	89	73	78	91	92	85	87	59	59	89	92
	87.75	87	88	85	84	84	83	73	73	91	90	85	84	58	41	89	91
	89.79	87	90	85	88	84	80	72	76	90	93	84	86	58	71	88	88
	90.00	87		84		84		72		90		84		58		88	
Medium	94.74	85	85	83	84	82	83	70	77	89	93	82	86	56	58	87	87
	95.48	85	81	82	80	82	77	70	72	89	86	82	81	56	56	87	84
	96.28	85	89	82	88	82	87	70	73	89	95	82	88	55	62	87	93
	98.70	84	75	81	76	81	77	69	61	88	80	81	74	54	39	86	77
	99.52	84	73	81	73	80	66	69	59	88	76	81	70	54	53	86	79
	99.92	84	89	81	83	80	80	68	74	88	93	80	82	54	72	86	87
	100.32	84	81	81	76	80	80	68	70	88	85	80	80	54	45	86	89
	101.60	83	83	80	80	80	84	68	76	88	89	80	82	53	59	85	90
	101.82	83	89	80	88	80	84	68	57	88	90	80	78	53	50	85	88
	102.19	83	85	80	79	80	82	68	72	88	92	80	87	53	49	85	89
	102.40	83	82	80	81	80	78	68	72	88	91	80	86	53	65	85	86
	103.74	83	82	80	85	79	82	67	71	87	91	79	85	53	52	85	87
	103.82	83	85	80	77	79	78	67	62	87	90	79	81	53	46	85	79
	103.92	83	86	79	80	79	85	67	77	87	91	79	86	53	57	85	88
	104.49	83	70	79	72	79	69	67	58	87	72	79	65	52	41	85	81
	105.00	82		79		79		67		87		79		52		85	
	106.84	82	86	78	82	78	84	66	77	87	91	78	85	52	47	84	85
	107.16	82	88	78	89	78	87	66	79	86	91	78	86	51	71	84	88
	110.00	81		77		77		65		86		77		50		83	

Continue...

Table 5. Continuation.

Vigor level		G		AA		FGC		SEF		TZVB		TZVG		SVC		SES	
	EC	E	O	E	O	E	O	E	O	E	O	E	O	E	O	E	O
Low	50.00	98		99		97		85		99		98		72		99	
	116.53	79	80	75	75	75	82	63	62	85	80	75	74	48	53	82	82
	118.46	78	84	74	79	74	78	62	58	84	90	74	73	47	47	81	85
	120.00	78		74		74		62		84		73		47		81	
	122.08	77	83	73	70	73	84	61	62	83	87	73	71	46	45	80	77
	125.00	77		72		72		60		83		72		45		79	
	127.08	76	69	71	66	71	67	59	61	82	71	71	66	44	44	79	80
	130.00	75		70		70		58		82		70		43		78	
	135.00	74		68		69		57		81		68		42		77	
	140.00	72		67		67		55		80		66		40		75	
	145.00	71		65		65		54		78		65		38		74	
	147.66	70	71	64	68	64	66	53	47	78	84	64	64	37	40	73	71
	148.26	70	73	64	62	64	57	52	49	78	83	64	64	37	40	73	72
	150.00	69		63		64		52		77		63		36		73	

Electrical conductivity (EC), germination (G), tetrazolium viability (TZVB), tetrazolium vigor (TZVG), accelerated aging (AA), first germination count (FGC), seedling vigor classification (SVC), seedling emergence in the field (SEF), and seedling emergence in sand (SES), as estimated (E) and obtained (O).

corresponded to the highest values of germination, tetrazolium vigor and viability, accelerated aging, first germination count, seedling vigor classification, seedling emergence in the field and seedling emergence in sand. The electrical conductivity test proved to be a good indicator of seed physiological potential.

The values of electrical conductivity related to the other vigor tests estimated by simple linear regression were efficient for separating the soybean seed lots into different vigor levels: very high – for lots that have EC ≤ 70 $\mu S.cm^{-1}.g^{-1}$; high – for lots with EC from 71 to 90 $\mu S.cm^{-1}.g^{-1}$, such that these two vigor levels showed good performance of the seed lots in the field under low soil moisture conditions, just as occurred in the trial of seedling emergence in the field; medium – lots that have EC from 91 to 110 $\mu S.cm^{-1}.g^{-1}$, which are lots inappropriate for sowing under water deficit conditions in the field; and low – lots that have EC ≥ 111 $\mu S.cm^{-1}.g^{-1}$, which are considered lots not viable for sowing. Similar classifications were mentioned for soybean seeds by Vieira (1994), indicating seed lots with EC values of 60-70 $\mu S.cm^{-1}.g^{-1}$ as high vigor, and from 70 to 80 $\mu S.cm^{-1}.g^{-1}$ as medium vigor. For sunflower seeds, Szemruch et al. (2015) proposed EC < 70 $\mu S.cm^{-1}.g^{-1}$ as high vigor, 70 to 110 $\mu S.cm^{-1}.g^{-1}$ as intermediate vigor and EC > 110 $\mu S.cm^{-1}.g^{-1}$ as low vigor.

Studies of the relationship between the results of the electrical conductivity test and those of the soybean seedling emergence in the field and in the laboratory test showed that seed lots with EC values up to 110 $\mu S.cm^{-1}.g^{-1}$ can be considered high performance lots as long as they are under adequate field environment conditions, without stress. However, for seed lots exposed to limited water restriction, the critical limit for EC is 90 $\mu S.cm^{-1}.g^{-1}$ (Vieira et al., 2004). In this regard, Colete et al. (2004) described the need to infer the performance potential of the seeds and under which conditions a determined seed lot can be recommended.

Restrictions on routine use of the electrical conductivity test as a vigor test center on the lack of reference values or range of values that indicate a lot as being of high, medium, or low vigor, as well as understanding of users in relation to the results, which are in a unit that is not as well understood by the seed community. Most of the main tests used give their results in percentage.

One possibility for defining a vigor standard for soybean seeds by the electrical conductivity test is proceeding in a way similar to the proposal made for pea seeds (Matthews and Powell, 1981), i.e., such that the vigor levels by electrical conductivity can indicate field performance of the soybean seed lots in accordance with environmental conditions. It was under this assumption that Table 6 was elaborated, with values and directives regarding the use of soybean seed lots, considering studies (Colete et al., 2004 and Vieira et al., 2004) already conducted with indications within this context.

From a practical point of view, we are aware that its use may still generate questions and difficulties, yet this is of practical and fundamental importance for it to be able to stimulate new studies considering other environments and different crops to verify its effectiveness. For the seed production company, it can be a useful tool for the initial route toward including the test in the quality control program. In this case, the company will be able to have a greater number of seed lots available and

Table 6. Recommendations for use of soybean seed lots in accordance with the value of electrical conductivity ($\mu S.cm^{-1}.g^{-1}$) of the seed lot.

EC ($\mu S.cm^{-1}.g^{-1}$)	Vigor	Recommendation for use of the seed lot
≤ 70	Very high	Good performance of the seed lots in the field under low soil moisture conditions.
71 to 90	High	
91 to 110	Medium	Seed lots inappropriate for sowing under water deficit conditions in the field.
≥ 111	Low	Seed lots unviable for sowing.

will be able to consider possible effects of genotype, as already reported (Panobianco et al., 1996, 1999; Vieira et al., 1996).

Conclusions

The electrical conductivity test has high potential for use in quality control programs of soybean seed lots.

The electrical conductivity test allows separation of seed lots into vigor levels: very high: EC ≤ 70 $\mu S.cm^{-1}.g^{-1}$; high: EC from 71 to 90 $\mu S.cm^{-1}.g^{-1}$; medium: EC from 91 to 110 $\mu S.cm^{-1}.g^{-1}$ and low: EC ≥ 111 $\mu S.cm^{-1}.g^{-1}$, related to performance in the field and in the tests of evaluation of the physiological potential of soybean seed lots.

References

BARBIERI, A.P.P.; MATTIONI, N.M.; HAESBAERT, F.M.; ANDRADE, F.F.; CABRERA, I.C.; MERTZ, L.M. Teste de condutividade elétrica individual em sementes de soja e a relação com emergência de plântulas a campo. *Interciência*, v.38, n.4, p.310-315, 2013. http://www.redalyc.org/articulo.oa?id=33926985001

BARROS, A.S.R.; MARCOS-FILHO, J. Testes para avaliação rápida do vigor de sementes de soja. *Revista Brasileira de Sementes*, v.19, n.2, p.288-294, 1997.

BEWLEY, J.D.; BRADFORD, K.; HILHORST, H.; NONOGAKI, H. *Seeds*: physiology of development, germination and dormancy. 3. ed. New York: Springer, 2013. 408p.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. *Regras para análise de sementes.* Ministério da Agricultura, Pecuária e Abastecimento. Secretaria de Defesa Agropecuária. Brasília: MAPA/ACS, 2009. 395p. http://www.agricultura.gov.br/assuntos/insumos-agropecuarios/arquivos-publicacoes-insumos/2946_regras_analise__sementes.pdf

CANTERI, M.G.; ALTHAUS, R.A.; VIRGENS-FILHO, J.S.; GIGLIOTI, E.A.; GODOY, C.V. SASM- Agri: sistema para análise e separação de médias em experimentos agrícolas pelos métodos Scoft-Knott, Tukey e Duncan. *Revista Brasileira de Agrocomputação*, v.1, n.2, p.18-24, 2001. http://www.alice.cnptia.embrapa.br/alice/handle/doc/512901

CARVALHO, N.M.; NAKAGAWA, J. *Sementes:* ciência, tecnologia e produção. 4. ed. Jaboticabal: FUNEP, 2000. 424p.

COLETE, J.C.; VIEIRA, R.D.; DUTRA, A.S. Electrical conductivity and soybean seedling emergence. *Scientia Agricola,* v.61, n.4, p.386-391, 2004. http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0103-90162004000400006

DIAS, D.C.F.S.; MARCOS-FILHO, J. Testes de vigor baseados na permeabilidade das membranas celulares: I. Condutividade elétrica. *Informativo ABRATES*, v.5, n.1, p.26-36, 1995.

FESSEL, S.A.; PANOBIANCO, M.; SOUZA, C.R.; VIEIRA, R.D. Teste de condutividade elétrica em sementes de soja armazenadas sob diferentes temperaturas. *Bragantia*, v.69, n.1, p.207-214, 2010. http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0006-87052010000100026

FESSEL, S.A.; VIEIRA, R.D.; CRUZ, M.C.P.; PAULA, R.C.; PANOBIANCO, M. Electrical conductivity testing of corn seeds as influenced by temperature and period of storage. *Pesquisa Agropecuária Brasileira,* v.41, n.10, p.1551-1559, 2006. http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-204X2006001000013

FRANÇA-NETO, J.B. Evolução do conceito de qualidade de sementes. *Informativo ABRATES*, v.19, n.2, p.76-80, 2009. https://ainfo.cnptia.embrapa.br/digital/bitstream/item/98570/1/Evolucao-do-conceito-de-qualidade-de-sementes.pdf

FRANÇA-NETO, J.B. Testes de tetrazólio para determinação do vigor de sementes. In: KRZYZANOWSKI, F.C.; VIEIRA, R.D.; FRANÇA-NETO, J.B. (ed.). *Vigor de sementes:* conceitos e testes. Londrina: ABRATES, 1999. p.1-28.

ISTA. International Seed Testing Association. *International rules for seed testing.* Bassersdorf: International Seed Testing Association, 2011.

MARCOS-FILHO, J. *Fisiologia de sementes de plantas cultivadas.* Londrina: ABRATES, 2015. 659p.

MARCOS-FILHO, J. Importância do potencial fisiológico da semente de soja. *Informativo ABRATES*, v.23, n.1, p.21-24, 2013. https://www.abrates.org.br/img/informations/950ff7fa-c03a-4960-a520-f6cb0870babe_IA%20vol.23%20n.1.pdf

MARCOS-FILHO, J. Testes de vigor: dimensão e perspectivas. *Seed News*, ed.15, n.1, 2011. https://seednews.com.br/edicoes/artigo/1111-testes-de-vigor:-dimensao-e-perspectivas-edicao-janeiro-2011

MARCOS-FILHO, J. Testes de vigor: importância e utilização. In: KRZYZANOWSKI, F.C.; VIEIRA, R.D.; FRANÇA-NETO, J.B. (ed.). *Vigor de sementes:* conceitos e testes. Londrina: ABRATES, 1999. p.1-21.

MARCOS-FILHO, J.; VIEIRA, R.D. Seed vigor tests: procedures – conductivity tests. In: BAALBAKI, R.; ELIAS, S.; MARCOS-FILHO, J.; MCDONALD, M.B. (org.). *Seed vigor tests handbook.* Ithaca: AOSA, 2009. p.186-200.

MATERA, T.C.; PEREIRA, L.C.; BRACCINI, A.L.; KRZYZANOWSKI, F.C.; SCAPIM, C.A.; PIANA, S.C.; MARTELI, D.C.V.; PEREIRA, R.C.; FERRI, G.C.; SUZUKAWA, A.K. Accelerated aging test and its relationship to physiological potential of soybean seeds. *Journal of Seed Science*, v.41, n.3, p.301-308, 2019. https://dx.doi.org/10.1590/2317-1545v41n3212746

MATTHEWS, S.; POWELL, A.A. Electrical conductivity test. In: PERRY, D.A. (ed.) *Vigour Test Handbook*. Zurich: ISTA, 1981. p.37-41.

NAKAGAWA, J. Testes de vigor baseados no desempenho das plântulas. In: KRZYZANOWSKI, F.C.; VIEIRA, R.D.; FRANÇA-NETO, J.B. (ed.). *Vigor de sementes:* conceitos e testes. Londrina: ABRATES, 1999. p.1-24.

PANOBIANCO, M.; VIEIRA, R.D. Electrical conductivity of soybean soaked seeds: I – Effect of genotype. *Pesquisa Agropecuária Brasileira*, v.31, p.621-627, 1996.

PANOBIANCO, M.; VIEIRA, R.D. ; KRZYZANOWSKI, F.C. ; FRANÇA-NETO, J.B. Electrical conductivity of soybean seed and correlation with seed coat lignin content. *Seed Science and Technology*, v.27, n.3, p.945-949, 1999. https://www.researchgate.net/publication/285910969_Electrical_conductivity_of_soybean_seed_and_correlation_with_seed_coat_lignin_content

PIMENTEL-GOMES, F.; GARCIA, C.H. *Estatística aplicada a experimentos agronômicos e florestais:* exposição com exemplos e orientações para uso de aplicativos. Piracicaba: FEALQ, 2002. p.21.

SCHUAB, S.R.P.; BRACCINI, A.L.; FRANÇA-NETO, J.B.; SCAPIM, C.A.; MESCHEDE, D.K. Potencial fisiológico de sementes de soja e sua relação com a emergência das plântulas em campo. *Acta Scientiarum Agronomy,* v.28, n.4, p.553-561, 2006. http://periodicos.uem.br/ojs/index.php/ActaSciAgron/article/view/928/928

SZEMRUCH, C.; DEL LONGO, O.; FERRARI, L.; RENTERIA, S.; MURCIA, M.; CANTAMUTTO, M.; RONDANINI, D. Ranges of vigor based on the electrical conductivity test in dehulled sunflower seeds. *Research Journal of Seed Science,* v.8, p.12-21, 2015. https://scialert.net/fulltext/?doi=rjss.2015.12.21

TEKRONY, D.M., BUSTAMAM, T.; EGLI, D.B.; PFEIFFER, T.W. Effects of soybean seed size, vigor and maturity on crop performance in row and hill plots. *Crop Science,* v.27, n.5, p.1040-1045, 1987. https://dl.sciencesocieties.org/publications/cs/pdfs/27/5/CS0270051040

VIEIRA, R.D. Teste de condutividade elétrica. In: VIEIRA, R.D.; CARVALHO, N.M. (ed.). *Testes de vigor em sementes.* Jaboticabal: FUNEP, 1994. p.103-132.

VIEIRA, R.D.; PANOBIANCO, M.; LEMOS, L.B.; FORNASIERI-FILHO, D. Efeito de genótipos de feijão e de soja na condutividade elétrica de sementes. *Revista Brasileira de Sementes*, v.18, p.220-224, 1996.

VIEIRA, R.D.; KRZYZANOWSKI, F.C. Teste de condutividade elétrica. In: KRZYZANOWSKI, F.C.; VIEIRA, R.D.; FRANÇA-NETO, J.B. (ed.). *Vigor de sementes:* conceitos e testes. Londrina: ABRATES, 1999. p.1-26.

VIEIRA, R.D.; PAIVA AGUERO, J.A.; PERECIN, D. Electrical conductivity and field performance of soybean seeds. *Seed Technology,* v.21, n.1, p.15-24, 1999. https://www.jstor.org/stable/pdf/23433438.pdf?seq=1\l%20%22page_scan_tab_contents#page_scan_tab_contents

VIEIRA, R.D.; SCAPPA-NETO, A.; BITTENCOURT, S.R.M.; PANOBIANCO, M. Electrical conductivity of the seed soaking solution and soybean seedling emergence. *Scientia Agricola,* v.61, n.2, p.164-168, 2004. http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0103-90162004000200007

VIERA, R.D.; BITTENCOURT, S.R.M.; PANOBIANCO, M. Seed vigour – an important component of seed quality in Brazil. *Seed Testing International*, n.126, p.21-22, 2003. https://www.seedtest.org/upload/cms/user/STI126Oct2003.pdf

ZOU, K.H.; TUNCALI, K.; SILVERMAN, S.G. Correlation and simple linear regression. *Radiology,* v.227, n.3, p.617-622, 2003. https://doi.org/10.1148/radiol.2273011499