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Physiological Quality of Soybean Seeds as a Function of Soil Management Systems and Pre-Harvest Desiccation

Gustavo Ferreira da Silva *, Larissa Chamma, Bruno Cesar Ottoboni Luperini, Prínscilla Pâmela Nunes Chaves, Juliano Carlos Calonego, João Nakagawa and Edvaldo Aparecido Amaral da Silva

Department of Crop Science, School of Agriculture, São Paulo State University (UNESP), Botucatu 18610-034, Brazil

* Correspondence: gustavo.ferreira@unesp.br

Abstract: Soil management systems directly interfere in the soil–plant relationship. However, there are still few studies evaluating the influence of long-term management systems on the physiological quality of soybean seeds. Another little-known topic is the influence of pre-harvest desiccation on the physiological quality of soybean seeds, especially on seed longevity. Thus, the aim of this research was to evaluate the physiological quality of soybean seeds cultivated under conventional tillage and no-tillage systems with and without desiccant use. The experiment was carried out in design is a split plot in a randomized complete block design. The treatments consisted of soil management systems (conventional tillage and no-tillage), with and without pre-harvest desiccation. In the treatment with desiccation, the herbicide Paraquat was applied, when the plants were at the R7.3 phenological stage (most of the seeds had a yellowish coat, with a shiny surface and were already detached from the pod). Seed germination, vigor (first germination count, seedling dry mass, seedling length, time to reach 50% germination (T50), seedling emergence and emergence speed index) and longevity (P50) were evaluated. Seeds cultivated under conventional tillage showed greater vigor for most traits evaluated, with values of T50 and seedling length higher by 24.39% and 24.77%, respectively, compared to NT. In addition, non-desiccation increased the seedling length and dry mass, in 15.45% and 21.59%, respectively. The use of desiccant aiming at seed vigor is dependent on the soil management system. Soybean seed longevity was superior in the no-tillage system, but desiccant application reduced seed longevity.

Keywords: conventional tillage; desiccation; *Glycine max*; longevity; no-tillage; soybean seed

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Citation: Silva, G.F.d.; Chamma, L.; Luperini, B.C.O.; Chaves, P.P.N.; Calonego, J.C.; Nakagawa, J.; Silva, E.A.A.d. Physiological Quality of Soybean Seeds as a Function of Soil Management Systems and Pre-Harvest Desiccation. *Agronomy* **2023**, *13*, 847. https://doi.org/10.3390/agronomy13030847

Academic Editors: Umberto Anastasi and Aurelio Scavo

Received: 14 February 2023
Revised: 7 March 2023
Accepted: 11 March 2023
Published: 14 March 2023

1. Introduction

Soybean [*Glycine max* (L.) Merill] has a great impact on the world economy, so any factor that interferes with its development and yield has become relevant. Thus, soil management systems are important to soybean farming, as they aim to promote ideal soil conditions for crop development [1]. There are many different management systems; however, conventional tillage (CT) and no-tillage (NT) are the most common [2].

CT is characterized by soil turning, usually to a depth of 0.20–0.30 m, promoting weed control and satisfactory conditions for crop development. However, due to soil mobilization, plant residues are incorporated, which accelerates the straw decomposition process. In addition, the soil becomes more susceptible to water erosion [3–5].

NT represents a milestone in water and soil conservation in agricultural systems, due to its precepts, such as no soil turning, crop rotation and soil maintenance through straw covering [6]. This system promotes positive alterations in the physical, chemical and biological soil quality, directly interfering in soybean productivity [7–9].

Although there are many reports about the influence of soil management systems on their properties and in soybean yield [10,11], little is known about the influence of NT and CT on soybean physiological quality, mainly seed longevity.

Physiological quality is acquired during the phases of seed development and comprises the acquisition of germination, vigor and storage capacity (longevity) [12], during embryogenesis, grain filling (maturation) and late maturation [13].

Physiological maturity is characterized by the moment when the seed no longer receives nutrients from the mother plant [14]. However, research has revealed that for soybean, the process of acquiring physiological quality continues after the seed is disconnected from the plant [15], making evident the importance of the late maturation phase for the acquisition of seed longevity [16]. During the late maturation phase, longevity increases two-fold until the R9 stage, which corresponds to a mature seed [12,17].

Despite the importance of the late maturation process in soybean seeds for the complete acquisition of seed physiological quality, the use of desiccants in seed production is still common. Desiccation is usually carried out at stages R7.2 (plants with 51% to 75% of leaves and pods yellow) or R7.3 (plants with more than 76% of leaves and pods yellow), with the intent of anticipating the harvest, in order to reduce the seeds exposure to climatic conditions and attacks of pests and diseases at the end of the crop cycle [18–20].

The desiccation process provides advantages related to seed moisture reduction, maturation uniformity and, mainly, and preservation of seed physiological quality, due to the shorter period of exposure in the field, minimizing the irreversible damages of deterioration by moisture [20–22]. However, current research shows that the use of desiccants can reduce the quality of soybean seeds [23–25]. In addition to this factor, it is still unknown whether the soil management system interferes with the soybean seed response to the desiccation process. Thus, the hypothesis of this research is that lower soil thermal amplitude, greater soil moisture conservation and nutrient cycling provided by straw and crop rotation in the no-tillage system, are less stressful for plants and favor greater nutrient absorption, thus contributing to better acquisition of seed physiological quality even under desiccation use. Therefore, the aim of this research was to evaluate the physiological quality of soybean seeds cultivated under a conventional tillage and a no-tillage system with and without desiccant use.

2. Materials and Methods

2.1. Site Description and Experimental Area

The field experiment was carried out at an experimental farm located at Botucatu, SP, Brazil (22°48′57″ S, 48°25′41″ W; 786 m a.s.l.), on a typical Rhodudalf soil, classified as clayey-textured, with chemical and textural characteristics shown in Table 1.

Table 1. Chemical, granulometric and physic soil analysis of seed production experimental area in conventional soil tillage system (CT) and no-tillage (NT), at 0.00–0.20 m depth.

Management System	pH	OM	P	S	H + Al	Ca	Mg	K	Sand	Silt	Clay
	$CaCl_2$		mg dm^{-3}			mmol$_c$ dm^{-3}				g kg^{-1}	
CT	5.0	27.1	61.2	3.6	36.3	39.5	12.7	4.7	147	239	614
NT	5.4	30.9	84.4	4.4	29.6	43.5	14.8	3.3			
	Mac	**Mic**	**TP**	**Bd**		**PR**					
		cm^3 cm^{-3}			g cm^{-3}	MPa					
CT	0.09	0.44	0.53	1.15		1.62					
NT	0.07	0.44	0.51	1.33		3.33					

pH: active acidity; OM: organic matter; P: exchangeable phosphorus; S: sulphur; H + Al: potential acidity; Ca: exchangeable calcium; Mg: exchangeable magnesium; K: exchangeable potassium; Mac: macroporosity; Mic: microporosity; TP: total porosity; Bd: bulk density; PR: penetration resistance; $CaCl_2$: 0.01 M calcium chloride solution; mg dm^{-3}: milligram per cubic decimeter; mmol$_c$ dm^{-3}: millimol charge per cubic decimeter; g kg^{-1}: gram per kilogram; cm^3 cm^{-3}: cubic centimeter per cubic centimeter; g cm^{-3}: gram per cubic centimeter; MPa: megapascal.

The study used seeds produced in a long-term experimental field, which has been used since 1985 under conventional tillage (CT) and no-tillage (NT) systems. In plots managed under CT, soil preparation is carried out with plowing and harrowing, as shown in Table 2. AIn a NT system, the soil has not been disturbed since 1985, as shown in Table 2.

Table 2. Soil management systems and crop succession used since 1985, highlighting management and species cultivated in fall-winter and spring-summer seasons of each agricultural year.

Year	Management System				Season
	Conventional Tillage		No-Tillage		Fall-Winter/Spring-Summer
	Fall	Spring	Fall	Spring	
1985/86	Plowing + harrowing	Plowing + harrowing	Plowing + harrowing	No-tillage	Wheat/soybean
1986/87 to 1994/95	Plowing + harrowing	Plowing + harrowing	No-tillage	No-tillage	Wheat/soybean
1995/96 to 1998/99	Without soil mobilization	Without soil mobilization	No-tillage	No-tillage	Fallow/fallow
1999/00	Plowing + harrowing	Plowing + harrowing	No-tillage	No-tillage	Black oat/maize
2000/01 and 2001/02	Without soil mobilization	Without soil mobilization	No-tillage	No-tillage	Fallow/fallow
2002/03 and 2003/04	Plowing + harrowing	Plowing + harrowing	No-tillage	No-tillage	Black oat/millet-bean
2004/05 and 2005/06	Plowing + harrowing	Plowing + harrowing	No-tillage	No-tillage	Black oat/maize
2006/07	Without soil mobilization	Without soil mobilization	No-tillage	No-tillage	Fallow/soybean
2007/08	Plowing + harrowing	Without soil mobilization	No-tillage	No-tillage	Yellow oat/bean
2008/09	Plowing + harrowing	Without soil mobilization	No-tillage	No-tillage	Yellow oat/bean
2009/10 to 2011/12	Plowing + harrowing	Without soil mobilization	No-tillage	No-tillage	Black oat/maize + brachiaria
2012/13	Without soil mobilization	Plowing + harrowing	No-tillage	No-tillage	Brachiaria/soybean
2013/14	Without soil mobilization	Plowing + harrowing	No-tillage	No-tillage	Wheat/soybean
2014/15	Without soil mobilization	Plowing + harrowing	No-tillage	No-tillage	Safflower/soybean
2015/16	Without soil mobilization	Plowing + harrowing	No-tillage	No-tillage	Safflower/maize
2016/17	Plowing + harrowing	Without soil mobilization	No-tillage	No-tillage	Black oat/maize
2017/18	Plowing + harrowing	Without soil mobilization	No-tillage	No-tillage	Black oat/soybean
2018/19	Plowing + harrowing	Without soil mobilization	No-tillage	No-tillage	Sorghum/soybean
2019/20	Plowing + harrowing	Without soil mobilization	No-tillage	No-tillage	Sorghum/soybean

The region climate, according to the Köppen classification, is CWa type, mesothermic climate with dry winter. The data on maximum, average and minimum temperatures and rainfall during the period of conducting the experiments in the crop seasons 2018/19 and 2019/2020 are shown in Figure 1.

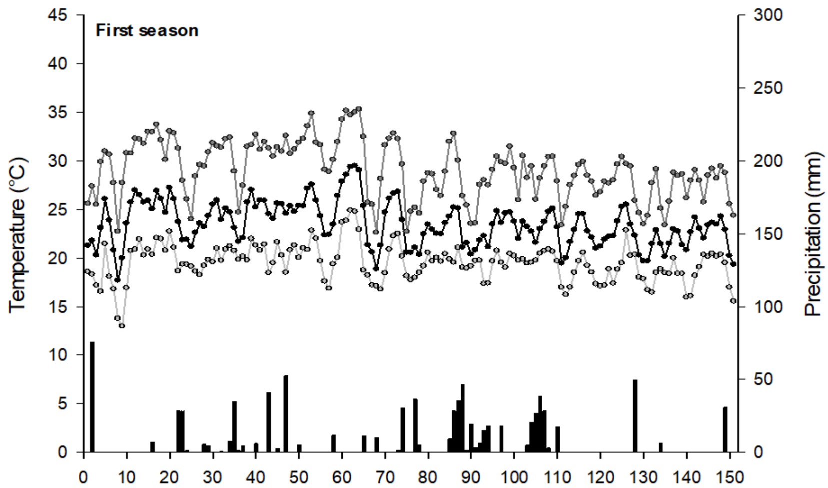

Figure 1. *Cont.*

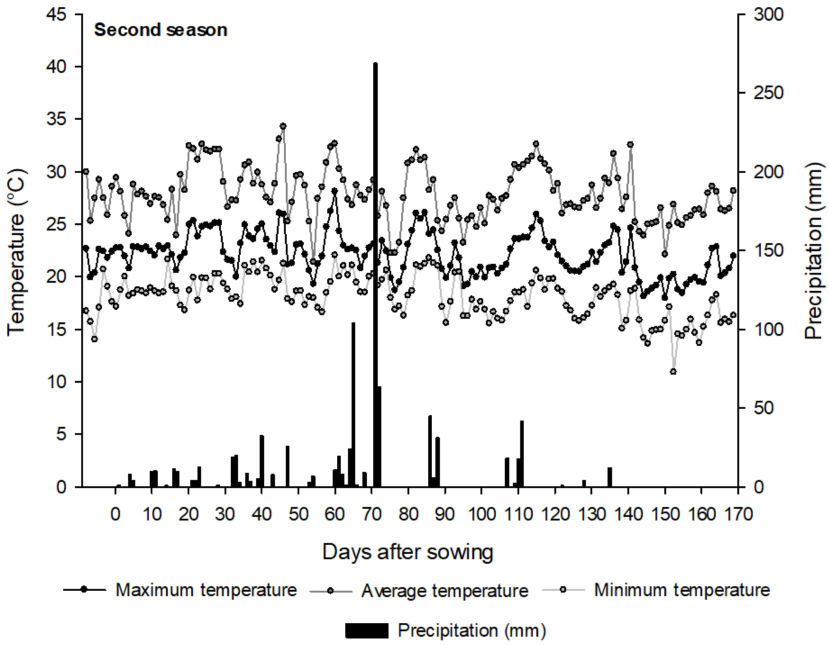

Figure 1. Maximum, average and minimum temperature and rainfall during the two soybean crop seasons.

2.2. Experimental Design and Management

The experiment was carried out in a randomized block design, in a split-plot scheme, with four replications. The plots (50 m × 9 m) were constituted of two subplots (25 m × 9 m), each with a different soil management system, conventional tillage (CT) and no-tillage (NT). These subplots were further divided into two, one with desiccant application (D) and one without (ND).

The experiment was performed during the 2018/19 (first season) and 2019/20 (second season) seasons, using soybean cultivar TMG 7062. The first season sowing was carried out on 17 December 2018 and the second on 6 December 2019, using a spacing of 0.45 m between rows, aiming for a density of 300 thousand plants ha^{-1}, using seeds treated with fungicide Carboxin + Thiram, insecticide Thiamethoxam, inoculant *Bradyrhizobium* sp., and micronutrients Co and Mo. Sowing fertilization was conducted with 60 kg ha^{-1} of K_2O and 60 kg ha^{-1} of P_2O_5, using KCl and simple superphosphate, respectively. In both seasons, soybean was cultivated in succession to sorghum cultivated during fall-winter (Table 2), which supplied the straw for the NT system (NT: 4500 and 4150 kg ha^{-1} of straw in the first and second season, respectively; CT: 3800 and 3200 kg ha^{-1} of straw in the first and second season, respectively). In CT, the soil was turned over only in April, before the sorghum sowing, with a harrow at a depth of 0.00–0.20 m (Table 2).

Soybean phytosanitary management involved weed control with the application of herbicide Glyphosate (1.8 kg a.i. ha^{-1}) associated with herbicide Sethoxidim (1.25 kg a.i. ha^{-1}). The fungicides Pyraclostrobin + Epoxiconazole (0.08 + 0.03 kg a.i. ha^{-1}, respectively) and Azoxystrobin + Cyproconazole (0.06 + 0.024 kg a.i. ha^{-1}, respectively) and the insecticides Thiamethoxam + Lambda-Cialotrin (0.028 + 0.21 kg a.i. ha^{-1}) were applied preventively.

Pre-harvest desiccation was carried out using herbicide paraquat (0.4 kg a.i. ha^{-1}; 200 L ha^{-1} of spray volume) at the R7.3 stage, when most of the seeds had a yellowish coat, with a shiny surface and were already detached from the pod [11,25,26]. The seed water content was of 55 ± 1% and more than 76% of the leaves and pods of the plants in the field were yellow. The desiccant application was carried out with a Jacto Falcon AM14/Vortex sprayer, with flat jet tips (fan) model ADI 11002, without wind and with an air temperature of 20 °C.

In the ND treatment, seeds were harvested when they reached the R9 stage, known as the harvest point, in which the seeds have a dry appearance and a water content below

15% [12,26,27]. Phenological stage characterization at the time of harvest considered the visual characteristics of the plants and seeds.

In the first season, harvest of treatments with desiccation (D) was carried out on 13 March 2019 and the treatments without desiccation (ND) on 16 March 2019; in the second season the desiccated plants (D) were harvested on 15 March 2020 and the non-desiccated (ND) on 19 March 2020. It should be noted that, during this period that the plants remained in the field, after the plant desiccation, there was no rain, and the climatic conditions were similar to the day of harvesting the seeds of the treatment with desiccation (Figure 1).

The pods were harvested and threshed manually and, later, the seeds were stored in a cold chamber (10 °C and 40% relative humidity) for 15 days to stabilize the water content.

2.3. Seed Quality Assessment

After the storage period in a cold chamber, the seed water content was evaluated by the oven method, at 105 ± 3 °C for a period of 24 h [28], with three replications of 15 seeds. Results were expressed as percentage of water on a wet basis.

The germination test was performed with four replications of 25 seeds, using a roll of paper moistened with distilled water equivalent to 2.5 times the dry mass of the paper. The rolls were placed in a germinator at 25 °C. The germination percentage was scored by counting normal seedlings at five (first germination count) and eight days (total germination) [28].

To evaluate radicle protrusion, four replicates of 25 seeds were used, arranged in Petri dishes, using three sheets of filter paper as substrate, which were moistened with distilled water equivalent to 2.5 times the paper dry mass. The Petri dishes were placed in a germinator at 25 °C. The evaluations were carried out every 6 h, counting the number of seeds that presented a radicle with two millimeters of length. The time required to reach 50% germination of viable seeds (T50) was calculated by analyzing the cumulative germination data using the curve-fitting model of the Germinator software [29] and the results were expressed in hours.

For the length and dry mass of seedlings, four replications of 10 seeds from each batch were used, arranged in a roll of paper moistened with distilled water equivalent to 2.5 times the paper dry mass. The seeds were arranged on a line drawn longitudinally in the upper third of the paper, with the seed hilum facing the lower portion of the paper, in order to guide the seedling growth in a straighter line [30]. Paper rolls were conditioned and tilted at 90° in a germinator at 25 °C in the dark. The seedling average length was measured on the seventh day after the beginning of the test. After analyzing the length, the seedlings were kept in an air circulation oven at a temperature of 60 °C to obtain the seed dry weight and the result were expressed in grams.

To evaluate the emergence speed index (ESI), daily counts were performed, considering as emerged seedlings those whose cotyledons were above ground level, at an angle greater than or equal to 90° in relation to the seedling stem, until there were no more emergences. The ESI test was performed on sand under field conditions. Data were submitted to the formula proposed by Maguire [31], in which:

$$ESI = E1/N1 + E2/N2 + \ldots\ En/Nn \quad (1)$$

where: E1, E2, ... En, refers to the number of emerged seedlings computed in the first, second and last counts; N1, N2, ... Nn refers to the number of days from sowing to the first, second and last count. At the end of the test, the total number of emerged seedlings was determined.

For longevity assessment, seeds of each lot were kept at 75% RH (using saturated NaCl solution) and 20 °C for 24 h and then stored in airtight boxes with a saturated NaCl solution and stored at 35 °C and 75% RH [32]. Germination of the seeds was evaluated from the fifth day after beginning of storage until the loss of protrusion capacity. For this, at each moment of evaluation, 25 seeds were removed from each treatment to mount the germination test. Since the intervals between evaluations were shorter at the beginning of storage, and from the moment that a marked loss of germination capacity of the seeds was verified, the tests were carried out at intervals of longer days. From the results obtained, the sigmoidal curve was analyzed for each batch and the longevity was expressed in P50 (time in days to loss 50% of viability) [27].

2.4. Determination of Nutrient in the Seeds

Sulfuric digestion was used to obtain an extract in order to determine the content of N, while P, K, Ca, Mg, S, Cu, Fe, Zn and Mn content in seeds were extracted by nitroperchloric acid digestion and determined by atomic absorption spectrophotometry, as described by AOAC [33].

2.5. Statistical Analysis

Data were tested for normality using the Anderson–Darling test, and homoscedasticity was checked using the Hartley test. Data were submitted to the analysis of variance and the mean differences were discriminated by *t*'s test at 5% probability.

The variables of physiological quality and nutrient content of the seeds were submitted to Pearson's correlation analysis, at the level of 5% of probability. All statistical analyzes were performed in the R software version 3.6.1.

3. Results

The seed water content ranged from 9.0 to 9.8%, without significant differences. The soil management system and desiccant application, in both seasons, did not influence soybean seed germination. However, there was significance for the isolated factors in the vigor and longevity of the seeds (Table 3), but there was no significant interaction between the tested factors.

Table 3. Mean values of germination (%), first germination count (FGC—%), time to reach 50% germination (T50—hours), seedling length (cm), seedling dry mass (g), emergence speed index (ESI) and mean time to loss of 50% viability during storage (P50—days) of soybean seeds as a function of the soil management system and desiccant application.

	First Season		Second Season	
	Conventional Tillage	**No-Tillage**	**Conventional Tillage**	**No-Tillage**
Germination	91.7 a	89.0 a	92.0 a	89.0 a
FGC	91.0 a	80.5 b	83.0 a	78.0 a
T50	48.0 a	54.4 a	57.0 a	43.1 b
Length	21.76 a	23.6 a	21.8 a	16.4 b
Dry mass	0.3405 a	0.3609 a	*	*
ESI	*	*	9.09 a	7.84 b
P50	40.84 a	41.03 a	31.21 b	44.30 a
	With desiccant	**Without desiccant**	**With desiccant**	**Without desiccant**
Germination	90.0 a	90.8 a	91.5 a	89.5 a
FGC	86.8 a	84.8 a	84 a	77 a
T50	49.7 a	52.8 a	49.2 a	50.8 a
Length	20.8 b	24.6 a	19.0 a	19.1 a
Dry mass	0.3083 b	0.3932 a	*	*
ESI	*	*	8.17 a	8.76 a
P50	37.20 b	44.67 a	33.72 b	41.80 a

Means followed by the same lowercase letter on the row do not differ from each other by the *t* test at the 5% probability level. *: there was no isolated significance of the factors.

Regarding seed vigor, the soil management systems affected the variables of first germination count (FGC), time for 50% of seeds to germinate (T50), seedling length and emergence speed index (ESI).

In the first season, the results of FGC in CT were higher than those obtained in NT. In the second season, there was no difference between soil management systems ($p > 0.05$), even with 6.02% more seeds germinated in FCG (Table 3) in CT.

The T50 and seedling length results were influenced by the soil management system only in the second season, with higher values of 24.39% and 24.77%, respectively, in seeds produced in CT (Table 3). Seeds produced in CT also showed higher ESI values in the second season.

Regarding the desiccation factor, the effect on seed vigor was verified in the variables of length and dry mass of seedlings in the first season. In this season, the ND treatment favored seedling growth by 15.45% and dry mass accumulation by 21.59% (Table 3), when compared to seedlings from seeds produced with pre-harvest desiccation.

Dry mass (second season), emergence (first and second seasons) and ESI (first season) showed a significant interaction between soil management and desiccant application factors (Table 4).

Table 4. Means values of dry mass of seedling (g), emergence of seedlings (%) and emergence speed index of soybean seedlings from seeds produced under different soil management systems and desiccant application.

	Dry Mass (g)			
	First Season		**Second Season**	
	With Desiccant	**Without Desiccant**	**With Desiccant**	**Without Desiccant**
Conventional tillage	ns	ns	0.3058 bB	0.4143 aA
No-tillage	ns	ns	0.4312 aA	0.4493 aA
	Emergence (%)			
Conventional tillage	56.5 bB	87.0 aA	51.0 bB	78.5 aA
No-tillage	72.5 aA	57.5 bB	65.5 aA	51.5 bB
	Emergence speed index			
Conventional tillage	7.02 bB	9.88 aA	ns	ns
No-tillage	6.99 aA	5.67 bB	ns	ns

Means followed by the same lowercase letter in the column and uppercase in the row do not differ from each other by the t test at the 5% probability level. ns: there was no significant interaction between the factors.

In the second season, desiccation reduced the dry mass of seedlings by 26% in CT, but did not affect this variable in NT. In the comparison between management systems, significant differences ($p < 0.05$) were obtained only in treatments with desiccation, where the dry mass of seedlings in chemical management in CT was 29% lower than that obtained in NT (Table 4).

A similar behavior was observed for emergence (first and second seasons) and ESI (first season), where in CT, the desiccant application reduced emergence and ESI by approximately 35% and 29%, respectively. In NT with desiccant application, these variables increased by 21% and 19%, respectively (Table 4).

In general, conventional soil preparation provides more vigorous seed production. However, the response to desiccant application varies depending on the soil management system. In CT there is better seed quality without application, while in NT the desiccant application favors the soybean seed vigor (Tables 3 and 4).

However, the same behavior was not observed in seed longevity (P50). For this trait, the soil management system influenced the response only in the second season, with NT providing a 30% increase in seed storage time without affecting their quality, compared to conventional soil preparation (Table 3). The desiccant factor showed a difference in both seasons, and the absence of desiccant increased seed longevity by 16.72% in the first season and 19.33% in the second season (Table 3).

The physiological quality results of soybean seeds as a function of soil management and desiccant application can be explained by the correlation between the physiological quality variables of the seeds and the nutrient contents exported to them, as can be seen in Table 5.

Table 5. Correlation between variables of seed physiological quality and macro and micronutrient content in soybean seeds produced in different soil management systems and desiccant application.

	First Season							
	G	**FGC**	**L**	**DM**	**E**	**ESI**	**T50**	**P50**
Ca	0.070	0.093	0.084	0.397	0.408	0.541 *	−0.338	0.659 **
Mg	−0.108	−0.419	0.123	−0.071	−0.666 **	−0.772 **	0.697 **	0.179
K	0.258	0.263	−0.220	−0.453	−0.316	−0.291	0.110	−0.259
Cu	−0.047	−0.465	0.484	0.705 **	−0.061	−0.238	0.334	0.713 **
Fe	−0.006	0.128	0.151	0.554 *	0.713 **	0.743 **	−0.308	0.559 *
Zn	−0.171	−0.535 *	0.149	0.067	−0.516	−0.734 **	0.644 **	0.313
Mn	−0.156	−0.351	−0.237	−0.523 *	−0.438	−0.665 **	0.317	−0.585 *
P	0.006	−0.391	0.194	−0.026	−0.802 **	−0.929 **	0.633 **	0.081
S	−0.079	−0.249	−0.236	−0.335	−0.461	−0.714 **	0.423	−0.383
N	−0.007	0.071	−0.265	−0.697 **	−0.548 *	−0.512 *	0.126	−0.694 **
	Second season							
Ca	0.319	0.229	0.393	0.229	0.255	0.348	0.443	−0.356
Mg	−0.38	−0.4	−0.359	−0.532 *	0.303	−0.225	−0.625 **	0.347
K	0.417	0.063	−0.367	0.405	−0.543 *	−0.16	0.08	0.048
Cu	−0.106	−0.315	−0.450	0.617 *	−0.48	−0.155	−0.25	0.631 **
Fe	0.106	0.108	0.653 **	0.217	0.542 *	0.661 **	0.877 **	−0.697 **
Zn	−0.117	0.108	0.346	0.565 *	−0.27	0.379	0.429	−0.211
Mn	0.105	0.359	0.535 *	0.044	0.085	0.334	0.717 **	−0.854 **
P	−0.211	−0.560 *	−0.469	0.326	0.001	−0.176	−0.435	0.837 **
S	−0.175	0.271	0.217	0.058	−0.623 **	−0.189	0.162	−0.462
N	−0.245	−0.283	−0.681 **	−0.198	−0.436	−0.573 *	−0.932 **	0.780 **

G: germination; FGC: first germination count; L: seedling lenght; DM: seedling dry mass; E: emergence; ESI: emergence speed index; T50: time to 50% germination; P50: longevity; *: significant at 5% probability; **: significant at 1% probability.

Soybean seed germination showed no significant correlation with nutrients, in both seasons. FGC was negatively correlated with Zn (first season) and with P (second season). For seedling length (L), there were significant correlations only in the second season, being positive for Fe and Mn and negative for N. The seedling dry mass variable, in the first season, was positively correlated with Cu and Fe and negatively with Mn and N, and in the second season there was a positive correlation with Cu and Zn, and a negative correlation with Mg (Table 5).

In seedling emergence (E) there was a negative correlation for Mg, P and N and a positive correlation for Fe (first season). In the second season, there was a positive correlation with Fe and a negative correlation with K and S. For the ESI, in the first season, there was a positive correlation with Ca and Fe and a negative correlation with Mg, Zn, Mn, P, S and N; in the second season a correlation was observed only with Fe, which was positive.

For T50, in the first season, Mg, Zn and P were positively correlated. In the second season, positive correlations were observed with Fe and Mn, and negative correlations with Mg and N. As for seed longevity (P50), in the first season there was a positive correlation with Ca, Cu and Fe, and a negative correlation with Mn and N; in the second season the positive correlations were with Cu, N and P, and the negative ones with Fe and Mn (Table 5).

Despite not being the focus of this research, the results of the correlation analysis showed that the micronutrient Fe was positively correlated with the variables of vigor and seed longevity in both seasons, making its importance evident in the physiological quality of soybean seeds. Thus, new studies aiming to explain the participation of this nutrient in the seed can contribute to a better understanding of the process of soybean seed physiological quality acquisition.

4. Discussion

In this work, we evaluated the physiological quality of soybean seeds cultivated under conventional tillage and no-tillage systems with and without desiccant use. Our results showed that in the no-tillage system, it is common to have a higher soil compaction index in the surface layers, when compared to the conventional system. Thus, it can negatively affect the root development of crops and, consequently, the water and nutrient absorption [34–36]. However, as this is an experiment performed in an area with long-term no-tillage, in which the soil properties are already consolidated [8,9], these factors probably did not harm the soybean plant development, to the point of affecting the seed germination capacity (Table 3).

The lack of desiccation management effect on soybean seed germination is due to the fact that the germination capacity is acquired at the R7.1 stage [12,17], and in this research the pre-harvest soybean desiccation was carried out in R7.3, when the acquisition of this capacity had already taken place. Studies on desiccant application at the physiological maturity stage also revealed that there were no significant differences in germination potential [20,37].

Although the soil management system did not affect seed germination, there was a difference in vigor, through changes in the responses of FGC, T50, length and ESI of soybean seedlings (Table 3). The soybean seed vigor evaluation characteristics were more sensitive for detecting alterations, when compared to the laboratory germination test [28,38]. So, despite the superficial physical and chemical characteristics of the soil managed under no-tillage not having affected germination, these were able to negatively influence seed vigor.

The physiological quality is acquired throughout the plant development stage [12,13]. Thus, the negative results of desiccant application on the vigor (length and dry mass of seedlings) and longevity of the seeds (Table 3), is due to this factor, since, possibly, the desiccation impaired the process of acquiring physiological quality. It should be noted that the desiccant used, paraquat, is a fast-acting contact herbicide, a factor that limits the translocation of the product of photosynthesis into the seeds [39]. So, the negative effect of the desiccant application on the vigor and longevity of the seeds, in this study, is due to physiological processes.

The variables DM, E and ESI (vigor) showed a significant interaction between soil management and desiccant application. So, it was possible to observe that in CT there was better seed quality without desiccant application, while in NT the desiccant application favored soybean seed vigor (Tables 3 and 4). Such results are probably related to the amount of nutrients in the soil available for absorption by the plant (Table 1). Previous works show that in the NT system there is greater nutrient accumulation in the surface layer of the soil, where there is a greater amount of soybean roots [40,41]. Thus, a compensatory effect may have occurred, since the greater supply of nutrients to the plant in NT may have promoted greater accumulation in the seed, and even with the desiccant application, there was no reduction in the nutritional content. In CT, despite having a lower nutrient content in the soil, the non-application of desiccant allowed more time for the absorption of nutrients by the plant and accumulation in the seed, resulting in seeds with greater vigor (DM, E and ESI).

It is worth mentioning that seed vigor is the set of properties that determine the activity and performance of seed lots with acceptable germination, under a wide range of environmental conditions [42]. Thus, from these test results, it was found that the need to apply a desiccant on the soybean seeds is dependent on the soil management system.

Seed longevity is a characteristic that impacts the commercialization of lots, considering that low longevity is associated with loss of vigor and viability [12,32]. In addition to the desiccant factor, soil management systems also affected seed longevity, with NT being the one that promoted the longest storage period (Table 3). Such results may be associated with the seed nutrient content, since in the second season there was a positive correlation with N, P and Cu (Table 5).

N acts on plant growth, on the formation of amino acids, proteins, enzymes and on the chlorophyll molecule [43,44], and its deficiency in the seed can negatively affect the protein content, resulting in a loss of quality [45,46], since the proteins in the seeds act as reserve substances and as chemical reactions catalysts [47]. Thus, during the seed deterioration process, there is a decrease in the content and synthesis of proteins, an increase in the amino acid content, a decrease in the content of soluble proteins and denaturation caused by high temperatures, causing the loss of performance of vital functions [47].

P acts in the formation of the seeds and during the germination process, where it performs fundamental functions, as it is a constituent of the membrane (phospholipids), of nucleic acids and of energy-storing compounds, such as ATP, which is the most important of these compounds [48–50]. Seeds with higher P content present higher initial energy for seedling metabolic activities; consequently, it has a higher physiological quality, contributing to the better performance of the plant in the field, since it makes it less dependent on the existing levels of this element in the soil [51].

Cu, on the other hand, participates in important physiological processes as a structural and metabolic component, as it acts in the composition of proteins involved in oxidation-reduction reactions, in carbohydrate synthesis and as a cofactor of enzymes, such as polyphenol oxidase and superoxide dismutase, which act in the lignin synthesis for cell wall formation and protection from oxidative stress due to the presence of reactive oxygen species [49,52,53]. In this way, the higher the Cu content in the seed, without generating toxicity, the greater the seed longevity.

As in NT there is greater nutrient accumulation [40,41], the greater content of N, P and Cu in the seed, provided by this management system, contributed to greater longevity of the seeds. Through greater protein synthesis, a constituent of DNA and RNA, the seed has a greater energy source for metabolic processes and a greater reduction of oxidative stress during the storage process.

The results of this research showed that the use of desiccant influenced the process of acquiring vigor and longevity of soybean seeds. In addition, it was possible to observe that factors such as the soil management system may be associated with the moment and process of seed quality acquisition. For longevity, a parameter that continues to be acquired until the last stage of seed maturation, this research showed that the desiccant, by accelerating the seed maturation process, impairs the complete acquisition of this characteristic.

Future research involving protein content, enzymatic activity, reactive oxygen species and accumulation of residues may contribute to the understanding of the physiological and biochemical mechanisms of soybean seeds produced in different soil management systems and with or without desiccant application.

5. Conclusions

Our results showed that soil management systems and desiccant use do not influence soybean seed germination. However, conventional soil preparation increases seed vigor when evaluated by the traits of first germination count, dry mass and length of seedling. In addition, the absence of desiccant application promotes the formation of seedlings with greater length and dry mass. In summary, the use of desiccant aiming at seed vigor is dependent on the soil management system. The soybean seed longevity is superior in the no-tillage system, but the desiccant application reduces seed longevity.

Author Contributions: Conceptualization, G.F.d.S. and L.C.; methodology, G.F.d.S., L.C., P.P.N.C. and B.C.O.L.; formal analysis, G.F.d.S. and L.C.; investigation, G.F.d.S., L.C., P.P.N.C. and B.C.O.L.; writing—original draft preparation, G.F.d.S. and L.C.; writing—review and editing, J.C.C., J.N. and E.A.A.d.S.; supervision, J.C.C. and E.A.A.d.S.; funding acquisition, G.F.d.S., L.C., J.C.C. and E.A.A.d.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by São Paulo Research Foundation (FAPESP), grant number 2017/50211-9 and by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), grant number 001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: To Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the productivity fellowship to E.A.A.d.S. (code 311526/2021) and for granting an award for excellence in research to J.C.C.

Conflicts of Interest: The authors declare no conflict of interest.

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