

Article

Statistical Process Control for Monitoring Soybean Seed Quality During Mechanical Harvest

Rafael Marani Barbosa ^{1,*} , Rayane Aguiar Alves ¹ , Caique Carvalho Medauar ¹ , Rouverson Pereira da Silva ²  and Roberval Daiton Vieira ² 

¹ Department of Agricultural and Environmental Sciences (DCAA), Universidade Estadual de Santa Cruz, Ilhéus 45662-900, BA, Brazil; rayaneaguiaralves@gmail.com (R.A.A.); caiquemedauar@hotmail.com (C.C.M.)

² Department of Agricultural Sciences, School of Agricultural and Veterinary Studies, São Paulo State University, Jaboticabal 14884-900, SP, Brazil; rouverson@pq.cnpq.br (R.P.d.S.); rdvieira@fcav.unesp.br (R.D.V.)

* Correspondence: rmbarbosa@uesc.br

Abstract

Seed moisture content (SMC) fluctuations and machine adjustments during mechanical harvesting are associated with soybean seed quality and process variability. This study aimed to monitor the physical and physiological quality of soybean seeds and evaluate process variability during mechanical harvesting using Statistical Process Control (SPC) tools. Seed samples were collected at pre-established intervals from two harvesting systems operating in the same production field. Seed moisture content, purity, mechanical damage, germination, and vigor were evaluated throughout the harvesting operation. The average SMC was 15.8%, exceeding the range commonly recommended for soybean seed harvesting. Temporal fluctuations in SMC were associated with adjustments in Cylinder Rotation Speed (CRS) and Cylinder Opening (CO), which coincided with differences in process stability between the evaluated harvesting systems. Control charts identified periods of instability and out-of-control observations associated with changes in moisture conditions, machine adjustments, and operator interventions. Under the evaluated conditions, the harvesting system represented by Combine A was associated with greater process stability and higher values for purity, germination, accelerated aging, and seedling emergence. Although mechanical damage did not differ between harvesting systems, physiological tests were more sensitive in detecting differences associated with harvesting conditions. Statistical Process Control effectively identified temporal variability and process instability throughout the harvesting operation, providing a comprehensive approach for monitoring soybean seed quality and supporting decision-making during mechanical harvesting.

Keywords: *Glycine max* L.; control charts; quality indicators; seed purity; seed vigor



Academic Editor: Jianping Wang

Received: 8 June 2026

Revised: 25 June 2026

Accepted: 29 June 2026

Published: 28 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Soybean [*Glycine max* (L.) Merr.] has become one of the main pillars of global agriculture, being widely utilized for both human and animal nutrition as well as a versatile raw material for several industrial sectors. In this context, the use of seeds with high physiological quality constitutes one of the major factors contributing to increased crop productivity [1], as it promotes greater uniformity and speed of seedling emergence, improved initial plant development, larger leaf area, and a higher number of fertile nodes and pods per plant [2].

During seed production, several factors may influence the physiological and physical quality of soybean seeds. Among these, the mechanized harvesting process is particularly noteworthy, especially the action of the threshing drum, a central component of the combine harvester, in which soybean grains are highly susceptible to mechanical damage, representing one of the primary causes of grain crushing [3].

Although the threshing drum plays a fundamental role in separating grains from straw during harvest, its high rotational speed combined with the intense friction generated during the process frequently results in severe mechanical damage to the seeds. Such damage compromises the overall quality of soybeans and may even reduce their commercial value, negatively affecting the economic efficiency of production [4]. Furthermore, physical damage can alter the organization and integrity of the cellular membrane, accelerating seed deterioration and reducing germination and vigor [5]. Since seed vigor is a key determinant of rapid and uniform crop establishment, such damage can ultimately compromise crop productivity [6,7]. In soybeans, mechanical damage incurred during harvest has been consistently associated with reductions in physiological quality [3,7,8].

Studies on mechanized harvesting and the physiological quality of soybean seeds have demonstrated that threshing cylinder speeds below 500 rpm promote lower levels of mechanical damage and broken seeds, resulting in improved physiological seed quality [9,10]. It has also been observed that increasing the harvester forward speed reduces seed vigor, even when the cylinder rotation speed is low [11]. Therefore, proper adjustment of parameters such as harvester speed and threshing mechanisms is essential to perform harvesting operations with lower rates of mechanical damage and reduced losses in seed quality [12].

Another important aspect to be considered during harvesting is seed moisture content. Moisture levels below 12% cause immediate mechanical damage, characterized by seed cracking, whereas seeds with moisture content above 14% are more susceptible to latent damage, which becomes evident only during quality assessment [12]. Therefore, harvesting is generally recommended when seed moisture content is close to 13–15%, a range that tends to reduce susceptibility to mechanical damage while maintaining harvesting efficiency and seed physiological quality [3,13]. Although previous studies have established the effects of machine settings and seed moisture content on soybean seed quality, harvesting performance is commonly evaluated using average values obtained after the operation has been completed. Such approaches provide limited information regarding temporal fluctuations in process performance and may overlook transient events associated with environmental changes, machine adjustments, and operator interventions.

Monitoring process performance through Statistical Process Control (SPC) has become an important component of modern quality management systems, providing a framework for detecting process instability, identifying variability sources, and supporting continuous improvement [14,15]. These principles have progressively been incorporated into agricultural systems, where SPC has been applied to monitor grain harvesting, sowing operations, peanut planting, soybean seed processing, and the systemic evaluation of multiple mechanized performance indicators, demonstrating its usefulness for identifying special causes of variation, quantifying process variability, and supporting continuous process improvement [16–21]. Previous studies have demonstrated that SPC provides information beyond conventional statistical comparisons by incorporating the temporal behavior of operational variables and facilitating the identification of process instability throughout agricultural operations.

In the seed sector, SPC has primarily been applied to monitor seed processing operations and laboratory quality assessments, enabling the identification of variability sources during processing and supporting the interpretation of seed quality tests [16–18]. These studies demonstrated the usefulness of continuous monitoring for detecting process devia-

tions that may not be identified through analyses based solely on average values. However, their focus remained on post-harvest operations or laboratory evaluations rather than on the harvesting process itself.

Collectively, these studies demonstrate the usefulness of SPC for monitoring agricultural operations and seed-related processes. However, their applications have predominantly focused on operational quality indicators, seed processing stages, post-harvest activities, or laboratory quality assessments. Comparatively less attention has been given to the continuous monitoring of physical and physiological seed quality together with operational harvesting parameters throughout the harvesting operation under commercial seed production conditions. Consequently, temporal variations associated with environmental conditions, machine adjustments, and operator interventions remain only partially characterized, limiting the understanding of process variability during mechanical harvesting.

Given the above, this study aimed to monitor the physical and physiological quality of soybean seeds and evaluate process variability during mechanical harvesting using Statistical Process Control tools. We hypothesized that SPC tools would identify temporal fluctuations in seed quality and detect periods of process instability associated with changes in harvesting conditions.

2. Materials and Methods

2.1. Experimental Area

The seeds were collected in a registered seed production field located in Campo Alegre de Goiás, state of Goiás, Brazil (17°27'03" S, 47°48'06" W; altitude 966 m, declivity 5%). The region presents a tropical savanna climate with dry winter, classified as Aw according to the Köppen–Geiger climate classification system [22]. The soybean seed production field was sown in November 2024 using the cultivar NA7337RR. Seed treatment was performed according to the recommendations described by [12].

2.2. Seed Harvest

Seed harvest was performed in March 2025 using two Case IH Axial-Flow 2388 combines (209 kW; 284 hp), manufactured in 2004 and equipped with an axial-flow threshing system and a 7 m (23 ft) header. The operational parameters monitored throughout the harvesting process were displacement speed (DS), cylinder rotation speed (CRS), and cylinder opening (CO).

Each combine was operated by its regular operator, who manually adjusted the operational parameters according to field and crop conditions observed during harvesting. Therefore, the evaluated harvesting systems represent the combined effects of machine characteristics and operator decisions under commercial harvesting conditions.

Variations in environmental conditions throughout the harvesting period influenced seed moisture content (SMC), which was associated with adjustments in DS, CRS, and CO. Operational parameters were recorded at each sampling interval using data obtained directly from the combine monitoring system. Engine rotational speed was not monitored during the harvesting operation.

2.3. Seed Analysis

Seed samples were collected from the discharge auger supplying the grain tank of each combine at 10-min intervals during a 3.2-h harvesting period, resulting in 20 samples per combine. Each sample consisted of approximately 1 kg of soybean seeds. Immediately after collection, seed moisture content (SMC) was determined using a portable grain moisture meter.

After field sampling, the seeds were stored in paper bags and transported to the Seed Analysis Laboratory in Jaboticabal, São Paulo State, Brazil (21°15' S, 48°18' W; altitude 613 m), where all subsequent analyses were conducted. Samples collected during harvesting were transferred to the laboratory within two days after harvest.

Prior to quality evaluation, seed samples were classified by size using 5.5 and 6.0 mm sieves. Only seeds retained on these sieves were used for subsequent analyses. This procedure was adopted to standardize the material evaluated and to represent the seed fraction with commercial potential typically retained after processing. By focusing on the commercial seed fraction, the analyses were intended to assess the extent to which harvesting operations affect the physical and physiological quality of seeds destined for commercialization.

Following size classification, the seeds were maintained in a dry and cold chamber until analysis. Subsequently, seed moisture content was determined by the standard oven method, and the samples were subjected to physical and physiological quality assessments.

2.3.1. Seed Moisture Content-SMC

For each sample, two replications of 25 seeds were used. The measurement was performed by the oven method at 105 ± 3 °C for 24 h [23]. The results are expressed as percentage of fresh weight.

2.3.2. Purity Analysis

For each sample, a work sample of approximately 500 g separated into three components: pure seed, other seeds and inert material. The results are expressed as percentage of pure seed by weight [23].

2.3.3. Mechanical Damage

MD was measured by the sodium hypochlorite test [24], performed with four replications of 50 seeds per sample. Seeds were immersed in a 0.13% sodium hypochlorite solution for 10 min. The seeds were then dried on paper towels and evaluated by computing the number of seeds soaked, and results are expressed as a percentage.

2.3.4. Germination

The tests were performed with four replications of 50 seeds, distributed on rolls of germination paper moistened with water equivalent to 2.5 times the mass of the dry substrate. The rolls were maintained in a germination chamber at 25 °C. Seedling evaluations were performed on the eighth day after sowing, and the results are expressed as the percentage of normal seedlings [23].

2.3.5. Accelerated Aging

Samples of 250 seeds were spread in a single layer on stainless steel screens and placed in plastic germination boxes (11 × 11 × 3.5 cm). Deionized water (40 mL) was added to each box, which was then incubated in a germination chamber at 41 °C for 48 h [25]. After the aging period, four replications of 25 seeds were submitted to the germination test. Evaluation was performed on the fifth day after sowing [23].

2.3.6. Electrical Conductivity

The test were performed with four replications of 50 seeds per sample weighed on an analytical balance (0.01 g precision) and soaked in 75 mL of deionized water. The seeds were maintained at 25 °C for 24 h in a germination chamber. After this period, the EC of the soaking solution was determined using a conductivity meter (mCA-150, MS Tecno, Piracicaba, Brazil). The results are expressed in $\mu\text{S cm}^{-1} \text{g}^{-1}$ [25].

2.3.7. Seedling Emergence in the Field

Four replications of 50 treated seeds per sample were sowed in 2 m rows at a 3–4 cm depth and with 0.04 m spacing between rows. SE count was made at 15 days after sowing, counting only seedlings whose leaves originated from the embryo (simple leaves), were developed, and had margins that were no longer in contact [25].

2.4. Statistical Analysis

The data were analyzed using descriptive statistics (arithmetic mean, median, range, standard deviation, and coefficient of variation) and analysis of variance (ANOVA), considering the harvesting systems as the source of variation. Mean values were compared using Tukey's test at the 5% probability level. Data normality was assessed using the Anderson–Darling test. Variables that did not meet normality assumptions were transformed using arc sine $(x/100)^{1/2}$, except for EC, which was transformed using $x^{1/2}$.

Statistical Process Control (SPC) charts were used to monitor temporal variability in seed quality attributes and operational parameters throughout the harvesting process. These were developed using the lower control limit (LCL) and the upper control limit (UCL), with the overall mean serving as the central line (CL). The control limits were calculated based on three standard deviations from the process mean, according to:

$$CL = \bar{x}, \quad (1)$$

$$LCL = \bar{x} - 3\sigma, \quad (2)$$

$$UCL = \bar{x} + 3\sigma. \quad (3)$$

where $\bar{x}$ is the overall process mean and σ is the process standard deviation. All analyses and graphical representations were performed using R software (version 4.6.0) [26], with the packages *readxl*, *dplyr*, *ggplot2*, and *patchwork*.

Special causes of variation were identified using standard statistical process control rules. Test 1, defined as the occurrence of a point above the upper control limit (UCL) or below the lower control limit (LCL), was used to indicate process instability and was represented by the numeral 1 in the control charts [27,28].

3. Results

3.1. Harvesting Conditions and Combine Adjustments

According to the seed production company, the seed production field achieved an average yield of 3480 kg ha⁻¹. Displacement Speed (DS) ranged from 4.1 to 5.1 km h⁻¹ for combine A and from 4.3 to 5.4 km h⁻¹ for combine B. Most observations remained within the control limits; however, after 16:20 h, combine B presented one observation above the Upper Control Limit (UCL) and another below the Lower Control Limit (LCL), indicating increased process variability (Figure 1).

Cylinder Rotation Speed (CRS) ranged from 550 to 590 rpm in combine A and from 470 to 530 rpm in combine B. Cylinder Opening (CO) ranged from 1.4 to 1.8 mm and from 2.8 to 3.7 mm for combines A and B, respectively. Machine adjustments performed during intervals (i) and (ii) coincided with changes in operational parameters and seed quality attributes throughout the harvesting operation (Figure 1).

The mean Seed Moisture Content (SMC) was 15.8% for both combines. The Lower Control Limit (LCL) and Upper Control Limit (UCL) were 14.4% and 17.3%, respectively (Figure 2).

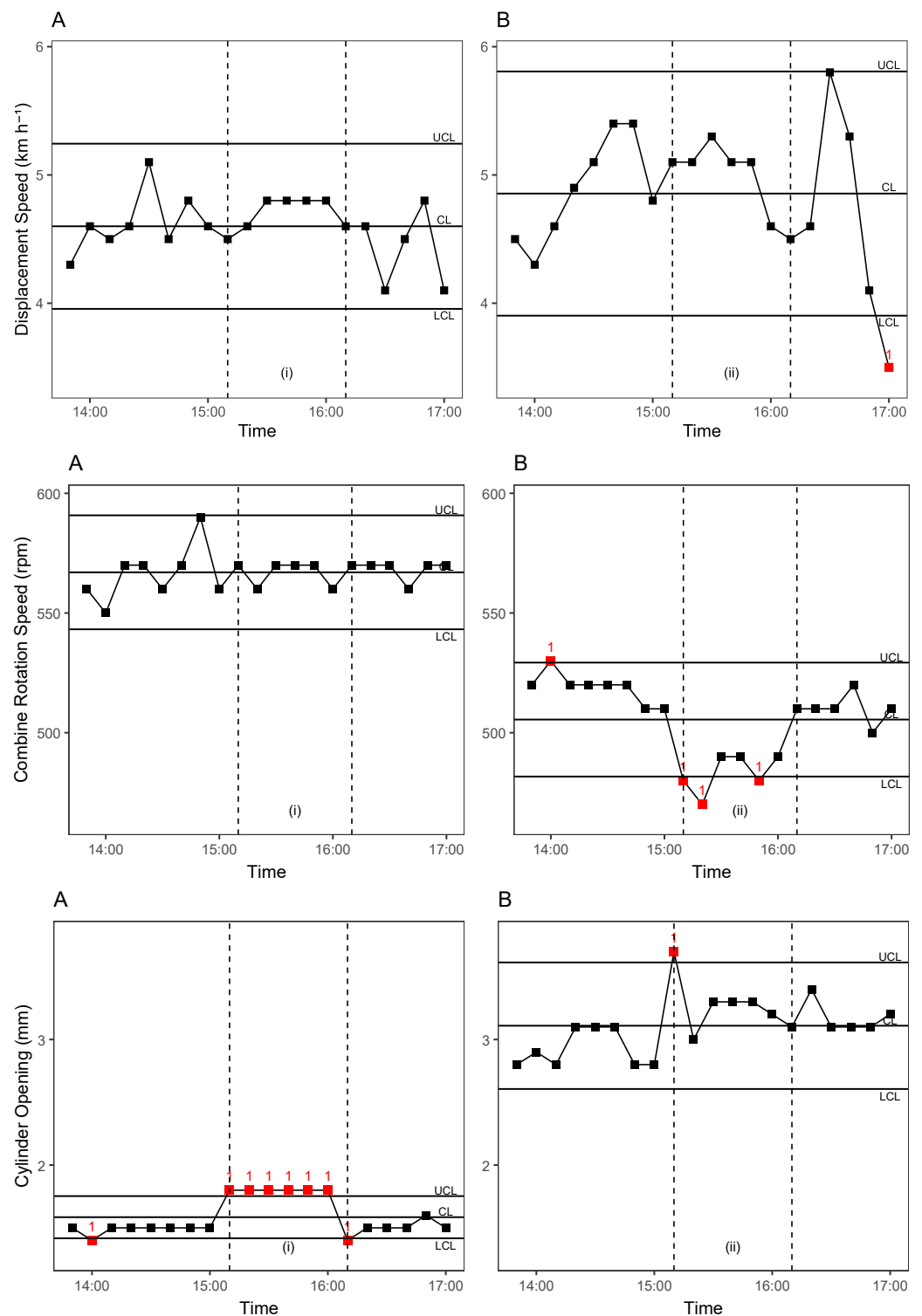


Figure 1. Statistical process control charts during soybean seed harvesting. Top row: displacement speed (DS); middle row: cylinder rotation speed (CRS); bottom row: cylinder opening (CO). Left and right panels correspond to harvesting systems A and B, respectively. Vertical dashed lines indicate the machine adjustment intervals. Roman numerals (i) and (ii) indicate the adjustment intervals for harvesting systems A and B, respectively. Red squares indicate observations outside the statistical control limits, whereas black squares indicate observations within the control limits. The red numeral “1” denotes Test 1 of the Statistical Process Control rules, indicating process instability caused by observations outside the control limits.

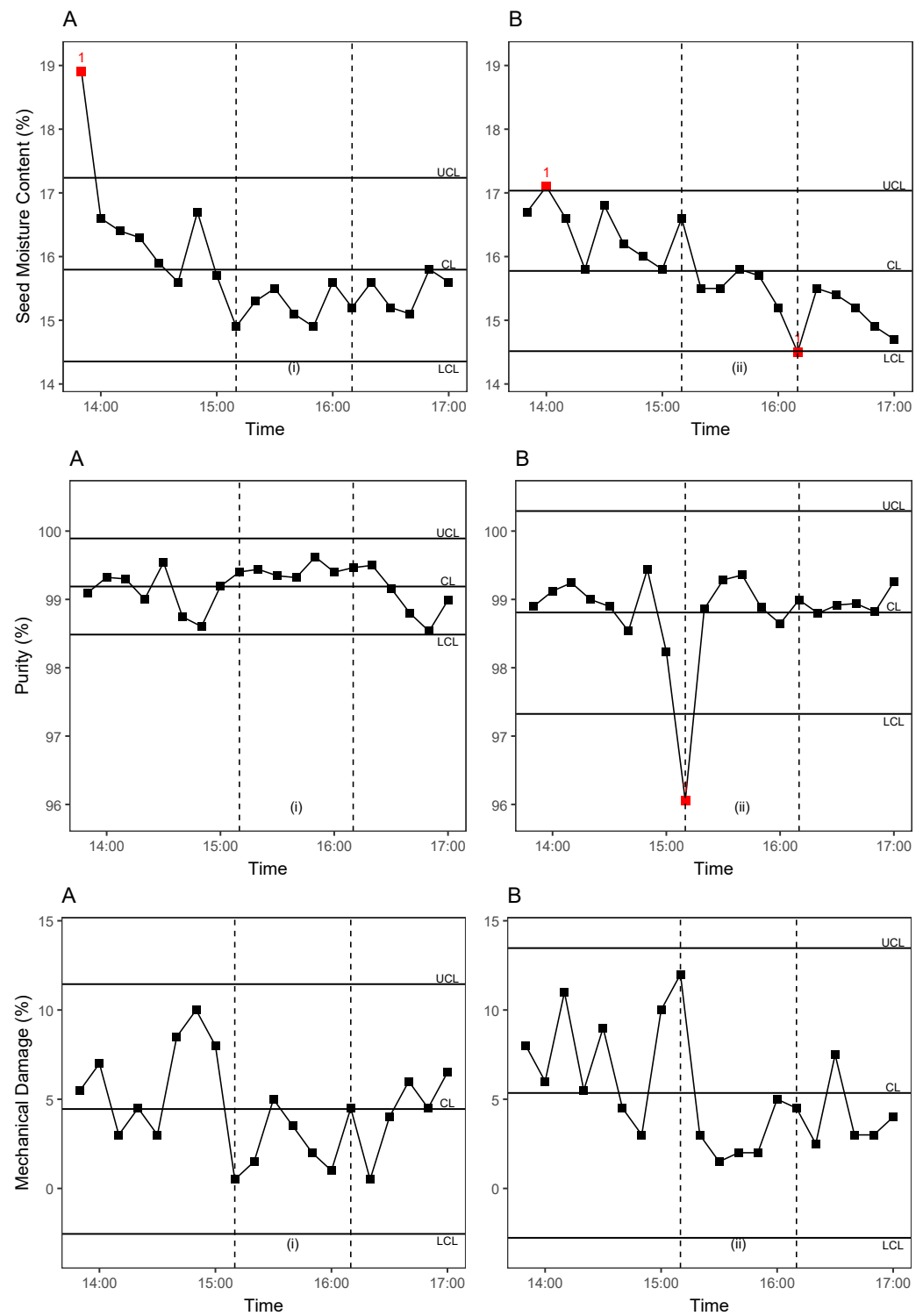


Figure 2. Statistical process control charts during soybean seed harvesting. Top row: seed moisture content (SMC); middle row: seed purity; bottom row: mechanical damage. Left and right panels correspond to harvesting systems A and B, respectively. Vertical dashed lines indicate the machine adjustment intervals. Roman numerals (i) and (ii) indicate the adjustment intervals for harvesting systems A and B, respectively. Red squares indicate observations outside the statistical control limits, whereas black squares indicate observations within the control limits. The red numeral “1” denotes Test 1 of the Statistical Process Control rules, indicating process instability caused by observations outside the control limits.

At the beginning of the harvesting operation, SMC was 18.9% in combine A and 16.7% in combine B. One out-of-control observation was detected for combine A, whereas two out-of-control observations were identified for combine B (Figure 2).

Machine adjustments performed during intervals (i) and (ii) were associated with changes in operational parameters and seed quality throughout the harvesting operation (Figure 1).

3.2. Physical Seed Quality

3.2.1. Seed Purity

Seed purity values obtained from combine A remained within the control limits throughout the harvesting operation (Figure 2). For combine B, one observation recorded at 15:10 h was below the LCL.

Following machine adjustments, purity values obtained from combine B became closer to the Center Line (CL), indicating greater process stability during the subsequent sampling intervals (Figure 2). Mean purity differed between combines, with higher values observed for combine A (Table 1).

Table 1. Physical and physiological quality of soybean seeds harvested by two combines.

Variable	Combine	Mean	Median	Range	SD	CV (%)
Purity (%)	A	99 a ^{†,‡}	99.3	1.1	0.32	0.32
	B	98 b	98.9	3.4	0.71	0.72
Mechanical damage (%)	A	4.5 a	4.0	12.0	3.43	77.0
	B	5.4 a	4.0	18.0	3.91	73.0
Germination (%)	A	97 a	98.0	10.0	2.70	2.78
	B	95 b	96.0	20.0	4.03	4.24
Accelerated aging (%)	A	88 a	90.0	34.0	7.94	9.0
	B	83 b	85.0	46.0	10.22	12.3
Electrical conductivity ($\mu\text{S cm}^{-1} \text{ g}^{-1}$)	A	87 b	83.6	62.0	16.67	19.1
	B	99 a	98.5	82.0	18.04	18.1
Seedling emergence (%)	A	95 a	96.0	20.0	4.68	4.9
	B	93 b	94.0	20.0	5.02	5.3

SD = standard deviation; CV (%) = coefficient of variation. [†] Means followed by the same letter within each variable do not differ significantly according to Tukey's test at 5% probability ($p \leq 0.05$). [‡] Original means are presented; however, transformed data were used for the statistical analyses.

3.2.2. Mechanical Damage

Mechanical damage assessed by the sodium hypochlorite test did not differ between combines A and B (Table 1). However, out-of-control observations were detected in both combines, indicating variability during the harvesting operation (Figure 2).

Variations in mechanical damage were observed after machine adjustments performed during intervals (i) and (ii), coinciding with changes in operational settings during the harvesting operation (Figure 2).

3.3. Physiological Seed Quality

3.3.1. Germination

All samples presented germination values above 80%, meeting the minimum requirement for soybean seed commercialization. Combine A consistently produced seeds with higher germination percentages than combine B (Table 1, Figure 3).

For combine B, observations below the LCL were detected during the harvesting operation, indicating greater process variability and reduced process stability (Figure 3).

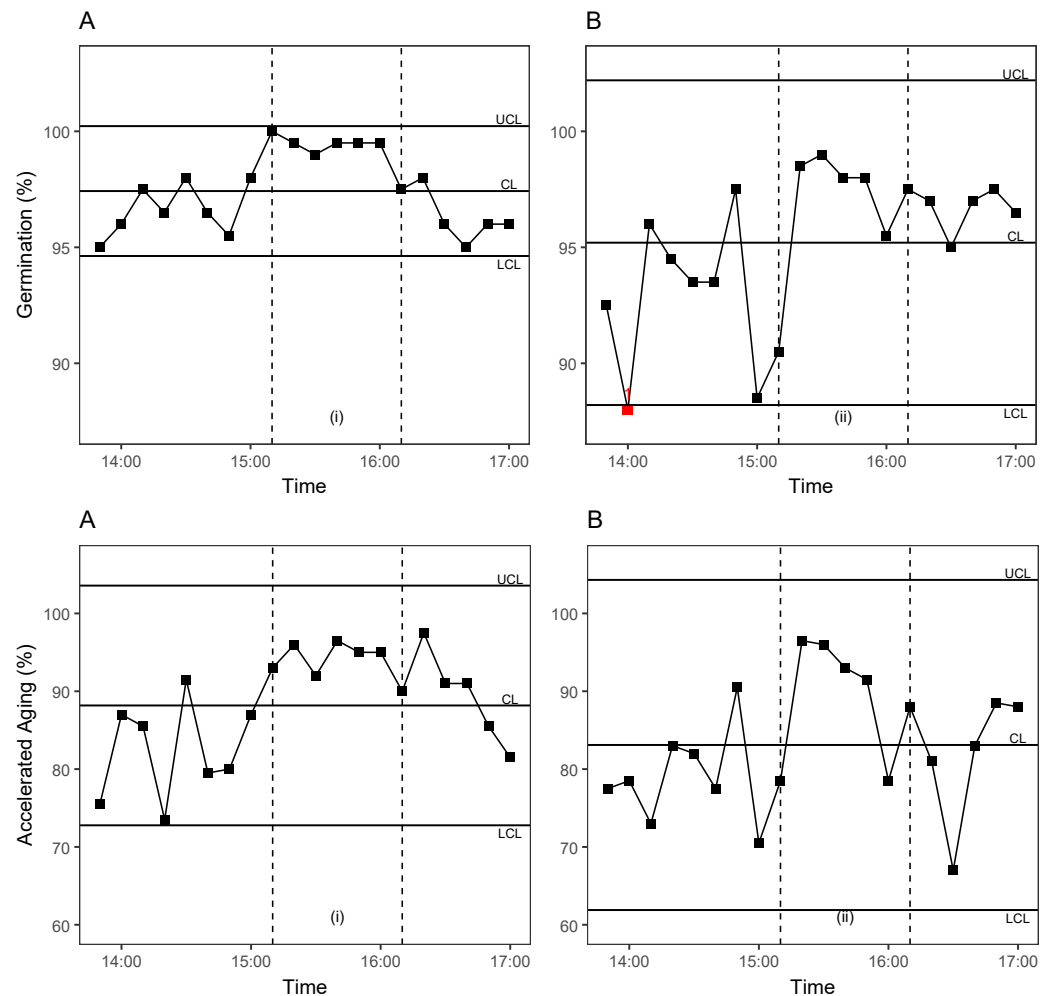


Figure 3. Statistical process control charts during soybean seed harvesting. Top row: germination; bottom row: accelerated aging (AA). Left and right panels correspond to harvesting systems A and B, respectively. Vertical dashed lines indicate the machine adjustment intervals. Roman numerals (i) and (ii) indicate the adjustment intervals for harvesting systems A and B, respectively. Red squares indicate observations outside the statistical control limits, whereas black squares indicate observations within the control limits. The red numeral “1” denotes Test 1 of the Statistical Process Control rules, indicating process instability caused by observations outside the control limits.

3.3.2. Seed Vigor

Accelerated Aging (AA) and Electrical Conductivity (EC) differed between combines, with higher vigor values observed in the harvesting system represented by combine A (Table 1, Figures 3 and 4).

For AA, observations recorded during intervals (i) and (ii) remained above the CL and, in some cases, exceeded the UCL, indicating a temporary improvement in seed vigor (Figure 3). Conversely, EC values reached their lowest levels during the same period (Figure 4), which is consistent with improved membrane integrity and higher seed vigor.

Seedling Emergence (SE) also differed between combines, with higher values observed for combine A (Table 1). Until approximately 14:40 h, emergence values remained close to 90% for both combines (Figure 4). Subsequently, combine A exhibited increased emergence values, whereas combine B showed abrupt reductions at specific sampling times.

For combine A, some observations recorded before 14:40 h were below the LCL. For combine B, marked reductions in SE were observed at 15:10 and 16:30 h, contributing to increased process variability (Figure 4).

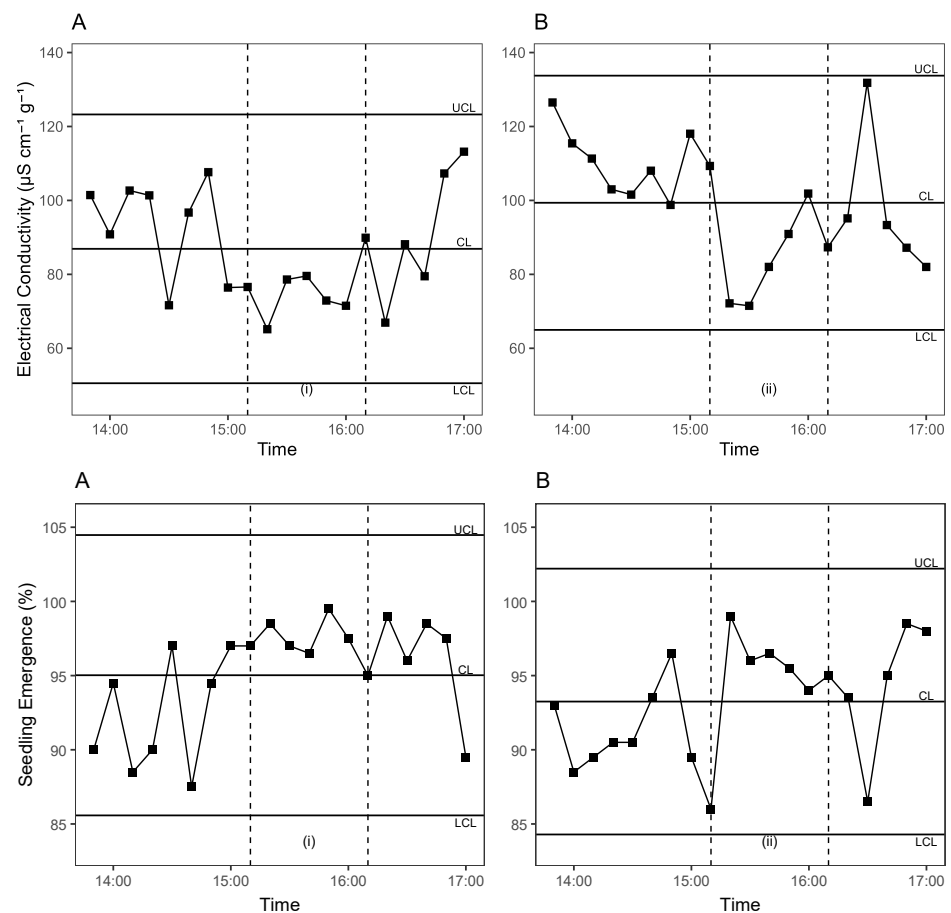


Figure 4. Statistical process control charts during soybean seed harvesting. Top row: electrical conductivity (EC); bottom row: seedling emergence (SE). Left and right panels correspond to harvesting systems A and B, respectively. Vertical dashed lines indicate the machine adjustment intervals. Roman numerals (i) and (ii) indicate the adjustment intervals for harvesting systems A and B, respectively.

3.4. Process Variability and Cause-And-Effect Analysis

The cause-and-effect diagram was used to identify factors associated with the variability of the process and seed quality during the harvesting operation (Figure 5). The factors identified were environment, machinery, manpower, methods, and raw material.

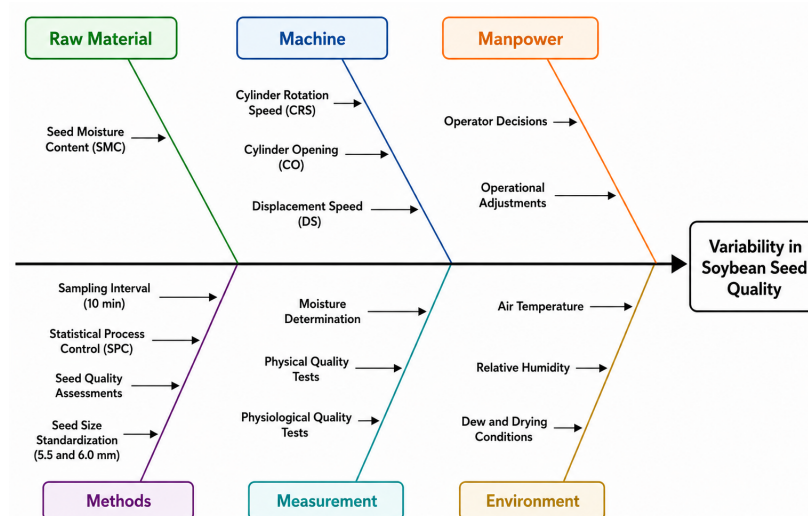


Figure 5. Cause-and-effect (Ishikawa) diagram illustrating potential sources of variability in soybean seed quality during mechanical harvesting.

Environmental conditions, machine adjustments, operator interventions, and Seed Moisture Content (SMC) were identified as potential sources of variability associated with out-of-control observations detected during the harvesting operation (Figure 5).

4. Discussion

4.1. Seed Moisture Content as a Driver of Harvest Variability

Seed Moisture Content (SMC) emerged as one of the main factors associated with process variability during the harvesting operation. Although the average SMC was similar between combines, temporal fluctuations were observed throughout the sampling period, resulting in successive machine adjustments and changes in process stability. This behavior reinforces the dynamic nature of soybean seed harvesting, in which seed moisture can vary considerably during the early morning hours due to fluctuations in temperature and relative humidity associated with dew formation and drying. These moisture dynamics are particularly important because they often determine the appropriate time to initiate harvesting operations, directly influencing both harvesting efficiency and process stability.

The average SMC observed in the present study (15.8%) exceeded the range commonly recommended for mechanized soybean seed harvesting. Previous studies have shown that seed moisture directly affects threshing efficiency, susceptibility to mechanical damage, and subsequent physiological performance. When harvested at elevated moisture contents, pods may become more resistant to threshing, increasing the demand for machine adjustments and potentially reducing harvesting efficiency. Conversely, excessively low moisture contents increase seed brittleness and susceptibility to impact damage, cracking, and seed coat disruption [13,29,30].

Beyond its direct effect on seed quality, SMC also influences the operational behavior of harvesting equipment. Variations in moisture content alter the interaction between crop material and threshing mechanisms, often requiring adjustments in Cylinder Rotation Speed (CRS), Cylinder Opening (CO), and Displacement Speed (DS) to maintain harvesting efficiency and minimize seed losses. The machine adjustments observed during intervals (i) and (ii) are consistent with this operational response and suggest that SMC was closely associated with both equipment regulation and process variability.

The occurrence of out-of-control observations during periods of greater moisture fluctuation further supports this interpretation. Several observations exceeding the control limits coincided with changes in SMC and subsequent machine adjustments, indicating the presence of special causes of variation affecting process stability. From a Statistical Process Control perspective, these findings demonstrate that SMC should not be considered solely a quality attribute but also a critical operational variable associated with the stability of the harvesting process.

Therefore, continuous monitoring of SMC during harvesting may contribute not only to preserving seed quality but also to improving process control, allowing operators to anticipate adjustments and reduce variability throughout the harvesting operation.

4.2. Machine Adjustment and Operator Intervention Affect Harvest Performance

Although both combines operated under similar field conditions, differences were observed in operational settings, process stability, and seed quality attributes. These results highlight the importance of machine adjustment and operator decision-making as key factors influencing the performance of soybean seed harvesting operations.

Harvesting is a dynamic process in which crop and environmental conditions change continuously throughout the day. Variations in seed moisture, plant architecture, crop residue flow, and threshing resistance often require adjustments in operational parameters to maintain harvesting efficiency and minimize seed losses. Consequently, operators must

frequently modify Cylinder Rotation Speed (CRS), Cylinder Opening (CO), and Displacement Speed (DS) in response to changing field conditions. The importance of monitoring operational parameters extends beyond machine adjustment itself, as harvesting performance is strongly influenced by variations in operational speed and machine workload. The variability inherent to soybean harvesting operations highlights the importance of continuously monitoring operational parameters, allowing the identification of process deviations and supporting timely management decisions [31].

Inadequate machine adjustments may compromise threshing efficiency, increase impurity levels, intensify mechanical damage, and ultimately reduce seed quality [17,32]. Current evidence indicates that combine settings should be continuously adjusted according to crop and environmental conditions to maintain harvesting efficiency and reduce operational losses [33]. Nevertheless, the combined effects of machine configuration, crop characteristics, and operator interventions on process variability and seed quality remain insufficiently explored.

The DS values observed in the present study remained within the operational range commonly reported for soybean harvesting. Operating speeds above 5 km h^{-1} do not necessarily result in greater harvesting losses [33], indicating that harvesting performance depends on the interaction among machine adjustments, crop conditions, and operating speed rather than on speed alone. This interpretation is consistent with the present results, in which DS remained relatively stable while variations in process stability were more closely associated with changes in SMC and machine adjustments.

The control charts revealed that several out-of-control observations occurred immediately before or after machine adjustments, particularly during intervals (i) and (ii). This pattern suggests that operator interventions were associated with measurable process variation and were directly associated with changes in process behavior. In practical terms, the observed adjustments likely represented attempts to compensate for variations in Seed Moisture Content (SMC) and threshing conditions throughout the harvesting operation. This interpretation agrees with recent evidence indicating that continuous adaptation of combine settings according to field conditions is essential for maintaining harvesting efficiency and minimizing operational losses [33].

An important contribution of the present study is the demonstration that Statistical Process Control (SPC) can identify operational events that are often overlooked when analyses are based exclusively on treatment means. While conventional statistical approaches describe average process performance, control charts reveal the temporal dynamics of the harvesting operation and allow the identification of special causes of variation associated with specific management actions.

The relationship observed between machine adjustments and process variability does not imply that operator interventions negatively affected harvesting performance. On the contrary, these adjustments were essential for maintaining process control under changing field conditions. However, the results demonstrate that operator decisions represent an important source of variability whose effects can be quantified and monitored through SPC tools.

From an operational perspective, these findings reinforce the importance of continuous process monitoring during harvesting. By identifying deviations from process stability in real time, SPC provides objective information that may support more efficient machine adjustments, improve harvesting performance, and reduce the risk of seed quality losses.

4.3. Mechanical Damage and Physiological Seed Quality

Mechanical damage is among the principal causes of soybean seed deterioration during mechanized harvesting. However, despite the absence of significant differences

between combines for mechanical damage assessed by the sodium hypochlorite test, clear differences were observed in germination, accelerated aging, electrical conductivity, and seedling emergence.

This response pattern indicates that physiological quality attributes were more sensitive to harvesting-induced stress than the physical damage assessment used in the present study. Although mechanical injuries may be expressed as visible cracks or ruptures, damage can also occur at levels not readily detected by conventional physical evaluations, affecting membrane organization, metabolic activity, and seed performance [7]. As a result, reductions in physiological quality may occur even when visible damage remains unchanged [34,35].

The superior physiological performance observed in seeds harvested by combine A suggests that harvesting conditions affected seed integrity beyond the damage detected by the sodium hypochlorite test. This interpretation is supported by the lower electrical conductivity values and higher accelerated aging, germination, and seedling emergence observed for this combine. Together, these results indicate that the harvesting operation was associated with differences in seed vigor and physiological potential, even though differences in visible damage were not detected [5,6,36].

Although lower Cylinder Rotation Speed (CRS) values are generally associated with reduced mechanical damage during soybean harvesting, the harvesting system represented by combine B, which operated at lower CRS values, did not exhibit superior physiological quality. This result suggests that seed quality cannot be explained by a single operational parameter. Instead, seed performance appears to reflect the combined influence of Seed Moisture Content (SMC), machine adjustments, process stability, and operator interventions throughout the harvesting operation. Therefore, the lower physiological quality observed in combine B was likely associated with the interaction among multiple operational and environmental factors rather than from CRS alone.

An additional aspect revealed by the control charts was the temporal variability of physiological quality throughout the harvesting operation. Several out-of-control observations were identified for germination, accelerated aging, electrical conductivity, and seedling emergence, indicating that seed physiological performance was not constant over time. This finding reinforces the importance of monitoring harvesting operations using quality indicators capable of detecting transient changes that may not be evident when only average values are considered.

Therefore, evaluating harvesting performance exclusively through physical damage assessments may provide an incomplete understanding of seed quality responses [2,7]. The combined use of physical and physiological tests offers a more comprehensive assessment of harvesting effects and may improve the identification of operational conditions associated with reductions in seed quality [7].

4.4. Contribution of Statistical Process Control to Harvest Monitoring

The main contribution of this study lies in demonstrating the applicability of Statistical Process Control (SPC) as a tool for monitoring soybean seed harvesting operations. While conventional statistical analyses were effective in identifying differences between combines, SPC provided additional insights into process behavior by incorporating the temporal dimension of operational and seed quality data. The control charts enabled the identification of periods of process instability characterized by out-of-control observations and revealed temporal variations that would not be evident from average values alone. Moreover, these events were associated with fluctuations in Seed Moisture Content (SMC), machine adjustments, and operator interventions, allowing a more detailed interpretation of the factors influencing harvesting performance and seed quality.

The variability inherent to agricultural operations such as sowing, spraying, and seed processing [18–20], reinforces the importance of continuously monitoring operational and quality indicators. In this context, SPC complements traditional analytical approaches by identifying special causes of variation and supporting the evaluation of process stability throughout the harvesting operation.

An important finding of the present study is that average values alone may mask temporary reductions in seed quality. Although both combines produced seed lots that met commercialization standards, the control charts revealed periods of instability associated with reductions in germination, vigor, and emergence potential. These transient events would likely remain undetected if the evaluation were based exclusively on treatment means.

Another relevant aspect is that SPC allowed the simultaneous evaluation of operational variables (SMC, CRS, CO, and DS) and seed quality attributes, providing an integrated view of the harvesting process. This approach facilitated the identification of potential relationships between machine performance, environmental conditions, and seed physiological responses, contributing to a more comprehensive understanding of process variability.

Therefore, SPC should be considered a complementary tool for monitoring soybean seed harvesting, as it enables the identification of variability sources, supports data-driven management decisions, and contributes to maintaining process stability and seed quality throughout the harvesting operation.

4.5. Study Limitations

The present study evaluated two harvesting systems operating under commercial conditions in a single production field, cultivar, and harvesting period. Therefore, the observed relationships should be interpreted within the context of the evaluated systems rather than as generalized differences among combine models. In addition, physical and physiological quality assessments were performed using the seed fraction retained on 5.5 and 6.0 mm sieves, representing the portion of the harvested material with commercial potential after processing. Although this approach reflects commercial seed production practices, it may not fully represent the variability present in the entire harvested seed mass. Nevertheless, the study provides valuable evidence regarding the application of Statistical Process Control (SPC) as a tool for monitoring temporal variability in soybean seed quality during harvesting operations.

4.6. Practical Implications and Future Research

The results demonstrate that integrating Statistical Process Control (SPC) into soybean seed harvesting operations can substantially improve process monitoring and provide a more comprehensive understanding of the factors affecting seed quality. By identifying periods of instability and associating them with changes in Seed Moisture Content (SMC), machine adjustments, and operator interventions, SPC proved to be a valuable tool for evaluating both operational performance and seed quality throughout the harvesting operation.

From a practical perspective, the findings reinforce the importance of continuously monitoring SMC and operational parameters such as Cylinder Rotation Speed (CRS), Cylinder Opening (CO), and Displacement Speed (DS). The results also demonstrate that physiological quality attributes are sensitive indicators of harvesting-induced stress and may provide valuable information for decision-making during seed production.

The application of SPC offers opportunities for a more proactive management approach, allowing the identification of deviations from process stability before substantial reductions in seed quality occur. Such information may assist seed companies and ma-

chine operators in optimizing harvesting practices and improving the consistency of seed production systems.

Future studies should evaluate the application of SPC under different cultivars, environmental conditions, harvesting systems, and production regions to verify the robustness of the relationships observed in the present study. Additional research should also investigate the interactions among SMC, machine adjustments, and seed physiological responses under a broader range of harvesting scenarios.

Furthermore, the integration of SPC with on-board monitoring systems, real-time sensors, precision agriculture technologies, and automated decision-support tools may enhance the ability to detect process instability and support dynamic machine adjustment during harvesting. Such advances could contribute to more efficient harvesting operations and improved seed quality management.

5. Conclusions

Statistical Process Control (SPC) was effective for monitoring the physical and physiological quality of soybean seeds during mechanical harvesting, revealing temporal variations and periods of process instability that were not detected by conventional analyses based solely on treatment means.

Variability in seed quality was associated with fluctuations in Seed Moisture Content (SMC), machine adjustments, and operator interventions throughout the harvesting operation. Although mechanical damage did not differ significantly between harvesting systems, physiological quality attributes were more sensitive indicators of harvesting-related variability and better reflected differences in seed performance.

Under the evaluated harvesting conditions, the harvesting system represented by combine A produced seeds with higher purity (99% versus 98%), germination (97% versus 95%), accelerated aging performance (88% versus 83%), and seedling emergence (95% versus 93%), as well as lower electrical conductivity (87 versus $99 \mu\text{S cm}^{-1} \text{g}^{-1}$), compared with combine B. Mechanical damage did not differ significantly between harvesting systems, with mean values of 4.5% and 5.4% for combines A and B, respectively.

The results demonstrate that SPC is a valuable complementary tool for monitoring soybean seed harvesting, supporting decision-making and contributing to improved process management and seed quality preservation. These findings apply to the commercial harvesting systems and operational conditions evaluated in the present study and should not be interpreted as generalized effects of combine harvester models.

Author Contributions: Conceptualization, R.M.B., R.P.d.S. and R.D.V.; methodology, R.M.B., R.P.d.S. and R.D.V.; software, R.M.B.; validation, R.M.B., R.P.d.S. and R.D.V.; formal analysis, R.M.B., R.A.A. and C.C.M.; investigation, R.M.B., R.A.A. and C.C.M.; resources, R.P.d.S. and R.D.V.; data curation, R.M.B., R.A.A. and C.C.M.; writing—original draft preparation, R.M.B., R.A.A. and C.C.M.; writing—review and editing, R.M.B., R.P.d.S. and R.D.V.; visualization, R.M.B.; supervision, R.M.B., R.P.d.S. and R.D.V.; project administration, R.M.B.; funding acquisition, R.P.d.S. and R.D.V. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001.

Data Availability Statement: The data presented this study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors would like to thank Santa Cruz State University, São Paulo State University and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES).

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

Abbreviations

The following abbreviations are used in this manuscript:

AA	Accelerated Aging
CL	Center Line
CO	Cylinder Opening
CRS	Cylinder Rotation Speed
DS	Displacement Speed
EC	Electrical Conductivity
GE	Germination
LCL	Lower Control Limit
MD	Mechanical Damage
SE	Seedling Emergence
SMC	Seed Moisture Content
SPC	Statistical Process Control
UCL	Upper Control Limit

References

1. Sampaio, F.R.; Mora-Ocampo, I.Y.; Silva, F.D.A.; Oliveira, K.R.; Pirovani, C.P.; Barbosa, R.M. Identification of Subtle Differences in the Physiological Quality of Commercial Soybean Seed Lots Using Shotgun Proteomics During Germination. *Agronomy* **2025**, *15*, 609. [\[CrossRef\]](#)
2. Ebone, L.A.; Caverzan, A.; Tagliari, A.; Chiomento, J.L.T.; Silveira, D.C.; Chavarria, G. Soybean Seed Vigor: Uniformity and Growth as Key Factors to Improve Yield. *Agronomy* **2020**, *10*, 545. [\[CrossRef\]](#)
3. Ni, Y.; Jin, C.; Chen, M.; Qian, Z.; Yang, T.; Xu, J.; Liu, G. Soybean crushing forms by mechanical harvesting and factors affecting the proportions of different forms. *Food Sci. Technol.* **2023**, *43*, e111822. [\[CrossRef\]](#)
4. Zhang, X.; Ji, S.; Chen, L.; Zhou, M.; Xia, X. A Review of Mechanized Harvesting, Threshing, and Cleaning Devices for Pulses. *Agriculture* **2026**, *16*, 1051. [\[CrossRef\]](#)
5. Rajjou, L.; Duval, M.; Gallardo, K.; Catusse, J.; Bally, J.; Job, C.; Job, D. Seed Germination and Vigor. *Annu. Rev. Plant Biol.* **2012**, *63*, 507–533. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Finch-Savage, W.E.; Bassel, G.W. Seed vigour and crop establishment: Extending performance beyond adaptation. *J. Exp. Bot.* **2016**, *67*, 567–591. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Oliveira, K.R.; Sampaio, F.R.; Siqueira, G.S.; Galvão, I.M.; Bennett, S.J.; Gratão, P.L.; Barbosa, R.M. Physiological Quality of Soybean Seeds Grown under Different Low-Altitude Field Environments and Storage Time. *Plant Soil Environ.* **2021**, *67*, 77–84. [\[CrossRef\]](#)
8. Oliveira, G.R.F.; Cicero, S.M.; Krzyzanowski, F.C.; Gomes-Junior, F.G.; Batista, T.B.; França-Neto, J.B. Treatment of soybean seeds with mechanical damage: Effects on their physiological potential. *J. Seed Sci.* **2021**, *43*, e202143023. [\[CrossRef\]](#)
9. Liang, Z.; Qin, Y.; Su, Z. Establishment of a Feeding Rate Prediction Model for Combine Harvesters. *Agriculture* **2024**, *14*, 589. [\[CrossRef\]](#)
10. Vu, T.T.H.; Vu, N.T.; Le, T.T.C.; Pham, T.N. Soybean Yield, Seed Quality and Thresh Efficiency by Mechanisation at Different Harvesting Stages and Postharvest Ripening. *Vietnam J. Sci. Technol. Eng.* **2023**, *65*, 66–74. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Cunha, J.P.A.R.; Piva, G.; Oliveira, C.A.A. Effect of Threshing System and Harvester Speed on Soybean Seed Quality. *Biosci. J.* **2009**, *25*, 37–42. [\[CrossRef\]](#)
12. França-Neto, J.d.B.; Krzyzanowski, F.C.; Henning, A.A.; Pádua, G.P.d.; Lorini, I.; Henning, F.A. *Tecnologia da Produção de Semente de Soja de Alta Qualidade*; Number 380 in Documentos; Embrapa Soja: Londrina, Brazil, 2016; p. 82.
13. Lemes, E.M.; Catão, H.C.R.M. Soybean Seed Coat Cracks and Green Seeds—Predisposing Conditions, Identification and Management. *Seeds* **2024**, *3*, 133–148. [\[CrossRef\]](#)
14. Sałaciński, T.; Chrzanowski, J.; Chmielewski, T. Statistical Process Control Using Control Charts with Variable Parameters. *Processes* **2023**, *11*, 2744. [\[CrossRef\]](#)
15. Zwetsloot, I.M.; Jones-Farmer, L.A.; Woodall, W.H. Monitoring univariate processes using control charts: Some practical issues and advice. *Qual. Eng.* **2024**, *36*, 487–499. [\[CrossRef\]](#)
16. Arcoverde, S.N.S.; Souza, C.M.A.d.; Cortez, J.W.; Guazina, R.A.; Maciak, P.A.G. Quality of the Sowing Process of Second-Crop Corn. *Eng. Agric.* **2016**, *24*, 383–392. [\[CrossRef\]](#)
17. Paixão, C.S.S.; Chrispin, C.P.; Silva, R.P.d.; Gírio, L.A.S.; Voltarelli, M.A. Physical and Physiological Quality of Soybean Seeds at Three Speeds of the Harvester. *Rev. Bras. Eng. Agríc. Ambient.* **2017**, *21*, 214–218. [\[CrossRef\]](#)

18. Jesus, M.A.; Reis, V.M.A.; Sampaio, F.R.; Posse, F.L.; Barbosa, R.M. Quality Control Charts in the Processing of Soybean Seeds. *J. Seed Sci.* **2021**, *43*, e202143031. [[CrossRef](#)]
19. Silva, J.E.R.; Cunha, J.P.A.R.; Nomelini, Q.S.S. Statistical Process Control Applied to Airblast Sprayer on a Coffee Crop. *Coffee Sci.* **2016**, *11*, 11–21. [[CrossRef](#)]
20. Zerbato, C.M.; Furlani, C.E.A.; Ormond, A.T.S.; Gírio, L.A.d.S.; Carneiro, F.M.; Silva, R.P.d. Statistical Process Control Applied to Mechanized Peanut Sowing as a Function of Soil Texture. *PLoS ONE* **2017**, *12*, e0180399. [[CrossRef](#)] [[PubMed](#)]
21. Peloia, P.R.; Milan, M.; Romanelli, T.L.; Gimenez, L.M. Monitoring Performance Indicators of Mechanized Agricultural Operations Through a Systemic Method. *Sci. Agric.* **2023**, *80*, e20210143. [[CrossRef](#)]
22. Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; Gonçalves, J.L.d.M.; Sparovek, G. Köppen's Climate Classification Map for Brazil. *Meteorol. Z.* **2013**, *22*, 711–728. [[CrossRef](#)] [[PubMed](#)]
23. Ministério da Agricultura e Pecuária. *Regras para Análise de Sementes*; Secretaria de Defesa Agropecuária: Brasília, Brazil, 2025.
24. Krzyzanowski, F.C.; França-Neto, J.d.B.; Costa, N.P.d. *Teste do Hipoclorito de Sódio Para Semente de Soja*; Technical Report 37; Embrapa Soja: Londrina, Brazil, 2004.
25. Krzyzanowski, F.C.; Vieira, R.D.; Marcos-Filho, J.; França-Neto, J.d.B. (Eds.) *Vigor de Sementes: Conceitos e Testes*, 2nd ed.; ABRATES: Londrina, Brazil, 2020; p. 601.
26. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2025.
27. Automotive Industry Action Group. *Statistical Process Control (SPC)*, 2nd ed.; Automotive Industry Action Group: Southfield, MI, USA, 2005.
28. Montgomery, D.C. *Introduction to Statistical Quality Control*, 8th ed.; John Wiley & Sons: Hoboken, NJ, USA, 2020.
29. Li, P.; Liu, Z.; Wang, J.; Lv, L.; Jiang, A.; Yan, H.; Jin, C. Effects of Moisture Content on Mechanical Crushing Performance of Soybean Seeds and Its Application in Mechanized Harvesting. *INMATEH-Agric. Eng.* **2025**, *75*, 231–242. [[CrossRef](#)]
30. Carvalho, T.C.; Novembre, A.D.d.L.C. Soybean Seed Quality, Harvested by Hand and Mechanically, with Different Levels of Moisture Content. *Semin. Ciênc. Agrár.* **2012**, *33*, 155–166. [[CrossRef](#)]
31. Nunes, H.D.; Cortez, J.W.; Comparin, P.J.d.S.; Reis, G.N.d. Variabilidade espacial do desempenho operacional de colhedora de soja. *Sci. Agrar.* **2025**, *21*, 1–7 [[CrossRef](#)]
32. Jasper, S.P.; Zimmermann, G.G.; Savi, D.; Strapasson Neto, L.; Kmiecik, L.L.; Sobenko, L.R. Operational Performance and Energy Efficiency of Axial Harvesters with Single and Double Rotor Systems in Soybean Seed Harvest. *Ciênc. Agrotecnol.* **2021**, *45*, e031720. [[CrossRef](#)]
33. Carreira, V.d.S.; Aleixo, E.V.; Ribeiro, N.M.; Santos, J.d.N.; Silva, R.P.d. A Systematic and Meta-Analytical Review of Soybean Mechanized Harvesting in South America. *Rev. Bras. Eng. Agríc. Ambient.* **2024**, *28*, e265804. [[CrossRef](#)]
34. Looh, G.; Xie, F.; Wang, X.; Looh, A.; Hind, H. Grain Kernel Damage During Threshing: A Comprehensive Review of Theories and Models. *J. Agric. Eng.* **2025**, *56*, 1674. [[CrossRef](#)]
35. Shahbazi, F. A Study on the Seed Susceptibility of Wheat (*Triticum aestivum* L.) Cultiv. Impact Damage. *J. Agric. Sci. Technol.* **2012**, *14*, 505–512.
36. Chandra, J.; Masilamani, P.; Suthakar, B.; Rajkumar, P.; Sivakumar, S.; Manonmani, V. Impact of Harvesting and Threshing Methods of Rice: A Comprehensive Review on Seed Quality and Storage Behaviour. *Plant Sci. Today* **2025**, *12*, 8241. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.