Soybean Industry: A Review of Properties related to Mechanical Damage in Soybean seeds

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Abstract

Soybean industrialization involves different stages; harvesting, processing, storage, and transportation, through which seeds suffer mechanical damages that result in significant economic losses for producers. Therefore, to improve production processes it is convenient to identify the damage causes and methods used in the industry for its measurement, in order to mitigate losses linked to machinery. The objective of this work is to provide the reader an overview of the methods of mechanical resistance analysis of soybean seeds during processing. A review of the literature related to methods and properties associated with mechanical damage in soybean seeds from harvest to storage was conducted. For this purpose, 51 bibliographic references from 1971 to 2018 were grouped according to the mentioned stages and reviewed according to a set of proposed dimensions of analysis. Finally, it is concluded about similarities found in the analyzed works and identified common trends of research in the applied methods.

Keywords

Soybean seeds/grains, mechanical damage/properties, processes improvement

1. Introduction

Paraguay ranks fifth as one of the largest producers of soybean in the world. Currently, Paraguay has a weighted yield of 3.000 kg/ha, similar to Argentina, Brazil, and the United States (Salcedo, 2018). In 2017, 6.128.700 tons of soybean seeds equivalent to US$ 2.132 million were exported (BCP, 2017), which represents an amount of US$ 348 per tonne and whereupon, soybean has become one of the main products of export. For this reason, seeking to offer seeds that are suitable for trade or sowing, an agricultural research in the country has begun, aiming to improve soybean quality (Tomassone, 2018). Figure 1 shows the evolution of soybean seeds production in Paraguay from 1996 to 2016 (CAPECO, 2018).

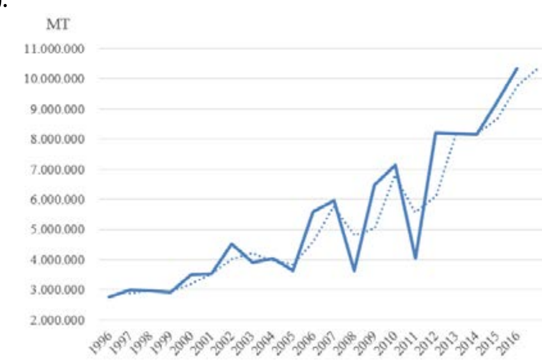

Figure 1. Evolution of soybean seeds production in Paraguay from 1996 to 2016.

In soybean industry seeds losses occur mainly due to mechanical damage at harvesting and processing, where a direct relation between damage and deterioration during storage exists. Since the rupture percentage of the seed is one of the parameters used to measure its quality, it is important to assess its evolution along all processes (Méndez and Roskopf, 2007). Damage can be mechanical, climatic, by insects, diseases or storage conditions (EEA INTA Manfredi, 2004).

For example, according to Bragachini *et al.* (2013), in 2012 harvest losses of soybean seeds in Argentina were in average 120 kg/ha. Considering a similar value for harvest in Paraguay, where planting area in 2017 was 3.388.709 hectares (CAPECO, 2018), losses would be 512.441 tons approximately, which means about US$ 178 million. If efficiency improved by 10%, based on (CAPECO, 2018) results, this improvement would represent US$ 18 million approximately, only at the harvesting stage.

This review article focuses on physical, geometric, and physiological properties associated with mechanical damage in soybean seeds due to handling, in order to propitiate decision making that allows processes improvement and design of machines at this industry.

2. Materials and Methods

This review of the literature was oriented to scientific articles, journals, and book chapters from different countries. These academic outputs were found in the following electronic databases: Elsevier Science Direct, Springer Link, Researchgate, Scielo, and Google scholar, which were chosen to achieve a comprehensive approach and cover transversal fields in the industrial area. The keywords were defined based on terms mostly used in the research field, including words related to soybean, mechanical properties, mechanical damage, and mechanical resistance of soybean seeds, combined with words linked to the industry and the stages of soybean production such as harvesting, processing and storage with variations and combinations in English, Portuguese, and Spanish.

To identify eligible cases, the titles and abstracts of articles and book chapters found were reviewed. For situations in which the title and abstract were unclear, a revision of the complete work was conducted. The total period was 48 years (from 1971 until 2018). The following data were extracted from each selected study (articles or book chapters): author/s, year of publication, country, stages (harvest, processing, storage), and dimensions of analysis: analyzed properties and/or effects, and methods applied by the authors.

3. Review of the literature

The compilation of studies has been focused specifically on soybean seeds, involving stages of harvesting, processing, and storage, without considering transport and distribution. Additionally, review articles were found, in which the quality of soybean seeds was analyzed (Salinas *et al*., 2008), and influenced during storage by mechanical damage suffered at harvesting and processing stages (Shelar, 2008). References found in these articles eased searching.

The thorough review of articles allowed a division of them into three groups: research related to harvesting, processing, and storage. These groups encompass articles where properties of soybean seed and their relation to mechanical damage were studied. For a better understanding of the research cited in the review, the following dimensions of analysis were proposed: properties, methods/techniques, and effects/results.

3.1. Research about harvesting

Philbrook and Oplinger (1989) presented a research in which the direct relation between mechanical damage produced by the harvester machines and the days of harvest delay were evaluated, this led to the reduction of soybean seed vigor and germination capacity, being these properties determined by germination and accelerated aging tests (Minuzzi *et al.*, 2007).

Mechanized and manual crop losses were quantified and evaluated by Compagnon *et al.* (2012) with an internal IntelliView monitor and, according to Gagare *et al.* (2014), based on the results of an analysis with the ferric chloride test, resistance to mechanical damage of soybean seeds is related to the threshing method, either this is mechanized or manual.

When the harvester's cylinder rotation increase, mechanical damage grows, and seeds with the least moisture content are most damaged (Neto and Troli, 2003). Because of this, the determination of the cylinder rotation depends on seed moisture, according to Pacheco *et al.* (2015), who pointed out that seed vigor and viability are inversely related to the cylinder rotation, based on the tetrazolium test. After a microscopic inspection of seeds collected by harvester machines, Ning *et al.* (2014) noted that mechanical damage is dependent on moisture content, and the greater the percentage of seed damage is, the germination capacity will be lower. Neto and Troli (2003) examined harvested seeds through a visual inspection and determined moisture content by drying them in an electric stove, similar to the research submitted by Magalhaes *et al.* (2009).

Seed moisture content was determined by Holtz and Fialho dos Reis (2013) through the oven drying method. In their work, they stated that the percentage of seed damage depends on its moisture content, which led to seed vigor and viability relation to the harvest moment (time).

Cunha and Zandbergen (2007) investigated about damage on soybean seeds with tangential flow combine harvesters and, evaluated losses through the methods of Embrapa (measuring cup) and Weighing. The authors conclude that losses have no correlation with age or ground speed of the combine harvester, unlike Paixão *et al.* (2017), who determined through a very used technique, the sodium hypochlorite test, that mechanical damage is dependent on the harvester ground speed. In addition, these authors measured electrical conductivity and vigor of soybean seeds through an electrical conductivity test. They also mentioned that as the damage is increased, seed vigor is reduced and electrical conductivity increased as well.

Costa *et al.* (1996) and Soza *et al.* (2014) also studied the damage caused by harvester machines. In the first study, they also considered manual harvesting in the analysis and concluded that there is a dependence of the damage on the threshing method and seed moisture. The second study affirmed the inverse relation of mechanical damage with moisture content and, in both studies, they analyzed damaged seeds with the sodium hypochlorite test. Costa *et al.* (1996) implemented the tetrazolium test for damage evaluation, and to determine the effects on seed germination, viability and, vigor they applied germination and accelerated aging tests, pointing out that these properties decreased with the increase of mechanical damage.

Costa *et al.* (2003) studied soybean seeds collected by harvester machines in different regions, evaluating seed damage with tetrazolium and sodium hypochlorite tests. They affirmed the damage dependence on the harvester machine type and determined the inverse relation of seed vigor, viability, and germination with damage, through germination and tetrazolium tests. Subsequently, they mentioned that damages were associated with moisture deterioration and insects, (Costa *et al*., 2005).

Cunha *et al.* (2009) analyzed the effects on soybean seeds resistance to mechanical damage with sodium hypochlorite test and determined that it depends on the harvester machine type (conventional cylinder, axial rotor and, double axial rotor). They agreed with the authors mentioned above, that seed germination and vigor were reduced with the increase of mechanical damage.

In a study presented by Sosnowski and Kuzniar (1999), soybean seeds were subjected to impacts with a rotating steel arm, determining that seed germination, studied through a sand bed test, was reduced with the increase of mechanical damage. On the other hand, Öztürk *et al.* (2017) analyzed the seed resistance to compression with a testing machine. Seed moisture content was determined through the oven drying method.
In the same way, using a Universal testing machine, Kuźniar *et al.* (2016) determined the inverse relation of mechanical damage with seed moisture content and elasticity modulus of soybean seeds.

3.2. Research about processing

Soybean seed quality can be affected through different processing stages, in which seeds are subjected to loads caused by machinery and manipulation.

In the research presented by Misra *et al.* (1985), it is stated that the use of a Conventional steel - flighting auger in handling causes damaged seeds, which were analyzed with the sodium hypochlorite test. According to the authors, from the germination test, it turned out that seed germination could change depending on seed moisture. With the increase of mechanical damage, seed germination capacity is reduced. In addition, it is mentioned that gravity separation and air screen cleaning in grain processing improved soybean lots.

To analyze soybean seed germination capacity, accelerated aging test was implemented by Parde *et al.* (2002), Vearasilp *et al.* (2001) and, Divsalar and Oskouie (2011). In the first study, authors observed seed resistance to mechanical damage through processing machinery. With the sodium hypochlorite test, they measured damage percentage and indicated that it depends on seed moisture. Through the oven drying method, they varied seed moisture and determined the inverse relation of seed germination and vigor with mechanical damage. Seed vigor was analyzed using a germination test, as in the second study, where seed germination was evaluated and, damages quantified with sodium hypochlorite test, concluding that there is a direct relation of mechanical damage with seed dimensions. Through the electrical conductivity test, seed vigor, viability and, electrical conductivity were evaluated, noting that damage increase reduced percentages of seed vigor and viability. This test was used in the third study, along with the tetrazolium test, through which authors determined that there was no variation in seed germination, viability and, vigor. With visual inspection and indoxyl acetate method, it was mentioned that there is a dependency of mechanical damage on seed size.

The authors, Polat *et al.* (2006) and Shirkole *et al.* (2011) implemented the oven drying method to determined soybean seed moisture and measured seeds terminal velocity in an air column, determining a direct relation of it with mechanical damage. In the first investigation, they measured the seed dimensions with a digital caliper, and the coefficient of friction using a friction testing machine, pointing out that these properties are directly related to seed moisture. In addition, the seed density was calculated with the liquid displacement method using water, unlike the second investigation in which the density was calculated with the mass per hectoliter method, noting that in both studies, the seed density decreased with the moisture increase. These last authors evaluated the coefficient of friction with a plastic cylinder on a tilting plane, measured the angle of repose, and also established a direct relation of these properties with soybean seed moisture content.

Similarly, Davies and El-Okene (2009), with a sample of soybean seeds in a box on a tilting plane indicated that there is a direct dependence of the coefficient of friction, the angle of repose, and seed dimensions on moisture content. They determined seed moisture through the oven drying method and calculated its density with the liquid displacement method, using water. According to the authors, density and moisture are inversely related.

Through a compression testing machine, Pan and Tangratanavalee (2003) analyzed soybean seed behavior when moisture content varies. They determined an inverse relation of elasticity modulus and compression with seed moisture.

3.3. Research about storage

The physicochemical characteristics of soybean seeds are affected by the period of storage, according to Narayan *et al.* (1988). They demonstrated through seed storage for periods of time, that density, moisture content, and seed weight decreased with time, while seed hardness is increased. They noted that seeds turned into brown color and infestation with insects was increased.

In order to evaluate soybean seed quality changes under established storage conditions, De Alencar *et al.* (2006) used the oven drying method to determine seed moisture, electrical conductivity test to measure vigor, and germination capacity.

Similarly, in the research conducted by Šimic *et al.* (2006), the changes in stored soybean seeds were analyzed and is mentioned that the length of time and storage conditions can affect the seed vigor and oil content. The authors determined the seed vigor through a cold test.

With the aim to design storage structures for soybean seeds, Kibar and Ozturk (2010) studied certain properties associated with seed moisture content. By determining the seed moisture level with the oven drying method, they noted its direct relation with seed dimensions and the coefficient of friction, calculated respectively, using a digital compass and a dynamometer. According to the authors, the angle of internal friction, measured with the direct shear method, grew with the increase in seed moisture, while the density, calculated with the liquid displacement method using toluene, decreased.

3.4. Research about harvest, processing and storage

The use of machinery for harvesting and processing leads to alterations in soybean seed quality that could generate significant losses depending on storage conditions. Evaluating soybean seeds mechanically harvested, Delouche (1971) noted that mechanical damage depends on seed moisture, and on the cylinder rotation of the harvester machine. Camolese *et al.* (2015) observed that seeds with lower moisture level suffered more mechanical damage. On the other hand, with the tetrazolium test, Lopes *et al.* (2010) analyzed seeds harvested manually and mechanically, pointing out that mechanical damage depends on the threshing method, as well as seed germination and vigor. Rollán *et al.* (2001) determined the dependence of germination with mechanical damage and moisture content. Paulsen *et al.* (1981) established an inverse relation of seed germination capacity with mechanical damage during harvesting. Through a rupture test the authors observed a direct relation of seed resistance with its moisture content and an inverse relation of resistance with the thresher cylinder speed.

Krittigamas *et al.* (2001) and El - Abady *et al.* (2012) determined that soybean seed germination and vigor are reduced over time in storage. These latest authors evaluated the quality of seeds stored for periods of time by calculating seed vigor, viability, and germination. They indicated that damage at harvesting stage is dependent on the seed coat thickness. Soybean germination capacity, and seed vigor were also analyzed by Schuch *et al.* (2009).

Deshpande *et al.* (1993) determined the soybean seed moisture level with the oven drying method and density through the liquid displacement method. They noted that seed dimensions grew with the moisture increase, while density decreased. The oven drying method was also used by Ribeiro *et al.* (2007) and Neves *et al.* (2016) to determine seed moisture. The first studied the seed resistance to compression through a Universal testing machine and determined that is inversely related to seed moisture content, as well as the seed elasticity modulus. The authors of the second study determined that seed vigor and viability are dependent on the processing stages.

Under compression, some properties of soybean seeds are affected depending on its moisture content. In order to optimize processes and machinery designs in seeds processing, Petru and Masin (2017) analyzed the mechanical behavior of seeds under compression, friction, or rupture forces. Tavakoli *et al.* (2009) used a tension/compression testing machine and observed that mechanical resistance decreases with the increase of the seed moisture level. On the other hand, they pointed out that the coefficient of friction, and the angle of repose are directly related to seed moisture, unlike density. In a study presented by Goli *et al.* (2016), seeds were tested under impact forces on a testing machine and then inspected visually. They pointed out that there is an inverse relation of compression with the velocity and number of impacts.

The soybean seed hardness is dependent on its moisture content, according to Lončarević *et al.* (2010), who studied seeds under compression with a testing machine and pointed out that the elasticity modulus decreases as seed moisture increases. The coefficient of friction was measured through a tilting plane test, presenting a direct relation with the seed moisture level.

Henry *et al.* (2000) analyzed soybean seeds resistance to compression using a testing machine and determined an inverse relation of resistance and elasticity modulus with moisture content. Tunde-Akintunde *et al.* (2005) compressed the seeds with a tensiometer machine and pointed out the dependence of damage with seed moisture. In addition, they established a direct relation of the seed terminal velocity in a wind tunnel with seed moisture and placed a sample of soybean seeds in a box on a tilting plane to calculate the coefficient of friction and the angle of repose. These latest properties were inversely related to moisture content. According to Kashaninejad *et al.* (2008) and Wandkar *et al.* (2012), the coefficient of friction and the angle of repose on different surfaces are higher with moisture content increase. In both studies, these properties were quantified with a sample of soybean seeds on an inclined plane.

The author Işik (2007) mentioned that seed coefficient of friction on different surfaces increased with the increase of seed moisture. In addition, seed density was determined through a standard test weight procedure, noting that it is inversely related to moisture, which was measured with a moisture meter. On the other hand, the terminal velocity of soybean seeds presented a direct relation with seed moisture and was obtained in an air column.

4. Discussion

The grouping of articles according to the stages: harvesting, processing, and storage allowed the elaboration of the following tables, which reflect the trend of research on the studied subject in accordance with the proposed dimensions of analysis: properties, Table 1; methods/techniques, Table 2; effects/results, Table 3.

Table 1. Studies on soybean seeds according to the properties

#	Author/s	**Properties** Physical	Geometrical	Physiological
1	Delouche (1971)	Mechanical damage resistance		
2	Paulsen *et al.* (1981)	Mechanical damage resistance, moisture		Germination
3	Misra *et al.* (1985)	Mechanical damage resistance		Germination
4	Narayan *et al.* (1988)	Density, moisture, mechanical damage resistance-hardness		
5	Philbrook and Oplinger (1989)	Mechanical damage resistance		

6	Deshpande *et al.* (1993)	Moisture, density	Dimensions	
7	Costa *et al.* (1996)	Mechanical damage resistance, moisture		Germination, vigor, viability
8	Sosnowski and Kuzniar (1999)	Compression resistance-impact		Germination
9	Henry *et al.* (2000)	Mechanical damage resistance-compression, elasticity modulus		
10	Vearasilp *et al.* (2001)	Mechanical damage resistance, electrical conductivity		Germination, vigor, viability
11	Rollán *et al.* (2001)	Mechanical damage resistance		Germination
12	Krittigamas *et al.* (2001)	Mechanical damage resistance, electrical conductivity		Germination, vigor, viability
13	Parde *et al.* (2002)	Mechanical damage resistance, moisture		Germination, vigor
14	Neto and Troli (2003)	Mechanical damage resistance, moisture		
15	Costa *et al.* (2003)	Mechanical damage resistance		Germination, vigor, viability
16	Pan and Tangratanavalee (2003)	Elasticity modulus, mechanical damage resistance-compression		
17	Costa *et al.* (2005)	Mechanical damage resistance, moisture		Germination, vigor, viability
18	Tunde-Akintunde *et al.* (2005)	Mechanical damage resistance-compression, moisture, terminal velocity, coefficient of friction, repose angle, volume	Dimensions	
19	Polat *et al.* (2006)	Moisture, density, terminal velocity, coefficient of friction	Dimensions	
20	Šimic *et al.* (2006)			Vigor
21	De Alencar *et al.* (2006)	Moisture, electrical conductivity		Germination, vigor
22	Minuzzi *et al.* (2007)			Germination, vigor
23	Cunha and Zandbergen (2007)	Mechanical damage resistance		
24	Ribeiro *et al.* (2007)	Mechanical damage resistance-compression, moisture, elasticity modulus		
25	Işik (2007)	Moisture, density, coefficient of friction, terminal velocity	Dimensions	
26	Kashaninejad *et al.* (2008)	Moisture, coefficient of friction, angle of repose, volume	Dimensions	
27	Cunha *et al.* (2009)	Mechanical damage resistance		Germination, vigor
28	Magalhães *et al.* (2009)	Mechanical damage resistance, moisture		
29	Davies and El-Okene (2009)	Moisture, density, angle of repose, coefficient of friction	Dimensions	
30	Tavakoli *et al.* (2009)	Mechanical damage resistance-compression, moisture, density, coefficient of friction, angle of repose	Dimensions	
31	Schuch *et al.* (2009)			Germination, vigor
32	Kibar and Öztürk (2010)	Coefficient of friction, moisture, angle of internal friction, density	Dimensions	
33	Lončarević *et al.* (2010)	Mechanical damage resistance-hardness, density, volume, coefficient of friction, elasticity modulus		
34	Divsalar and Oskouie (2011)	Mechanical damage resistance, electrical conductivity, moisture		Germination, vigor, viability
35	Shirkole *et al.* (2011)	Moisture, angle of repose, density, coefficient of friction, terminal velocity		
36	Lopes *et al.* (2011)	Mechanical damage resistance, moisture, electrical conductivity		Germination, vigor
37	Compagnon *et al.* (2012)	Mechanical damage resistance, moisture		
38	El - Abady *et al.* (2012)	Mechanical damage resistance, moisture, electrical conductivity		Germination, vigor, viability
39	Wandkar *et al.* (2012)	Moisture, angle of repose, coefficient of friction, density	Dimensions	
40	Holtz and Fialho dos Reis (2013)	Mechanical damage resistance, moisture, electrical conductivity		Vigor, viability
41	Gagare *et al.* (2014)	Mechanical damage resistance		
42	Ning *et al.* (2014)	Mechanical damage resistance		Germination
43	Soza *et al.* (2014)	Mechanical damage resistance, moisture		
44	Pacheco *et al.* (2015)	Mechanical damage resistance, moisture		Germination, vigor, viability
45	Camolese *et al.* (2015)	Mechanical damage resistance, moisture		
46	Kuźniar *et al.* (2016)	Mechanical damage resistance, moisture, elasticity modulus		
47	Goli *et al.* (2016)	Resistance to compression-impact, moisture		Germination
48	Neves *et al.*(2016)	Electrical conductivity, mechanical damage resistance, moisture		Germination, vigor, viability
49	Paixão *et al.* (2017)	Mechanical damage resistance, moisture, temperature, electrical conductivity		Vigor
50	Öztürk *et al.* (2017)	Mechanical damage resistance-compression, moisture		
51	Petru and Masin (2017)	Mechanical damage resistance		

Table 2. Studies on soybean seeds according to methods and measurement techniques

#	**Author/s**	**Methods and techniques of measurement**	
		Properties	Effects
1	Delouche (1971)	Combine harvester	
2	Paulsen *et al*. (1981)	Tetrazolium test, cold germination test, Stein breakage test, combine harvester, storing for periods of time, drying in containers	Tetrazolium test
3	Misra *et al*. (1985)	Conventional steel-flighting auger, germination test	Sodium hypochlorite test
4	Narayan *et al*. (1988)	Storing for periods of time	
5	Philbrook and Oplinger (1989)	Combine harvester	
6	Deshpande *et al*. (1993)	Micrometer, oven drying method, liquid displacement method	
7	Costa *et al*. (1996)	Combine harvester, manual harvesting, moisture meter: Dole 400, tetrazolium test, accelerated aging test, germination test	Sodium hypochlorite test, tetrazolium test
8	Sosnowski and Kuzniar (1999)	Germination test in a sand bed	Rotating steel arm machine
9	Henry *et al*. (2000)	Testing machine: Instron	
10	Vearasilp *et al*. (2001)	Accelerated aging test, tetrazolium test, electrical conductivity test	Visual inspection, Indoxyl acetate method
11	Rollán *et al*. (2001)	Germination test	Sodium hypochlorite test
12	Krittigamas *et al*. (2001)	Storing for periods of time, germination test, tetrazolium test, accelerated aging test, electrical conductivity test	
13	Parde *et al*. (2002)	Accelerated aging test, germination test, oven drying method, seeds processing machinery	Sodium hypochlorite test
14	Neto and Troli (2003)	Oven drying method, combine harvester	Visual inspection
15	Costa *et al*. (2003)	Germination test, tetrazolium test	Tetrazolium test, sodium hypochlorite test
16	Pan and Tangratanavalee (2003)	Compression testing machine	
17	Costa *et al*. (2005)	Tetrazolium test, moisture meter, combine harvester, germination test	Sodium hypochlorite test, tetrazolium test
18	Tunde-Akintunde *et al*. (2005)	Tensiometer machine: Avery, liquid displacement method, moisture meter, micrometer, wind tunnel, seeds sample on an inclined plane	
19	Polat *et al*. (2006)	Oven drying method, digital caliper, liquid displacement method-water, air column, friction testing machine	
20	Šimic *et al*. (2006)	Cold test	
21	De Alencar *et al*. (2006)	Oven drying method, electrical conductivity test	
22	Minuzzi *et al*. (2007)	Germination test, accelerated aging test	
23	Cunha and Zandbergen (2007)	Combine harvester	Embrapa method, Weighting method
24	Ribeiro *et al*. (2007)	Universal testing machine: TA Hdi Texture Analyser, oven drying method	
25	Işik (2007)	Moisture meter, standard test weight procedure, digital compass, cylindrical pipe on inclined plane, air column	
26	Kashaninejad *et al*. (2008)	Liquid displacement method, oven drying method, digital caliper, seeds sample on an inclined plane	
27	Cunha *et al*. (2009)	Germination test	Sodium hypochlorite test
28	Magalhães *et al*. (2009)	Combine harvester, oven drying method	Visual inspection
29	Davies and El-Okene (2009)	Oven drying method, micrometer, topless and bottomless cylinder, seeds sample on an inclined plane, liquid displacement method-water	
30	Tavakoli *et al*. (2009)	Tension/compression testing machine, oven drying method, digital caliper, liquid displacement method-toluene, angle of repose apparatus	
31	Schuch *et al*. (2009)	Accelerated aging test, germination test	
32	Kibar and Öztürk (2010)	Digital dynamometer, digital compass, direct shear method, oven drying method, liquid displacement method-toluene	
33	Lončarević *et al*. (2010)	Compression testing machine: TMS - PRO, liquid displacement method, inclined plane test	
34	Divsalar and Oskouie (2011)	Electrical conductivity test, germination test, accelerated aging test, moisture meter	Sodium hypochlorite test
35	Shirkole *et al*. (2011)	Oven drying method, sun drying method, mass per hectoliter method, angle of repose apparatus, plastic cylinder on inclined plane, air column	
36	Lopes *et al*. (2011)	Manual harvesting, combine harvester, oven drying method, electrical conductivity test, germination test, accelerated aging test, tetrazolium test	Tetrazolium test
37	Compagnon *et al*. (2012)	Combine harvester, moisture meter: Dicker-John multigrain model	Internal IntelliView monitor
38	El - Abady *et al*. (2012)	Storing for periods of time, manual and mechanized harvesting, germination test, accelerated aging test, oven drying method, electrical conductivity meter: CMD 830 WPA	
39	Wandkar *et al*. (2012)	Oven drying method, Vernier caliper, bottomless cylinder on inclined plane, seeds sample on an inclined plane, liquid displacement method-toluene	
40	Holtz and Fialho dos Reis (2013)	Combine harvester, moisture meter: Motonko, oven drying method, tetrazolium test, electrical conductivity test	
41	Gagare *et al*. (2014)	Combine harvester, manual threshing	Ferric chloride test

42	Ning *et al*. (2014)	Germination test, combine harvester	Microscopic inspection
43	Soza *et al*. (2014)	Combine harvester, moisture meter	Sodium hypochlorite test
44	Pacheco *et al*. (2015)	Combine harvester, moisture meter, germination test, tetrazolium test	
45	Camolese *et al*. (2015)	Combine harvester, moisture meter: Agrologic AL-101	Visual inspection
46	Kuźniar *et al*. (2016)	Universal testing machine: Zwick, oven drying method	
47	Goli *et al*. (2016)	Germination test, oven drying method, impact testing machine	Visual inspection
48	Neves *et al*.(2016)	Tetrazolium test, germination test, accelerated aging test, electrical conductivity meter, oven drying method	Sodium hypochlorite test
49	Paixão *et al*. (2017)	Combine harvester, moisture meter: G600, electrical conductivity test	Sodium hypochlorite test
50	Öztürk *et al*. (2017)	Testing machine: Lloyd LRX plus, oven drying method	
51	Petru and Masin (2017)		

Table 3. Studies on soybean seeds according to the analyzed effects or results

#	Author/s	Effects or results
1	Delouche (1971)	*Dependency of mechanical damage on the cylinder rotation of harvester machine and moisture; dependency of storage conditions on moisture content*
2	Paulsen *et al*. (1981)	*Inverse relation of germination with mechanical damage; direct relation of mechanical damage resistance with moisture and an inverse relation with cylinder speed*
3	Misra *et al*. (1985)	*Inverse relation of germination with mechanical damage and dependency on moisture content*
4	Narayan *et al*. (1988)	*Inverse relation of density and moisture with the period of storage; direct relation of hardness with the period of storage*
5	Philbrook and Oplinger (1989)	*Direct relation of mechanical damage with days of harvest delay*
6	Deshpande *et al*. (1993)	*Direct relation of seed dimensions and volume with moisture; inverse relation of density with moisture*
7	Costa *et al*. (1996)	*Dependency of mechanical damage on threshing method and moisture; inverse relation of germination, vigor, and viability with mechanical damage*
8	Sosnowski and Kuzniar (1999)	*Inverse relation of germination with mechanical damage*
9	Henry *et al*. (2000)	*Inverse relation of resistance to compression and elasticity modulus with moisture content*
10	Vearasilp *et al*. (2001)	*Dependency of mechanical damage on seed size; there was no variation of germination, vigor, and viability*
11	Rollán *et al*. (2001)	*Dependency of germination on mechanical damage and moisture content*
12	Krittigamas *et al*. (2001)	*Inverse relation of germination and vigor with the period of storage*
13	Parde *et al*. (2002)	*Inverse relation of germination and vigor with mechanical damage; dependency of mechanical damage on moisture*
14	Neto and Troli (2003)	*Inverse relation of moisture with mechanical damage; direct relation of mechanical damage with cylinder rotation speed*
15	Costa *et al*. (2003)	*Inverse relation of vigor, viability, and germination with mechanical damage; dependency of mechanical damage on the harvester machine type*
16	Pan and Tangratanavalee (2003)	*Inverse relation of elasticity modulus and compression with seed moisture*
17	Costa *et al*. (2005)	*Inverse relation of germination, vigor, and viability with mechanical damage*
18	Tunde-Akintunde *et al*. (2005)	*Dependency of mechanical damage on moisture; direct relation of seed dimensions and terminal velocity with moisture; inverse relation of coefficient of friction and angle of repose with moisture*
19	Polat *et al*. (2006)	*Direct relation of seed dimensions, terminal velocity, and coefficient of friction with moisture content; inverse relation of density with moisture content*
20	Šimic *et al*. (2006)	*Dependency of vigor and oil content on storage conditions*
21	De Alencar *et al*. (2006)	*Resulting measurement of moisture content, electrical conductivity, germination, and vigor*
22	Minuzzi *et al*. (2007)	*Inverse relation of seed germination and vigor with harvest delay*
23	Cunha and Zandbergen (2007)	*There is no relation of seeds losses with age nor ground speed of the harvester machine*
24	Ribeiro *et al*. (2007)	*Inverse relation of resistance to compression and elasticity modulus with moisture content*
25	Işik (2007)	*Direct relation of seed dimensions, coefficient of friction, and terminal velocity with moisture; inverse relation of density with moisture*
26	Kashaninejad *et al*. (2008)	*Direct relation of volume, seed dimensions, coefficient of friction, and angle of repose with moisture content*
27	Cunha *et al*. (2009)	*Dependency of mechanical damage on the harvester machine type; inverse relation of seed germination and vigor with mechanical damage*
28	Magalhães *et al*. (2009)	*Resulting measurement of mechanical damage resistance and moisture content*
29	Davies and El-Okene (2009)	*Direct relation of dimensions, angle of repose, and coefficient of friction with moisture content; inverse relation of density with moisture content*
30	Tavakoli *et al*. (2009)	*Inverse relation of resistance to compression and density with moisture content; direct relation of seed dimensions, coefficient of friction, and angle of repose with moisture content*
31	Schuch *et al*. (2009)	*Resulting measurement of seed vigor and germination*
32	Kibar and Öztürk (2010)	*Direct relation of coefficient of friction, seed dimensions, and angle of internal friction with moisture content; inverse relation of density with moisture content*
33	Lončarević *et al*. (2010)	*Dependency of seed hardness on moisture; direct relation of volume and coefficient of friction with moisture; inverse relation of density and elasticity modulus with moisture*
34	Divsalar and Oskouie (2011)	*Inverse relation of vigor and viability with mechanical damage; direct relation of mechanical damage with seed dimensions*

35	Shirkole *et al.* (2011)	*Direct relation of angle of repose, coefficient of friction, and terminal velocity with moisture content; inverse relation of density with moisture content*
36	Lopes *et al.* (2011)	*Dependency of mechanical damage, germination, and vigor on threshing method*
37	Compagnon *et al.* (2012)	*Resulting measurement of mechanical damage resistance and moisture content*
38	El - Abady *et al.* (2012)	*Dependency of mechanical damage on seed coat; inverse relation of germination, vigor, and viability with the period of storage*
39	Wandkar *et al.* (2012)	*Direct relation of seed dimensions, angle of repose, and coefficient of friction with moisture; inverse relation of density with moisture*
40	Holtz and Fialho (2013)	*Dependency of vigor and viability on harvest time; dependency of mechanical damage on moisture*
41	Gagare *et al.* (2014)	*Dependency of mechanical damage on threshing method*
42	Ning *et al.* (2014)	*Inverse relation of germination with mechanical damage; direct relation with moisture content*
43	Soza *et al.* (2014)	*Inverse relation of mechanical damage with moisture content*
44	Pacheco *et al.* (2015)	*Dependency of cylinder rotation on moisture content; resulting measurement of moisture; inverse relation of vigor and viability with cylinder rotation*
45	Camolese *et al.* (2015)	*Inverse relation of mechanical damage with moisture content*
46	Kuźniar *et al.* (2016)	*Inverse relation of mechanical damage resistance and elasticity modulus with moisture content*
47	Goli *et al.* (2016)	*Inverse relation of germination with mechanical damage; inverse relation of resistance to compression with number and velocity of impacts*
48	Neves *et al.*(2016)	*Dependency of vigor and viability on processing stages*
49	Paixão *et al.* (2017)	*Dependency of mechanical damage resistance on harvester ground speed; inverse relation of seed vigor with electrical conductivity; direct relation of electrical conductivity with mechanical damage*
50	Öztürk *et al.* (2017)	*Resulting measurement of mechanical damage resistance*
51	Petru and Masin (2017)	*Resulting evaluation of mechanical behavior of seeds*

5. Conclusion

The research on this area is mostly developed in Brazil, where seeds resistance to mechanical damage caused mainly at the harvesting stage is analyzed. See Figure 2. In addition, considering the most studied stages, it is concluded that 37% of works are focused on harvest, 16% on processing, 8% on storage and, 39% on the combination of these stages.

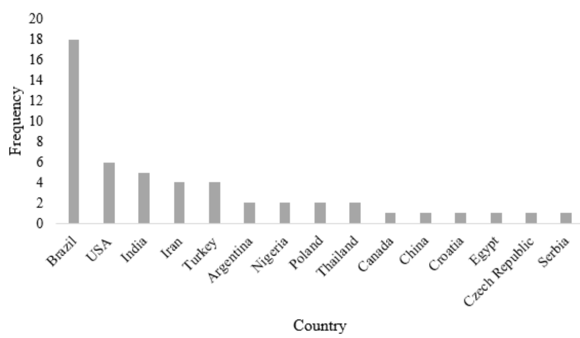

Figure 2. Number of studies presented by country

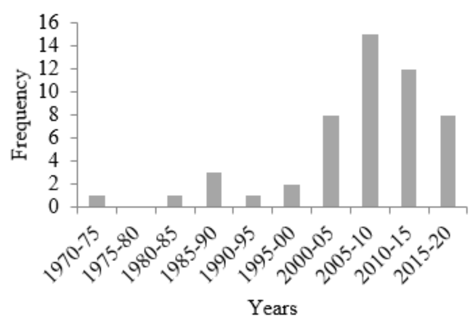

Figure 3. Number of studies presented by year

In chronological order, Figure 3 shows that the scientific interest in issues related to properties of soybean seeds tends to increase. In the last decade, the most commonly used methods to analyze the effects of mechanical damage on soybean seeds are the sodium hypochlorite test and visual inspections. While, for the analysis of properties related to mechanical damage the predominant methods are: oven drying method, to determine the grain moisture content; germination test, to evaluate the germination capacity of seeds; the use of different models of combine machines to study mechanical damage at harvesting; electrical conductivity test, to determine the grain electrical conductivity; fluid displacement method, to determine the density and volume; accelerated aging test, to evaluate the strength and viability of seeds; and the test of tetrazolium, to analyze the germination, vigor, viability, and damage in soybean seeds.

Deterioration of soybean seeds is influenced by mechanical damage caused at the stages of harvesting and processing (Salinas, 2008), which leads to a decrease of seed quality during storage, which is consistent with Shelar (2008). After the review, most applied methods to study mechanical damage in soybean seeds and the relation with their properties can be identified, in order to design tests that allow studying the mechanical behavior of grains. The study in this area offers the possibility of achieving improvements in machine design used in the stages of harvesting and processing, reducing the losses of soybean grains in the industry.

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