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Review

A systematic and meta-analytical review of soybean mechanized harvesting in South America[1]

Uma revisão sistemática e meta-analítica da colheita mecanizada de soja na América do Sul

Vinicius dos S. Carreira[2*], Edward V. Aleixo[2], Nágilla M. Ribeiro[3], Jamile do N. Santos[2] & Rouverson P. da Silva[2]

[1] Research developed at Universidade Estadual Paulista, Faculdade de Ciências Agrárias e Veterinárias, Jaboticabal, SP, Brazil
[2] Universidade Estadual Paulista/Faculdade de Ciências Agrárias e Veterinárias/Departamento de Engenharia e Ciências Exatas, Jaboticabal, SP, Brazil
[3] Universidade Estadual Paulista/Faculdade de Ciências Agrárias e Veterinárias/Departamento de Ciências da Produção Agrícola, Jaboticabal, SP, Brazil

HIGHLIGHTS:
Combine harvesters with over 10 years of use may present higher soybean losses.
Operations at ground speeds exceeding 5 km h^{-1} does not increase grain losses.
The monitoring of soybean losses lacks a thoroughly analysis of crop-machine interactions.

ABSTRACT: Grain losses pose a threat to agricultural sustainability, particularly in developing countries. Mechanized harvesting is a key process in which losses occur; thus, its investigation is essential. Therefore, a systematic and meta-analytical review was conducted to encompass studies on quantitative soybean losses during harvesting in South America from the last two decades. The initial search yielded 1,094 scientific articles; however, only 25 studies met the inclusion criteria. This study provides an overview of technical aspects monitored on farms, guidelines to ensure efficient harvesting and literature gaps for further innovations. Because studies on soybean losses were predominantly based on continuous observational data and lacked methodological quality according to a quality scoring, only four studies were included in the meta-analysis. The meta-analysis results showed a significant relation between losses and the combine age, indicating that combines with over 10 years of use result in higher losses than newer ones ($p \leq 0.05$). Conversely, operating at speeds exceeding 5 km h^{-1} did not lead to significant increases in soybean losses ($p > 0.05$). Many decisions can be taken at the farm-level to reduce losses, such as proper training of workers and adequation of combine harvesters according to each crop condition. The insights described here are timely for paving the way towards innovation in harvesting systems and minimizing grain losses by understanding the critical points within the context improving yields during soybean harvesting.

Key words: crop monitoring, combine harvester, sustainability, agricultural mechanization

RESUMO: As perdas de grãos ameaçam a sustentabilidade na agricultura, especialmente em países em desenvolvimento. A colheita mecanizada é um importante estágio em que as perdas ocorrem, sendo crucial investigá-la. Portanto, uma revisão sistemática e meta-analítica foi conduzida para analisar estudos das últimas duas décadas no tema de perdas quantitativas de soja durante a colheita mecanizada na América do Sul. A pesquisa inicial resultou em 1094 artigos científicos, entretanto, apenas 25 estudos foram selecionados devido ao critério de inclusão estabelecido. Essa revisão descreve uma visão ampla dos aspectos técnicos monitorados no campo, instruções para garantir uma colheita eficiente e lacunas da literatura para futuras inovações. Os estudos foram predominantemente baseados em dados contínuos e observacionais, além de possuírem falhas metodológicas de acordo com uma pontuação qualitativa. Assim, apenas quatro estudos foram incluídos na meta-análise. Os resultados mostraram uma relação significativa entre perdas relacionadas à idade da máquina, indicando que colhedoras com mais de 10 anos de uso produziram perdas maiores que as novas ($p \leq 0.05$). Por outro lado, operar em velocidades maiores que 5 km h^{-1} não levou a um aumento significativo das perdas de grãos ($p > 0.05$). No campo, muitas decisões podem ser tomadas para reduzir as perdas, e.g., treinar operadores e configurar a colhedora de acordo com as condições da lavoura. As discussões apresentadas nessa revisão são importantes para guiar as inovações em sistemas de colheita e diminuir as perdas de grãos ao entender os pontos críticos em um conceito de maior lucratividade durante o processo.

Palavras-chave: monitoramento agrícola, colhedora de grãos, sustentabilidade, mecanização agrícola

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* Corresponding author - E-mail: vs.carreira@unesp.br
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Introduction

Global food demand has increased due to population growth. It has become an agricultural challenge considering the limited expansion of croplands and scarcity of natural resources (Liu et al., 2021). Moreover, food security is threatened by large food losses. South America is under this global pressure and faces a sustainability challenge. The unprecedented growth in soybean croplands since 2000 promoted the deforestation, mainly in the Brazilian Amazon and Cerrado biomes (Song et al., 2021). Scientists and lawyers have proposed policy recommendations, but a thought-provoking mindset remains: to produce without deliberately expanding the agricultural frontier. Soybeans have been grown worldwide in an area that expanded from 23.2 million hectares in 1961 to 120.5 million hectares in 2019 (FAO, 2020), resulting in an annual production of 363.4 million Mg (FAO, 2020). This production is attributed to the soybean grain properties as a rich source of proteins, essential amino acids and oil (Chen et al., 2022; Szpunar-Krok & Wondołowska-Grabowska, 2022). In South America, soybean has become a strategic commodity, with massive growth over the last twenty years (Song et al., 2021; Zalles et al., 2021). Moreover, South American countries share a similar agribusiness system, driven by the demand from the People's Republic of China for this versatile grain (Giraudo, 2020).

Therefore, considering soybean losses and the importance of mechanized harvesting in South America, a systematic and meta-analytical review was conducted to: (i) establish and analyze the state-of-the-art in soybean harvesting; (ii) understand the interactions between combine harvesters, crop conditions and quantitative grain losses (iii) identify techniques, insights, policies and future directions towards grain losses reduction.

Material and Methods

Data source and search strategy

The PRISMA protocol was used to guide this systematic review and meta-analysis (Page et al., 2021). All authors were aware of each topic, adopting the same search, review and commentary strategy. A literature survey was performed in May 2021 to collect studies from four databases: Scopus, Web of Science, Scielo and Latindex, selecting high-visibility scholarly items published from 2000 to 2021. Keywords related to the main topics were used, combined with Boolean operators in search engine strings: soybean loss* AND harvest* OR combine harvest*, limited to English, Spanish and Portuguese languages. Recent articles were used to execute the 'backward snowballing technique' to find and include relevant and frequent articles. Two authors performed an initial search through titles and abstracts, and a third author resolved discrepancies.

Eligibility criteria

The inclusion criteria were: (i) original article; (ii) after 2000; (iii) monitored losses during soybean harvesting; (iv) described the combine harvester; (v) monitored combine harvesters in South America. Thus, a double-check was conducted to ensure consistency of the documents, especially regarding materials and methods.

Data extraction and analysis

A spreadsheet was developed containing the main variables during soybean mechanized harvesting, which were categorized into five groups: general crop information, combine harvester information, material and methods, soybean loss results and social characteristics. The GetData software (http://getdata-graph-digitizer.com) was used for graph-only data to extract values using their coordinates. Moreover, manufacturer websites and manuals were searched for obtaining machine information, such as threshing system and engine power. A systematic process of qualitative selection was conducted before meta-analysis of these observational data. The studies were not randomized (only monitoring), and the usual risk-of-bias assessment was not performed. Thus, seven variables were selected and ranked as indispensable for effective monitoring practices, aiming to reduce risk-of-bias through methodological quality score (Almeida & Goulart, 2017). Subsequently, a percentage ranking was developed to determine included studies (number of indispensable variables addressed by the articles). Then, studies falling below a 50% threshold were excluded from the meta-analysis. Studies presenting only a single observation were also excluded. These articles, along with those presenting data without providing comparisons of attributes, were used only for data summarization in the systematic review without any meta-analysis.

The data was analyzed using the programming language R v. 4.3.0. A dataset with values of mean, range, standard deviation and number of observations was created. The meta-analysis was conducted only when more than two articles were available. To express the difference between groups in the articles selected for the meta-analysis, Cohen's d was used to estimate the Standardized Means Difference (SMD) as effect size. A p-value ≤ 0.05 was considered statistically significant. The data heterogeneity was assessed using the I^2 and Cochran's Q-test (Higgins et al., 2003; Huedo-Medina et al., 2006).

Results and Discussion

The number of publications remained constant until 2014, and had a threefold increase from 2014 to 2020, as illustrated in Figure 1. A total of 1,094 articles were initially identified in the databases. After an analysis of duplicates, 824 articles were excluded. A second screening was conducted, resulting in the elimination of another 216 articles due to titles and abstracts not meeting the established eligibility criteria. Subsequently, 54 studies were thoroughly examined based on the inclusion criteria, and then 25 articles were selected and incorporated into the database, as represented in the flowchart (Figure 2). The systematic and meta-analytical review encompassed approximately 1,336 combine harvesters across the analyzed studies. Considering the selected articles, sixteen of them were published in the past decade, the oldest is dated 2003 and the most recent is from 2021 (Table 1).

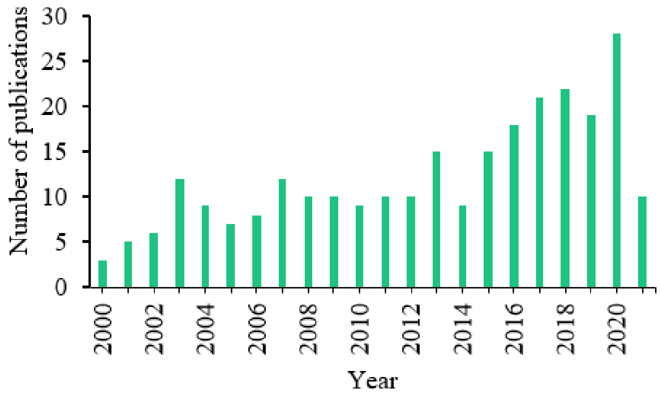

Figure 1. Number of publications related to the research topic 'soybean harvesting losses' from 2000-2021 in the databases Scopus, Web of Science, Scielo and Latindex

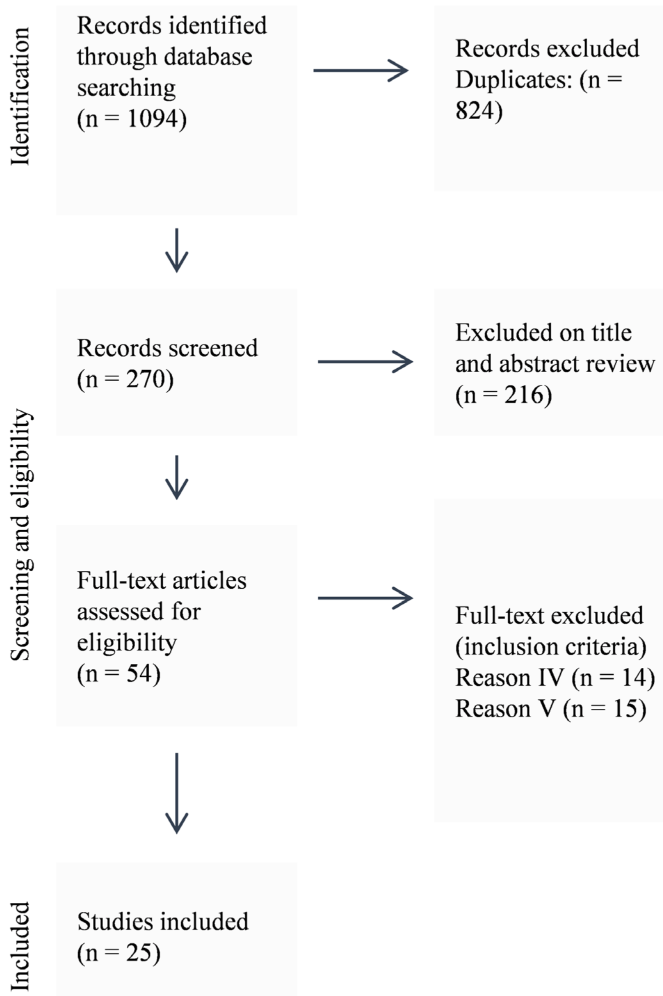

Figure 2. PRISMA flowchart indicating the number of articles in each screening step

Information on affiliation and funding sources were obtained from the unscreened articles. The affiliation with the highest number of citations was the Brazilian Agricultural Research Corporation (EMBRAPA) (n = 16). Most research studies were funded by government agencies focused on education and research (n = 27). Two private agribusiness institutions were also acknowledged, indicating a weak yet emerging public-private partnership. Soybean loss monitoring was heterogeneous across South America. This heterogeneity can be attributed to various factors, including socioeconomic differences and inequality. Moreover, the number of combine harvesters may be related to the researcher's workplace or affiliation.

Table 1. ID and references used in the literature review

ID	Reference	ID	Reference
1	Pinheiro Neto & Troli (2003)	14	Paulsen et al. (2014)
2	Campos et al. (2005)	15	Cassia et al. (2015)
3	Mesquita et al. (2006)	16	Camolese et al. (2015)
4	Ferreira et al. (2007)	17	Zandonadi et al. (2015)
5	Cunha & Zandbergen (2007)	18	Paixão et al. (2016)
6	Bauer & Gonzatti (2007)	19	Lima et al. (2017)
7	Toledo et al. (2008)	20	Menezes et al. (2018)
8	Magalhães et al. (2009)	21	Acosta et al. (2018)
9	Schanoski et al. (2011)	22	Cortez et al. (2019)
10	Chioderoli et al. (2012)	23	Vega et al. (2021)
11	Machado et al. (2012)	24	Jasper et al. (2021)
12	Holtz & dos Reis (2013)	25	Souza et al. (2021)
13	Loureiro Junior et al. (2014)		

These studies primarily focused on monitoring commercial areas, where a wide range of combine harvester models were employed. No individual manufacturer exerted dominant control over the majority of the observed combine harvesters. However, New Holland (Amsterdam, Netherlands) (n = 26) and Massey Ferguson (Duluth, USA) (n = 26) combine harvesters were the most cited. Additionally, there was a greater presence of axial (n = 35) over tangential (n = 33) threshing systems. Engine power was diverse (108-468 hp, n = 65), as well as header size (4.80-12.1 m, n = 28), which were strongly correlated with farm size.

Soil conditions, including the presence of stones, moisture levels and presence of weed, as well as plant inclination, were not mentioned in any of the studies. Furthermore, the observed straw cover after harvesting ranged from 60.26 to 82.64% (n = 4), which is below the recommended levels for no-till crop systems (Chioderoli et al., 2012). A proper distribution of plant residues is essential in no-till systems to ensure an effective conservative system, minimizing soil-related issues and enhancing nutrient availability (Yin et al., 2018). Four studies considered pod insertion height, and no assessment of spatial variability was found within these datasets. Pod insertion heights were found to be close to the ground and above the header's height, ranging from 105 to 187 mm (n = 4), which is consistent with the determinate and erect growth characteristic of soybean plants. Grain moisture was the most cited variable (n = 63), which can be quickly measured using a portable meter (n = 4), making it a convenient and rapid method. Alternatively, laboratory drying methods were also employed, with longer processing times of up to one day (n = 5). Plant morphological characteristics and yield measurements were typically evaluated by randomly sampling and measuring plants within experimental plots (n = 4). Reported soybean yields ranged from 2,340 to 4,861 kg ha^{-1} (n = 39), close to the average soybean yield in Brazil (CONAB, 2021). Area slope was given as general topography but not measured (n = 1). None of the articles described the use of desiccants; few studies showed a positive correlation between climate conditions and quantitative or qualitative losses (n = 4).

A gap was identified in the literature concerning specific settings related to combine harvesters (Table 2), such as fan speed (n = 0), concave opening (n = 3), reel speed (n = 22), and

Table 2. Machine and method-related variables extracted from each study in the literature review

ID	Man.	Age	TS*	HM*	GS*	CS	FS	CO	RS	HH	ET	RM*	HL*	TL*	UC	EA
1	-	-	-	-	-	X	-	-	-	-	-	X	-	X	-	-
2	X	X	X	-	X	-	-	-	-	-	-	X	-	X	X	-
3	-	X	-	-	X	-	-	-	-	-	-	X	-	X	-	-
4	X	X	X	X	X	X	-	X	X	-	-	-	X	X	X	-
5	-	X	-	-	X	-	-	-	-	-	-	X	-	X	-	-
6	X	X	X	X	-	-	-	-	-	-	-	-	X	X	X	-
7	X	-	X	X	X	X	-	-	-	-	-	X	-	X	X	-
8	X	X	X	X	X	X	-	-	X	-	-	X	-	X	-	-
9	-	X	-	-	X	-	-	-	-	-	-	X	X	X	-	-
10	X	-	X	-	X	X	-	-	-	-	X	X	-	X	-	-
11	X	-	X	X	-	X	-	-	X	-	-	-	X	-	-	-
12	X	X	X	X	X	X	-	-	X	-	-	X	X	X	X	-
13	X	X	X	X	X	-	-	-	-	-	-	-	-	X	-	-
14	X	-	X	X	X	X	-	-	X	-	-	X	X	X	-	X
15	X	X	X	-	X	X	-	X	-	-	X	-	X	X	-	-
16	X	-	X	-	X	-	-	-	-	-	-	-	X	X	-	-
17	X	-	X	-	-	-	-	-	-	-	-	X	X	X	-	-
18	X	X	X	X	-	-	-	-	-	-	-	-	-	X	-	-
19	X	-	X	X	X	X	-	-	-	X	X	-	-	X	-	-
20	X	X	X	-	X	-	-	-	-	-	-	-	-	X	-	X
21	X	-	X	X	X	-	-	-	-	X	X	X	X	X	X	-
22	X	-	X	X	X	-	-	-	-	-	-	X	-	X	-	-
23	X	X	X	X	-	-	-	-		-	-	-	-	X	-	-
24	X	X	X	X	X	X	-	X	-	-	-	X	X	X	-	-
25	X	-	X	X	X	X	-	-	-	X	-	X	X	X	X	-

Man. - Manufacturer; Age - Years of use; TS - Threshing system; HM - Header model; GS - Ground speed; CS - Cylinder/rotor; Speed FS - Fan speed; CO - Concave opening; RS - Reel speed/position; HH - Header height; ET - Embedded technology; RM - Reference method; HL - Header losses; TL - Total losses; UC - Use condition (rented/owned); EA - Economic analysis; "X" - Indicates the presence of data; "-" - Indicates the absence of data; * - Indicates an indispensable variable, used for the methodological quality scoring

header height (n = 8). Conversely, more emphasis was placed on general harvester characteristics, such as manufacturer (n = 89), age (n = 112), ground speed (n = 109), threshing system (n = 68) and cylinder/rotor speed (n = 73). It is worth noting that general characteristics are readily accessible to operators and farmers, but specific setting details require specialized knowledge and are not commonly consulted. Regarding technologies, modern combine harvesters include embedded systems to monitor and control mechanisms, which are more reliable components compared to manual measurements (n = 5). These technologies collect data at regular intervals and present them to the operator in real-time. Furthermore, data can be extracted for external storage and analyzed through control charts, which is a statistical method to monitor data variability (such as header height, ground speed, and engine speed) and ensure operational quality (Lima et al., 2017). The low number of observations of these embedded technologies can be attributed to the prevalence of old combine harvesters, as well as a potential negligence in utilizing embedded systems even in studies involving newer models.

Approximately 49% of the articles (n = 12) provided detailed data on header losses, consistently identified as a significant external mechanism (Paulsen et al., 2014; Bermudez & Pinheiro, 2020). There are numerous methods to quantify grain losses. Despite variations in publication years, these protocols share a common underlying principle: the utilization of a rectangular frame to collect and categorize grains into natural, header, and internal losses. A common alternative is the use of circles distributed transversely across the machine's path, immediately after its passage (n = 5 studies). However, these quantification methods rely solely on manual assessments, without incorporation of technological components. Notably, only two studies assessed the economic costs associated with total losses. The authors converted bags per hectare into money per hour, assuming a situation in which a well-trained operator could potentially yield substantial savings by adjusting minimal settings on the combine harvester.

Overall, a substantial number of studies exhibited deficiencies in describing crucial aspects of soybean loss monitoring. Therefore, the meta-analysis focused exclusively on losses related to combine harvester age (n = 3 studies) and ground speed (n = 4 studies). Considering the small number of studies, a funnel plot was not used to assess publication bias. The level of heterogeneity was also carefully analyzed, using a higher p-value. The meta-analysis (Figure 3) indicated a significant correlation between the combine harvester age (> 10 years of use) and total soybean losses (n = 64, $p \leq 0.05$, SMD = 0.59) with no indices of heterogeneity ($I^2 = 0\%$, p = 0.92). However, a significant correlation was not found between ground speed (> 5 km h^{-1}) and total soybean losses (n = 62, $p > 0.05$, SMD = 0.37), also with no indices of heterogeneity ($I^2 = 0\%$, p = 0.74), although with a wider confidence interval. Moreover, combine harvesters can be from the farm itself or rented/outsourced. This condition was identified in the texts or by consulting available authors (n = 37). Losses in rented combine harvesters were reported as higher due to lack of attention and maintenance (Campos et al., 2005). Unfortunately, no data on operator knowledge in these cases were found.

Threshing systems were divided into tangential and axial; the tangential model is the predecessor and, therefore, found mainly in older combine harvesters. The difference between these systems is only within the machine itself. The axial system has a rotor that separates the grain from the plant by centrifugal force, and the mass flows through the entire system under this mechanical condition. Contrastingly, in tangential systems, the

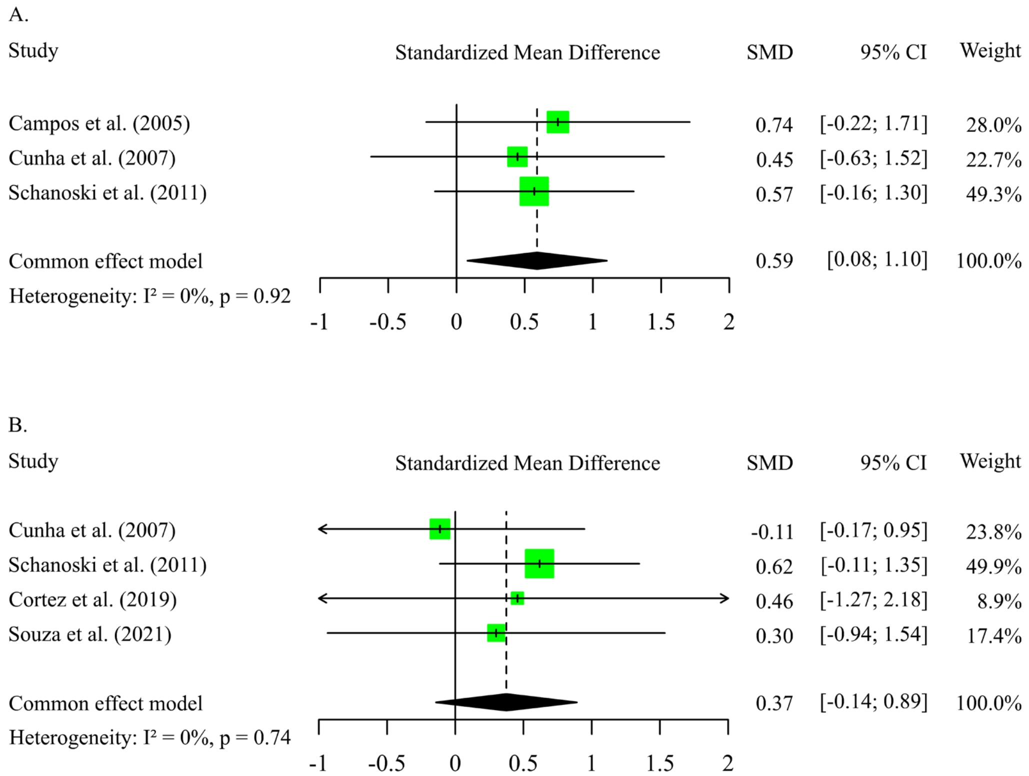

Figure 3. Meta-analysis of continuous data: (A) comparison of soybean losses between newer combine harvesters (control group) and combine harvesters with over 10 years of use; (B) comparison of soybean losses between ground speeds lower (control group) or higher than 5 km h^{-1}

mass flows tangentially to the cylinder passing between it and the concave, undergoing friction due to threshing over a short period of time. The axial threshing system has been identified as a superior method for minimizing soybean losses due to its enhanced grain flow process, whereas tangential systems have been associated with higher losses (Campos et al., 2005; Camolese et al., 2015). This distinction arises from the axial system's ability to achieve a more efficient and effective grain flow. Employing an axial flow design allows this system to ensure a continuous and controlled movement of soybean grains, thus mitigating the risk of grain damage and losses.

Moreover, the harvester header accounted for approximately 70.01±4.41% of soybean losses (n = 69) and was often reported as the main contributor to losses (Holtz & dos Reis, 2013; Schanoski et al., 2011; Menezes et al., 2018). The reel may be positioned in the upper third of the plant, guiding it onto the header. The reel speed must be 10 to 25% higher than the combine harvester's ground speed to avoid poor synchronization (Paulsen et al., 2014). However, the reel speed index ranged from 12 to 139% (n = 15) and only five reports were in accordance with the recommendations. Speeds below the recommended range cause the reel to fail in supporting and steering the plant, significantly worsening cutting and feeding. Contrastingly, higher reel speeds can damage the plant by detaching pods and throwing them onto the ground. Finally, the cutting height is determined by considering the first pod height, but it is recommended to keep it close to the ground to reach low insertion pods.

Combine harvesters have varying engine powers (Table 3). This characteristic can be classified by the manufacturer's protocols into each engine power range. Considering the classification by the Association of Equipment Manufacturers (AEM), these classes are as follows: 5 (up to 268 hp), 6 (268-321 hp), 7 (322-374 hp), 8 (375-429 hp), 9 (429-483 hp), and 10 (over 483 hp). Most machines were class "5" (n = 25), which may be related to the small size of the areas, but also to the publication dates, as the use of smaller combine harvesters has been more frequent in the last decades. Speeds ranged from 3.0 to 9.3 km h^{-1}, with a mean of 5.42±0.26 km h^{-1} (n = 23), as recommended in the literature (Paulsen et al., 2014). However, slower combine harvesters can generate higher losses during back-to-back maneuvers due to irregular feeding (Chioderoli et al., 2012). These sites are often avoided in field loss sampling as they are at the field edge (Paixão et al., 2016). Cylinder/rotor speeds ranged from 350 to 900 rpm (n = 62). These studies did not assess qualitative variables, often associated with seed production rather than grain production. Moisture of grains (MOG) ranged from 9 to 22.1% (n = 53). Sometimes, farmers postpone harvest to achieve lower grain moisture content. However, the moisture content in non-grain materials may be lower at the end of the harvest than at the beginning, mainly in large areas (Bauer & Gonzatti, 2007). In such cases, there is a possibility of very dry pods being threshed by the reel and subsequently dispersed in the field (Schanoski et al., 2011).

Harvesting monitoring, policies, and future directions

This study is the first comprehensive systematic and meta-analytical review of high-visibility studies related to soybean losses during mechanical harvesting. Supplementary files containing all extracted data from the evaluated articles can be made available upon request. Minimizing losses within the food chain is a critical concern. However, a limited

Table 3. Frequently mentioned data summarized from reviewed articles

Authors	MOG (%)	Yield (kg ha^{-1})	Engine power (hp)	Ground speed (km h^{-1})	Cylinder speed (rpm)	Total losses (kg ha^{-1})
Pinheiro Neto & Troli (2003)	12.50-14.50	-	-	-	600-700	17.88-85.31
Campos et al. (2005)	-	-	108-321	-	-	19.62-169.38
Mesquita et al. (2006)	-	-	-	-	-	69.40
Ferreira et al. (2007)	9.00	-	138	3.00-6.00	550	33.50-54.60
Cunha et al. (2007)	-	-	-	3.80-7.00	-	28.97-76.03
Bauer et al. (2007)	11.40-14.60	2,340	-	-	-	44.21-64.28
Toledo et al. (2008)	17.40	-	173	4	350	58.8
Magalhães et al. (2009)	22.10	3,359	173	4.50-6.50	900	78.4-98.8
Schanoski et al. (2011)	-	-	-	3.60-9.30	-	44.59-129.49
Chiederoli et al. (2012)	13.55	3,470	389	7.00	720	61.26
Machado et al. (2012)	15.00	-	178	5.00-7.00	-	-
Holtz & Reis (2013)	13.8-16.0	-	168	6	800	72.50-160.10
Loureiro Júnior et al. (2014)	13.50	3,232	175	4.80	-	118.94
Paulsen et al. (2014)	11.00-19.50	2,663-4,861	237-385	4.50-6.50	525-720	50.1-265.9
Cassia et al. (2015)	15.70	-	280	4.60-4.86	505-506	27.4-29.94
Camolese et al. (2015)	15.30-19.80	2,880	236-320	4.60-7.60	-	7.67-11.17
Zandonadi et al. (2015)	-	-	-	-	-	62.50-79.60
Paixão et al. (2016)	-	-	175	-	-	4.88
Lima et al. (2017)	12.50	2,616	444	5.00-7.00	565-610	22.33-28.19
Acosta et al. (2018)	-	3,749	-	5.50	-	49.59
Menezes et al. (2018)	-	3,781	355	6.00-8.00	-	99.81-165.59
Cortez et al. (2019)	-	-	325-378	5.00-7.00	-	32.87-84.82
Vega et al. (2021)	-	-	-	-	-	35.45-262.91
Jasper et al. (2021)	-	3,125	268-271	3.00-8.00	340-610	13.34-14.79
Souza et al. (2021)	12.60-13.00	-	468	4.00-7.00	500-800	54.09-157.50

MOG - Moisture of grains; The symbol '-' Between values indicates range from minimum to maximum value

number of 25 studies were identified. Exploration of 'grey literature' revealed several articles predominantly published in conferences. Furthermore, certain data sources were limited to regional departments and, therefore, were not included in the analysis, which valued only peer-reviewed studies as the basis for the state of the art (Schöpfel & Prost, 2020). Most affiliations and funding institutions were governmental, with only five unrelated to public universities. Contrastingly, a weak public-private partnership was evident, even though the soybean chain is primarily constituted by private companies (agrochemicals, machinery, consultants etc.) and its complexity extending beyond the farmer-consumer relationship (Jia et al., 2020). The monitoring of losses also revealed research inequality. Only two combine harvesters represented the MATOPIBA region, which refers to the Cerrado portions in the Brazilian states of Maranhão, Tocantins, Piaui, and Bahia, totaling 4,803,471 ha (Lima et al., 2019). Similarly, only two combine harvesters represented the Amazonia region, which is constantly referred as unsustainable production (Stabile et al., 2020). It remains unclear whether companies and agencies are actively promoting measures to reduce soybean losses in these emerging but strategically significant production regions. Public-private partnerships have the potential to be a promising policy approach, considering the financial costs. Regional annual monitoring would suffice to characterize soybean losses and guide farmers.

Most of these studies monitored commercial fields. Therefore, authors who manually measured each configuration have greater reliability for comparison than those who only consulted farmers. This is suitable for regional monitoring and observational data collection; however, the methods should be more rigorous (e.g., comparison and randomized groups) for scientific purposes and new insights. Additionally, several lacks were identified in these studies, mainly related to the conditions of crops and harvesters. Although it is possible to quantify soybean losses, the lack of these attributes can lead to misinterpretations. For instance, morphological characteristics are essential for understanding the relationship between the cutting mechanism and the plant. The insertion of the first pod is directly related to the header's height. The plant's inclination is important for adjusting the reel's position. A few specific combine harvester settings were observed, such as fan speed, concave opening, reel speed, and header height. Therefore, studies should create a broader context to understand the machine-plant-farmer interaction during harvesting. Therefore, a quick and robust checklist based on all the reviewed studies was proposed, which can be useful for researchers and farmers (Table 4). Decision-making processes can be more carefully conducted with all this information collected and organized properly. However, cleaning and transportation systems were not included.

Most studies reviewed in this analysis focused on total grain losses, but there was a lack of emphasis on header losses. This can be attributed to the convenience of sampling in commercial fields. The primary method employed to characterize losses involves the use of a rectangular frame for counting or weighing grains, which is effective for quantification purposes. However, this method requires the combine harvester to be stopped, potentially impacting operational efficiency and farmer satisfaction. A less used alternative involves placing a circular frame immediately after the passage of the harvester. Despite these approaches, no technologies were identified in the reviewed studies that could replace manual methods for measuring soybean losses. Some authors briefly mentioned the presence of embedded monitors in combine harvesters, but their purpose was limited to monitoring harvester settings.

Table 4. Checklist of key points to assist researchers and farmers during harvest monitoring

Filter		Description	Results
1	Operator	Are harvester operators properly trained?	1: Yes; 2: No
		Do operators have adequate working hours to prevent fatigue?	1: Yes; 2: No
2	Combine harvester maintenance	Is the combine harvester maintenance frequent?	1: Yes; 2: No
3	Combine harvester type of use	Is the combine harvester outsourced?	1: Yes; 2: No
4	Crop	What is the first pod height?	cm
		What is the plant's inclination?	degrees
		What is the moisture of grains?	percentage
		What is the range of moisture of grains from the beginning to the end of harvesting?	percentage
		What is the crop yield?	kg ha^{-1}
		What is the maturation group?	< 6: very early; 6-6.5: early; 7: normal; > 7: late
		What is the relative air humidity?	percentage
		How many days did it rain during the harvesting?	days
		Were desiccants used?	1: Yes; 2: No
5	Combine	How old is the combine harvester?	years of use
		What is the year of the combine harvester?	year
		What is the threshing system?	1: Tangential; 2: Axial
		What type of header is used?	1: Conventional; 2: Belt
		Is there any embedded technology (e.g., telemetry monitor, auto-guidance, yield sensors etc.)?	1: Yes; 2: No
6	Operation	What is the combine harvester's ground speed?	km h^{-1}
		What is the cylinder/rotor speed?	rpm
		What is the fan speed?	rpm
		What is the concave opening?	mm
		What is the header height?	cm
		What is the reel index?	-
		Is there a justification for soybean losses? (e.g., increased speed due to planting schedule, ripeness, rainfall etc.)	1: Yes; 2: No
7	Results	Straw cover	kg ha^{-1}
		Natural losses	kg ha^{-1}
		Header losses	kg ha^{-1}
		Internal losses	kg ha^{-1}
		Total losses	kg ha^{-1}
		Economic losses	\$ ha^{-1}

Contrastingly, a grain-loss sensor already incorporated in other cereal harvesters provides remote and real-time analysis of losses (Bomoi et al., 2022). It is essential to incorporate these technologies and assess their accuracy and limitations by comparing them with field-based methods. The existing literature insufficiently addresses these practices, indicating a lag in keeping up with technological advancements in the field.

The economic consequences of grain losses are critical, yet only one study assessed this aspect, indicating a lack of attention to the social impact. Goldsmith et al. (2015) conducted a microeconomic study and concluded that soybean losses in Brazil were generally acceptable to farmers. The main argument presented was the need for improved operational efficiency during harvesting to meet the planting schedule for the subsequent crop. This mindset is further reinforced by the challenges associated with accurately assessing losses in the field, as previously mentioned. However, due to the absence of a direct correlation between the economic cost of soybean losses and the profitability of the subsequent corn crop (succession crop), it was not possible to definitively determine the adequacy of this justification. Achieving economic balance is essential as a decision-making tool to assist farmers in optimizing their operations.

The sustainable analysis of soybean losses during harvesting is crucial in the context of the South American and global economy, considering the potential for promoting deforestation to meet growing production demands (Stabile et al., 2020). Brazil is the largest soybean producing country and presented increases of 8.8% in production, 4.4% in yield, and 4.2% in cultivated areas in the 2020/2021 crop season (CONAB, 2021). Considering a soybean yield of 3.5 Mg ha^{-1} (CONAB, 2021) and hypothetically reducing soybean losses by 30 kg ha^{-1} (the recommendation from current agencies is < 60 kg ha^{-1}), Brazil could maintain the total production while reducing cropland by 324,046 ha. Therefore, prioritizing effective loss management strategies before pursuing yield increases or expanding cropland is essential. South American governments should adopt a comprehensive approach that includes harvest monitoring as an indirect policy to combat deforestation and enhance farmers' profitability.

Soybean losses and measures farmers can adopt

Despite significant advancements in combine harvester technology in recent years, a wide diversity of combine harvesters remains in the field, including various manufacturers, different years of use, and distinct threshing systems. The engine power of these harvesters can often be correlated with farm size and mechanization level, with larger, modern machines typically utilized in extensive crop areas. Other factors, such as harvest timing and weather events, may also have a significant impact on machine size. Consequently, the selection of the combine harvester class size should be based on the specific needs of the farm rather than solely relying on available power.

Combine harvesters with over 10 years of use resulted in significant higher losses compared to newer ones. This finding underscores the importance of considering replacement options for older combine harvesters. Extended usage leads to increased wear and tear on components (Schanoski et al., 2011), affecting mechanism performances and demanding frequent maintenance. Regarding very old and poorly maintained combine harvesters, vibrations resulting from component clearance become pronounced, increasing the probability of grain loss. For instance, excessive vibration of the header or reel can cause threshing of pods before they enter the combine harvesters, throwing them onto the ground (Schanoski et al., 2011). Moreover, older combine harvesters tend to operate at slower speeds due to wear-related issues and engineering design. Consequently, this affects operational efficiency, which has an additional demand due to crop maturation, weather conditions, and planting schedule. Particularly regarding ground speed, no significant correlation was found between higher speeds and greater soybean losses. However, it is important to recognize that the ground speed strongly depends on the machine, particularly its threshing system, for an effective grain flow management. Modern and larger machines have higher feed rates; therefore, they can operate at higher speeds under favorable conditions, not necessarily adhering strictly to the recommendation of < 5 km h^{-1}.

Combine harvesters can be categorized based on their external and internal mechanisms. The interaction between these elements, as well as the crop conditions, are essential for determining the level of soybean losses. The initial harvesting process involves the task of driving the plant into the machine, which is not only an essential but also highly complex process. Considering conventional headers, the recommendation is to operate the machine at lower speeds to reduce mass flow and friction. Contrastingly, belt systems reduce losses by eliminating friction, thus allowing operators to work at higher ground speeds. It is important to note that the internal mechanisms of combine harvesters, such as the cylinder/rotor, contribute relatively less to overall quantitative losses.

Concerning small-scale farmers, investing solely in axial combine harvesters or those white belt header systems for the primary purpose of reducing grain losses may not be financially feasible due to the higher equipment costs. Consequently, other alternatives need to be explored. A questionnaire conducted in the state of Parana, Brazil, revealed that only 5% of operators reported not performing regular maintenance and checks on machines; however, a closer analysis showed that this percentage is actually 33%. In comparison, combine harvesters operated by well-trained individuals had resulted in lower soybean losses (Schanoski et al., 2011). Therefore, while providing training for operators may incur additional costs for farmers, enhancing knowledge and skills through training can effectively reduce soybean losses, improve machine maintenance practices, and increase long-term profitability, even when utilizing tangential combine harvesters or conventional header systems. Alternatively, losses in rented combine harvesters are significantly greater than farm-owned machines.

Conclusions

1. This systematic and meta-analytical review covered twenty years of studies, resulting in 25 peer-reviewed articles.

2. The insights described here provide clear pathways to fill gaps in the literature and assist farmers.

3. Overall, studies should employ more rigorous methods to collect comprehensive data. There is a negligence about crop conditions, specific combine settings, and socio-economic impact.

4. The literature's methods lack no innovation and are significantly outdated compared to recent technologies. A checklist with key points for assessing soybean losses during mechanical harvesting was outlined, which can effectively assist researchers and farmers.

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