Review Article

Effect of moisture content on combine harvested seed crop and its quality

Abstract

The moisture content during harvesting significantly influences post-harvest losses, encompassing factors that collectively diminish both the quantity and quality of agricultural produce. These factors involve pre-harvest sprouting, mechanical damages and susceptibility to diseases at post-harvest. To mitigate the risks associated with excessive moisture, farmers have to employ proper harvesting techniques such as using a combine harvester. The combine harvester proves invaluable by efficient harvesting, threshing and winnowing various crops like rice, corn, wheat, sunflower and pulses directly in the field. This streamlined process not only saves time and reduces the need for human labour but also lowers overall work costs for farmers. Additionally, the utilization of these machines enhances agricultural productivity, ensuring a more efficient harvesting process and contributing to greater profitability in farming practices. Consequently, effective moisture content management becomes essential for minimizing losses and preserving seed quality. A multipurpose nature of a combine harvester minimizes the need for manual labour in harvesting, leading to a reduction in workforce requirements, time expenditure and effort. Consequently, this enhances overall productivity.

Key words: Moisture content, Pre and post- harvest losses, Combine harvester and Seed quality.

Introduction

Agriculture encompasses a broad spectrum of activities, extending from the land preparation to seed storage. When these operations rely on manual labour due to labour-intensive and time-consuming methods, the risk of failing to meet specified time frames can result in substantial reductions in crop production. Additionally, this manual approach may contribute to post-harvest losses and diminished seed quality, which is a critical factor influencing crop growth, development and overall yield. Therefore, the need for more efficient and timely agricultural operations is paramount to ensure optimal crop outcomes and mitigate the negative impacts on post-harvest and seed quality (Govindaraj *et al.*, 2017).

The moisture content of crops during harvesting stands a crucial role in determining the quality and subsequent storage of the harvested product. It is essential to harvest crops at the appropriate time, typically in paddy crop when the moisture content falls within the range of 20-25% or when approximately 80% of the grains exhibit a straw colour and at least 20% of the grains at the panicle base reach the hard dough stage (IRRI, 2013). The moisture content for some of the crops during harvesting described below (Table 1).

Table 1. Moisture content of different crops during harvesting

S. No.	Crops	Moisture content %	Reference
1.	Rice	20-25%	IRRI (2013)
2.	Wheat	14% and 18%	Matthes *et al.* (2021)
3.	Maize	20-25%	Li *et al.* (2020)
4.	Sorghum	18-35%	Thai *et al.* (2015)
5.	Groundnut	15% and 20%	Santos *et al.* (2021)
6.	Soybean	13%-15%	Matthes *et al.* (2021)

Harvesting crops with highest moisture levels might experience difficulties during threshing and separation processes especially when using combine harvesters. Wet crops are more prone clogging and increased damage to seeds during harvesting. Harvesting prematurely may lead to preharvest sprouting and immature kernels, while delayed harvesting can result in high shattering loss and increased susceptibility to diseases (Baloch, 2010). Achieving the right balance in the timing of harvesting is crucial to optimize both crop yield and quality. Excess moisture in harvested crops can lead to various issues such as mold growth, insect infestation and other forms of deterioration during storage (Khan, 2010). Furthermore, it can adversely impact the seed germination. Conversely, insufficient moisture may result in cracked or broken grains, ultimately diminishing the overall quality of the harvested crop.

Countries such as India, China, Thailand, Vietnam, and Cambodia, there is a rapid and increasing adoption of combine harvesters, also known simply as combines, for paddy. This trend is driven by a significant shortage of labour and the consequent rise in harvesting costs, making the utilization of combines economically appealing. Combine harvesting consolidates multiple operations into a single process, encompassing cutting the crop, feeding it into the threshing mechanism, threshing, cleaning, and discharging the grain into a bulk wagon or directly into bags. Typically, straw is discharged behind the combine in a windrow (IRRI, 2013). The desired goal is to obtain the seeds (of rice, corn, soybean, black gram *etc.*) In mechanical threshing, either by a field thresher or a combine, the peripheral velocity of the cylinder or rotor and the tightness of clearance to the fixed concave are crucial factors. A higher peripheral threshing velocity is required as crop moisture increases. Conversely, as crops dry, the crop material becomes easier to thresh, and peripheral velocity should be reduced. It's important to note that the outer hull, pericarp or seed coat of the seed is typically soft when moisture levels are high. Therefore, excessive peripheral velocity combined with too close of concave clearance can be detrimental to the quality of the threshed grains (Alizadeh and Khodabakhshipour, 2010). Adjusting these parameters appropriately is essential for ensuring the quality of the harvested crop.

The widespread adoption of combine harvesters for rice crop harvesting is acknowledged and implemented to mitigate the peak demand of farm labour and to minimize field losses attributed to manual harvesting. Deploying a combine harvester with crops at their optimal moisture content is a strategic approach to mitigate losses during both pre and post-harvesting stages. This method offers advantages that outweigh the potential disadvantages related to seed quality. By employing a multipurpose machine like a combine harvester, the need for manual labour is significantly reduced, saving time and effort. This reduction in manpower translates to increased overall productivity. The efficiency of combine harvesters becomes especially evident when harvesting vast expanses of crops, leading to better grain yields and ultimately benefiting farmers financially.

The versatility of combine harvesters, equipped with various removable heads, enhances convenience in harvesting different crop types. This adaptability contributes to increased output and improved profitability for farmers. Modern versions of combine harvesters incorporate cutting-edge technologies that allow for gentler treatment of delicate seeds, preventing the crushing and destruction that earlier versions often caused. Investing in a high-quality harvester has become a common practice among farmers due to its ability to produce cleaner grains, reduce crop losses, maintain crop quality and lower overall labour costs. The advancements in technology have made these machines suitable for all types of farms, regardless of size, thereby making the harvesting process less labour-intensive and more efficient. The objective of the present review is to describe the effect of moisture content and other crop, machine and operational parameters on seed quality of combine harvested crops.

Effect of crop, machine and operational parameters on seed/grain quality of combine harvested crops:

a) **Crop parameters**

According to Thomison (2010), when moisture levels in maize is high, the kernel pericarp is soft especially at 28%. Conversely, when moisture levels drop below 16%, there is a higher incidence of kernel breakage. To mitigate these issues, it is recommended to harvest the maize crop within the moisture range of 23 to 25%. This range is suggested because, if the crop dries below 20% moisture, there is a significant rise in yield loss due to factors such as stalk lodging, ear rot and insect feeding.

In cumin, Saeidirad and Javad *et al.* (2011) observed that the utilization of a rub bar cylinder type combine harvester resulted in a reduction in the percentage of separated seeds from 92.8% to 90.4% as the moisture content increased from 7% to 13%. Simultaneously, the proportion of damaged seeds decreased from 10.1% to 7.6% within the same moisture content range. Conversely, elevating the cylinder speed from 12.8 to 16.5 m s^{-1} led to an increase in the percentage of separated seeds, shattered stems, and damaged seeds, as detailed in Table 2. These findings are consistent with the conclusions drawn by Ajav and Adejumo (2005), who noted a decrease in seed damage loss with an increase in moisture content.

Table 2. Means comparison of characteristics in different variations:

S. No.	Factors	Factor levels	Separated seeds (%)	Shattered Stems (%)	Damaged Seeds (%)
		12.8	91.3 a	5.9 a	8.5 a
1.	Cylinder speed (m s^{-1})	16.5	92.9 a	6.3 a	9.2 ab
		22	90.1 b	8.5 b	9.5 b
2.	Moisture content (%)	7	92.8 a	7.4 a	10.1 a
		13	90.4 b	6.4 a	7.6 b
3.	Cylinder type	Rasp bar	92.6 a	8.2 a	9.5 a
		Rub bar	93.1 a	6.0b	8.3 b

(Source: Saeidirad and Javad *et al.*, 2011)

Masilamani and Tajuddin (2012) examined the impact of combine harvesting, manual harvesting and threshing on two rice varieties namely ADT 36 and BPT 5204. Following the harvest, the seeds undergone with drying and processing before being stored in gunny bags at ambient temperature within a seed godown for a duration of 12 months. The study revealed that seeds harvested by the combine harvester maintained an optimal germination rate reaching 83% for ADT 36 and 82% for BPT 5204 even after 12 months of storage. Their recommendation emphasized harvesting these rice varieties at 20% moisture content using a combine harvester to meet the minimum seed certification standard of 80%, sustaining quality for up to 9 months of storage (Table 3).

Table 3. Effect of harvesting methods on germination on ADT 36 and BPT 5204

Method of harvest	Seed germination (%)		Storage period (months)							
	ADT 36 Fresh	BPT 5204 Fresh	3		6		9		12	
			ADT 36	BPT 5204	ADT 36	BPT 5204	ADT 36	BPT 5204	ADT 36	BPT 5204

Manual	94.52	91.67	93.41	89.31	90.12	86.67	87.51	86.00	85.21	83.51
Combine	94.32	91.33	92.28	87.44	89.52	84.62	86.23	83.60	83.28	82.00

(Source: Masilamani and Tajuddin, 2012)

Varga *et al.* (2012) explored the correlation between seed harvesting techniques and the germination, as well as seed vigour, of eight Pioneer Hi-Bred Maize hybrids. The assessment was initially carried out immediately after harvesting, and a year later, it was repeated following one year of storage. Germination tests were conducted on the seeds of four hybrids. The findings indicated that, for three out of the four hybrids, germination capacity experienced a decline of 1.5-1.6% in both treatments. Concurrently, there was an increase in the number of abnormal seeds by 1.5-5.0%. Notably, a higher number of abnormal seedlings were observed in lots from shelled harvesting, with significant differences noted for hybrids PR35Y65, PR39F58, PR39R86LR and PR 39986LF. Further analysis revealed that the seed vigour of three hybrids was highest when maize seeds were harvested shelled rather than on the ear. After a year, the germination percentage was lower for both groups when analysed, with whole ear harvesting showing better results compared to the shelled group, although the difference was not significant. In vigour tests, mechanically shelled seeds demonstrated superior results compared to whole ear harvesting for the same hybrids, yet again, the difference was not significant.

Ferreira *et al.* (2013) investigated the influence of mechanical husking on the quality of Dent BM 3061 hybrid maize seeds with moisture levels of 45%, 40% and 35%. Their findings revealed that seeds with a moisture content of 45% exhibited lower seed quality compared to those with 40% and 35% moisture content. The higher moisture content, attributed to an increased susceptibility to mechanical damage, particularly during the husking and threshing processes, was primarily responsible for the highest incidence of damage. The progressive increase in mechanical damage, corresponding to elevated moisture content during harvest, contributed to a reduction in the physiological potential of the seeds and an increased occurrence of fungi during storage (Table 4).

Table 4. Mean values of germination (G), Speed of Emergence index (SEI) and Mean Emergence Time (MET) of BM 3061 hybrid maize seeds, harvested at different moisture contents

S. No.	Moisture content %	Germination (%)	SEI (%)	MET (%)
1.	45%	96	11	6
2.	40%	99	12	3
3.	35%	98	11	4
CV (%)		2.43	3.87	3.85

(Source: Ferreira *et al.,* 2013)

Govindaraj *et al.* (2017) conducted the experiment to find out the influence of harvesting and threshing methods on seed quality of rice varieties *viz.,* CR 1009 Sub 1, IW Ponni and CO 51. The treatments included manual harvesting and manual threshing, manual harvesting and mechanical threshing (axial flow thresher) and combine harvesting (with pneumatic wheel). The results revealed that the moisture levels of the seed during harvest was 22.50%, 19.72% and 19.51% in CO 51, CR1009 Sub 1 and improved white ponni, respectively. The result revealed that the germination and vigour index were highest in manually harvested and threshed seeds of 94.7 % and 3362 followed by combine harvested seed at 91.7 % and 3133 and the lowest vigour observed in manual harvesting and mechanical threshing at 94% and 3017, respectively due to the presence of cracked seed coat damage, indicating a reduction in seed vigour. The findings suggested that rice seeds harvested and threshed using manual methods or a combine harvester enhanced higher threshing efficiency and had no adverse effects on germination and seedling vigour when harvesting the seed crop in the optimum moisture level (Table 5).

Table 5. Effect of different harvesting and threshing methods on seedling characteristics of different rice varieties

Methods of harvesting and threshing methods	Treatments	Germination (%)	Root length (cm)	Shoot length (cm)	Dry matter production (g seedlings^{-10})	Vigour index
Manual harvesting and threshing	CO51 (V_1)	94.7	22.7	10.0	0.079	3091
Manual harvesting and mechanical threshing	CR1009 Sub 1 (V_2)	91.7	24.3	11.6	0.106	3298
Combine harvesting	Improved White Ponni (V_3)	94.0	23.1	10.1	0.079	3124
Mean		93.4	23.4	10.6	0.088	3171
S. Ed		4.78	0.867	0.572	0.004	151.02
CD (P = 0.05)		NS	NS	NS	NS	NS

(Source: Govindaraj *et al.*, 2017)

The different harvesting and threshing methods were experimented with Sunn hemp, revealing that manually harvested and threshed seeds exhibited germination of 92%. Following closely were seeds harvested manually and threshed through tractor treading and combine harvesting, achieving a germination rate of 89% with highest seedling vigour at 1818. This superior performance in seedling vigour may be attributed to the presence of a hard testa of the seed coat, providing an advantage for mechanical harvesting by minimizing damage. Even in instances where hairline cracks occurred during the mechanical harvesting and threshing process, it was observed that seed coat dormancy was reduced, leading to enhanced germination and seedling vigour. Based on these findings, the study suggests that opting for a combine harvester with a moisture content of 21.5% is advisable for harvesting sunn hemp seed crop (Table 6). This method ensures efficient harvesting without adversely affecting seedling growth, providing practical insights for optimizing the cultivation and harvesting practices of sunn hemp (Masilamani *et al.*, 2017).

Table 6. Effect of harvesting and threshing methods on germination and initial seedling vigour of sunn hemp

Treatment	Mechanical damage (%)	Germination (%)	Root length (cm)	Shoot length (cm)	Dry matter Production (g seedlings^{-10})	Vigour index
Manual harvesting and manual threshing	3.0	92	4.3	14.2	0.197	1692
Manual harvesting and mechanical threshing	4.8	83	4.7	14.8	0.167	1606
Manual harvesting and threshing by tractor treading	4.0	89	4.9	13.8	0.176	1667
Harvesting and threshing by Combine	3.8	89	5.3	15.1	0.182	1818
Mean	3.9	88	4.8	14.5	0.181	1696
Sed	0.58	3.14	0.58	0.38	0.006	102.87
CD (P=0.05)	1.23	NS	NS	0.8377	0.0145	NS

(Source: Masilamani *et al.*, 2017)

Gunathilake *et al.* (2018) conducted a study to examine the variations in germination of paddy samples harvested by different combine harvesters. The results revealed that the Kubota combine harvester exhibited the highest germination percentage at 97.06% and the lowest seed damage at 13% among the four types of combine harvesters. In contrast, the Agrotech combine harvester reported the lowest germination percentage at 94.25% and the highest seed damage percentage at 24%, which showed a significant difference in seed damage and germination percentage in samples collected from the Agrotech combine harvester compared to control samples (Table 7). The findings emphasized that the seed damage has an impact on reducing germination percentage and also the occurrence of lowest damage seed samples have shown higher germination. The study indicated that the harvesting paddy seeds with a new or well-maintained combine harvester did not significantly affect the reduction in seed germination and mechanical damage. However, mechanical damage to seeds was found to occur during machine harvesting, leading to a decrease in seed germination percentage. The study further enhanced that the mechanical damage to seeds could increase over the time due to the wear and tear of mechanical parts in machines used for an extended period without replacement. The result is in assessment with the Chandrajith *et al.* (2014).

Table 7. Variation of germination in paddy samples harvested by different combine harvesters and control

S. No.	Type of combine harvester use for experiment	Germination (%)
1.	Class	96.83
2.	Kubota	97.16
3.	Agrotech	94.25
4.	Mubota	95.74

5.	Control	97.31

(Source: Gunathilake *et al.,* 2018)

The various harvesting and threshing techniques of daincha at 17% moisture content was examined with the methods included manual harvesting and manual threshing with a pliable stick (T_1), manual harvesting with threshing by tractor treading (T_2), manual harvesting and mechanical threshing by multipurpose thresher (T_3) and harvesting and threshing by a paddy combine harvester (T_4) on germination and seedling vigour. Among the threshing methods, seeds harvested and threshed by manual method had higher germination at 84% followed by seeds harvested manually and threshed by tractor treading at 80.5%, whereas the lowest germination of 80% was observed in seeds harvested and threshed by the combine harvester. Mechanical damage was observed in seeds harvested manually and threshed by a thresher (20%), followed by harvesting and threshing by a combine (15%). While manual harvesting and threshing methods may have higher germination rates, they pose economic challenges due to labour-intensive processes, seed loss during handling, and lower threshing efficiency compared to the combine harvester although with utilizing a combine harvester for harvesting and threshing proved to be a more efficient approach, consolidating both operations into a single pass and thereby saving time which also facilitates the harvesting and threshing of mature and immature seeds without seed loss (Table 8). The enclosed system of combine harvester significantly reduced seed loss and provided a sophisticated cleaning system. The daincha crops harvested at 17% moisture content by the combine harvester met the seed standards specified by IMSCS (Indian Minimum Seed Certification Standards), achieving a 75% germination (Masilamani *et al.,* 2021).

Table 8. Effect of harvesting and threshing methods on mechanical damage (%), germination and initial seedling vigour of Daincha

Treatments	**Mechanical damage (%)**	**Germination%**	**Root length (cm)**	**Shoot length (cm)**	**Dry matter production (g seedlings^{-10})**	**Vigour Index I**	**Vigour Index II**
Manual harvesting and manual threshing with pliable stick	8	85.00	7.6	5.28	0.089	1094	7.56
Manual harvesting with threshing by tractor treading	20	80.50	9.43	7.35	0083	1350	6.68
Manual harvesting and mechanical threshing by multipurpose thresher	5	84.00	10.27	6.97	0.089	1448	7.47
Harvesting and threshing by paddy combine harvester	15	80.00	9.18	7.37	0.094	1315	7.47
Mean	12.0	82.25	9.12	6.74	0.088	1302	7.29
Sed	0.111	0.787	0.119	0.072	0.001	9.198	0.104
CD (P= 0.05)	0.243	1.716	0.259	0.157	0.003	20.042	0.227

(Source: Masilamani *et al.,* 2021)

Santhos *et al.* (2021) observed the impact of harvesting peanut pods with 15% and 20% moisture contents using a combine harvester. Higher machine losses were observed at 15% moisture content which attributed to the lower water content making pod detachment easier during harvesting. However, in peanuts, lower moisture content also increased the susceptibility of gynophores to breakage when the harvester contacted the windrow, contributes to higher losses. Conversely, a moisture content of 20% resulted in increased losses due to challenging pod detachment, especially during the digging process. Moreover, the losses were further intensified by rainfall occurring during the drying period in the field. Despite this, 20% moisture content led to higher whole pod variability and a lower number of open pods. The moisture content in pods identified as a critical factor influencing harvester internal mechanisms in various crops, including beans (Souza *et al.*, 2001). Specifically, a 15% moisture content was associated with a reduction in the number of whole pods in the bulk tank and an increase in open pod variability. The efficiency of threshing and separation mechanisms significantly improved with 15% moisture content, leading to decreased quantities of internal mechanisms and variability. The authors suggested that peanut harvester machines exhibit better process quality with a 15% moisture content of pod.

Olufelo *et al.* (2023) studied the impact of different moisture content levels (12%, 15% and 17%) on seed yield attributes across 10 pigeon pea genotypes. Pigeon pea seeds harvested at 12% moisture content displayed the highest 100-seed weight, signifying optimal physiological and field maturity before harvesting. This moisture level facilitated the maximal accumulation of essential nutrients protein, carbohydrates, minerals and dry matter within the seeds, importantly, the 12% moisture content proved low enough to inhibit microbial activities within the seed lot, ensuring safe conditions for both harvesting and storage. However, seeds harvested at 12% moisture content produce lower seed/pod ratio, fewer pods per plant, and lower pod weight per plant which leads to shattering losses. Seeds harvested at 15% moisture content followed closely, demonstrating a balance between water content and microbial control, may be ascribed to the presence of water content within the seeds, which limited the activities of microorganisms within the seed lot, as evidenced by the occurrence of perforated holes around the seeds. Interestingly, pigeon pea seeds harvested at 17% moisture content recorded the least 100-seed weight. In summary, the findings suggest that harvesting at 15% moisture content resulted in the highest seed/pod ratio, seed production efficiency and the second-highest 100-seed weight after the 12% moisture content. The genotypes NSWCC-18b, NSWCC-19 and NSWCC-18 exhibited outstanding performance across all evaluated seed-yield attributes under various moisture conditions. The study concludes by recommending the harvesting of pigeon pea seeds at 15% moisture content for effective maintenance of quality, quantity and vigour.

b) Machine parameters:

Mbuvi (1994) suggested the shelling of green soybeans was examined using two pea combine harvesters: the rubber roller-type (Taylor) and the rotary drum-beater type (Sinclair-Scott). The impact of blanching green soybean pods for durations ranging from 0 to 10 minutes before shelling was investigated in terms of shelling efficiency, seed damage, and the quality of the shelled product. The results indicated that shelling efficiency was significantly lower only after blanching the pods for 10 minutes. Comparison between the two shellers over different blanching times revealed that the Taylor sheller yielded a higher seed recovery of 95.1% with lower seed damage at 3.4%, whereas the Sinclair-Scott showed 77.1% seed recovery with higher seed damage at 7.2%. Blanching of soybean pods as a pretreatment for shelling played a significant role in improving shelling efficiency and reducing seed damage. Shelling efficiency notably increased and seed damage was significantly reduced with a 1minute blanching period. However, both seed damage and shelling efficiency remained relatively constant between blanching times of 1 to 5 min. Blanching for 10 minutes resulted in a significant increase in damage and a decrease in seed recovery. Additionally, texture reading and colour factors were adversely affected by blanching. When utilizing the FMC pea combine harvester (FMC, model HCPSC-156) for harvesting green soybeans, the study found a seed recovery of 87%, seed damage of 10.8% and seed and pod losses of 5%. The FMC combine demonstrated effective performance in harvesting green soybeans and minor design adjustments could enhance its efficiency further.

In canola grain losses, the impact of a modified platform and two platform extensions was investigated. Three types of platforms were compared namely the current cereal platform, Hamed header extension with a mechanical side knife cutter bar, and Biso header extension with a hydraulic side knife cutter bar. The experiment revealed that average grain losses per hectare for the current cereal platform, Hamed, and Biso header extensions were 599.35 kg, 71.27 kg and 52.83 kg respectively. Preferably, the side knife loss in the Hamed header extension was 18.9 kg, while the Biso header extension exhibited half of this quantity due to the primary distinction between the two header extensions was their structural and operational mechanisms. Hamed utilized a mechanical mechanism, whereas Biso employed a hydraulic mechanism for operating cutterbars, among the biso header extension, demonstrated a significant decrease. However, no significant differences were observed between Hamed and Biso cutter bar extension losses in the canter of the horizontal cutter bar, despite some variations. With the application of Hamed and Biso header extensions, overall grain loss with Biso cutter bar extension (52.8 kg ha^{-1}) did not significantly differ from Hamed (71.3 kg ha^{-1}), it was evident that reducing side knife loss was significant which suggested that increasing distances between the auger and cutter bar, utilizing vertical and horizontal double knife cutterbars, and creating spaces for better crop flow entrance could significantly reduce losses. Additionally, minimizing direct contact between the crop and the moving reel, reducing vibrations to stems through header extension use and incorporating hydraulic-operated cutterbars were identified as crucial considerations for designers, particularly in the design of oilseed rape harvesting platforms (Asoodar *et al.*, 2008).

Four different rice combine harvesters, each equipped with different threshing systems, were employed to assess various components of losses, including shattering loss, blower/screen losses and unstrapped loss. The experiment involved operating the combines at different forward speeds both lower and higher while harvesting two rice varieties, NSIC RC222 and NSIC RC238.The results revealed that when harvested by Thai and Wintersteiger combines, the shattering losses of NSIC RC238 were lower than those of NSIC RC222. However, when CLAAS and Kubota combines were used, the shattering losses in NSIC RC238 increased by 44.7% and 7.6%, respectively, compared to the NSIC RC222. This increase was possibly attributed to the lower grain moisture content at the time of harvesting for both varieties averaging 22.1%. The maximum harvesting capacity recorded was 0.473 ha h^{-1} for Kubota when harvesting NSIC RC238 with higher forward speed, because of faster forward speed 2.4 km h^{-1} compared to the other combine harvester, because harvesting capacities generally followed a logical trend with speed and width, CLAAS combine faced challenges with feeder house plugging due to overfeeding at higher speeds. This led to a lower harvesting capacity at higher speeds, as additional time was required for re-adjustment. It's important to note that the combine harvester were operated with settings that were not optimized for maximizing capacity and minimizing losses before the trials, though additionally due to unskilled operators, improper maintenance and in-field draw backs, further contributed to suboptimal performance, therefore the study recommends conducting more trials to address these issues and gain a comprehensive understanding of the various factors influencing combine harvester performance (Hegazy *et al.*, 2015).

To investigate header grain losses and assess the quality of paddy grains, experiments were conducted considering three cutter bar heights 10, 15, 20 and 25 cm and three forward speeds 2.4, 3.84 and 4.28 km h^{-1} in rice cultivation. The analysis of header losses at different forward speeds indicated an increase at 10 cm, 20 cm, and 25 cm cutter bar heights, while a decline was observed at the 15 cm height. The highest losses at 10 cm were attributed to the larger volume of crop harvested, causing plant jamming in front of the cutter and subsequent grain loss on the ground. Moreover, losses at cutting heights of 20 cm and 25 cm were due to the growth characteristics of paddy bushes, reaching approximately 1m in height. Panicles typically begin growing from 75 cm above the ground, varying by variety. Higher cutter bar heights made it challenging to cut panicles completely, resulting in some parts remaining on the plant, contributing to losses. The forward speed of 4.28 km h^{-1} exhibited significantly higher losses at 42.41 kg ha^{-1}, while the forward speeds of 2.4 km h^{-1} and 3.84 km h^{-1} demonstrated significantly lower losses at 23.96 kg ha^{-1}. This difference was attributed to increased vibration in the header unit with higher forward speeds. Additionally, the mismatch between the reel speed and the combine harvester's forward speed led to increased scattering of grains from the spikes (Bawatharani *et al.*, 2016).

Stefanoni *et al.* (2022) opined the dwarf Kaiima hybrid C1012 of castor beans was evaluated using two different headers, namely the New Holland CX8060 combine harvester equipped with a cereal header and a sunflower header. Machinery performance, seed loss from impact (ISL) and cleaning systems (CSL) were assessed. The ISL was observed to average at 282.02±60.22 kg DM ha^{-1} (14% w/w of Potential Seed Yield) when using the cereal header and 158.16±18.8 kg DM ha^{-1} (8% w/w of PSY) with the sunflower header. This suggests that the Hybrid C1012, characterized by its short height, demonstrated high potential seed yield. The reduced height of the plant allowed for mechanical harvesting with both headers without encountering issues such as clogging in the machinery. Furthermore, CSL averaged at 162.41 kg DM ha^{-1} in the cereal header and 145.56 kg DM ha^{-1} in the sunflower header, corresponding to 8% and 7% w/w of PSY respectively. The results indicate that the sunflower headers cutting and conveying systems performed better in castor bean harvesting compared to the common cereal header. The latter may induce more mechanical stress on plants, leading to the detachment of capsules from the raceme and resulting in higher impact seed loss.

c) Operational parameters

Singh (1981) observed the impact of threshing speed and post threshing storage duration on the threshing performance and quality of two soybean varieties Ankur and PK 71-21. The threshing was conducted at intervals of 0, 2, 3, 7, 15 and 30 days after harvest employing three different cylinder peripheral speeds (8.2, 11 and 13.7 m s^{-1}). This indicate that the quantity of unthreshed grain increases with higher pod moisture content but decreases with an increase in cylinder speed whereas, threshing behaviour varies between the two varieties, with Ankur proving slightly more challenging to thresh compared to PK 71-21. Damage assessment suggests that Ankur exhibits greater resistance to damage compared to PK 71-21. Despite variations in storage time and threshing speed, the germination of both varieties shows minimal impact, with only a slight decrease observed with increases in these parameters. Overall, Ankur demonstrates strong resistance to damage and consistently maintain germination levels across different conditions.

The threshing efficiency of the soybean harvester with shaft rotational speeds of 1000, 1800 and 2600 rpm with corresponding mechanisms at these speeds were recorded as less than 50%, 87.3% and 93.7%, respectively. Despite the aggressive threshing action observed at 2600 rpm, the increase in threshing efficiency was relatively lower, attributed to a significant occurrence of pods being snapped from the plant unopened. The study also noted seed breakages ranging from 0.35% to 1.11% and seed coat damages between 11.8% and

16.6% (Table 9). Higher shaft rotational speeds of the threshing mechanism were associated with an increase in both seed breakage and seed coat damage (Fernando *et al.*, 2004).

Table 9. Mean comparison of threshing efficiency and seed breakage for different mechanism

Treatment	Shaft speed (rpm)	Threshing efficiency (%)	Seed breakage (%)
1.	1000	46.2	0.35
2.	1800	87.3	0.57
3.	2600	93.7	0.11

(Source: Fernando *et al.,* 2004)

Muhammad Shafi *et al.* (2005) studied different combinations of forward speeds at 2.4, 3.34 and 4.28 km h^{-1} and cutting heights at 10, 20, and 30 cm on various parameters including header performance, threshing cylinder efficiency, separation and cleaning processes, overall harvester losses and the efficiency of the combine harvester. The outcomes revealed a substantial increase in header loss, reaching 3.24% with the lowest cutting height of 10 cm compared to the 1.86% was observed at the highest cutting height of 30 cm. This rise was attributed to the extended length of plant stalks, causing plant congestion in front of the cutter, resulting in the spikes falling to the ground and subsequently escalating losses. The threshing cylinder loss percentages for threshing cylinder efficiency were 2.13% and 1.42% for 10 cm and 30 cm cutting heights, respectively. The increased loss percentage at 10 cm cutting height was attributed to the constriction of the threshing cylinder due to a large volume of crop entering it. The increased length of stalks resulted in a higher amount of straw, acting as a cushion, impeding the threshing process and causing insufficient time for effective threshing between the threshing cylinder and concave (Table 10). The highest percentage of threshing cylinder loss at 3.15% was observed at a speed of 4.28 km h^{-1} and a cutting height of 10 cm. In contrast, the lowest percentage of loss, recorded at 0.59%, occurred for the 2.4 km h^{-1} × 30 cm interaction. This resulted from the consistent feeding of crops to the threshing unit, ensuring a steady and sufficient cushion of straw as a result, it improved the efficiency of the threshing operation. This result aligns with (Al-Jubouri *et al.,* 1997).

Table 10. The effect of interaction between forward speed and cutting height on quantitative loss and harvester efficiency

S. No.	Forward speed (km h^{-1})	Cutting height (cm)	Header loss (%)	Threshing loss (%)	Total Harvester loss (%)	Total loss (%)	Combine Efficiency (%)
1	2.4	10	2.39	1.09	4.55	6.39	91.74
		20	1.60	0.94	3.51	5.34	92.55
		30	1.15	0.59	2.58	4.42	93.82
2	3.34	10	3.19	2.15	6.64	8.48	87.81
		20	2.41	1.58	5.06	6.90	89.56
		30	1.86	1.29	4.18	6.02	91.03
3	4.28	10	4.13	3.15	8.97	10.81	84.19

		20	3.17	2.85	7.57	9.41	85.12
		30	2.57	2.36	6.07	7.91	86.38
	LSD		0.221	0.185	0.255	0.255	0.606

(Source: Muhammad Shafi *et al.*, 2005)

Lashgari *et al.* (2008) revealed on wheat grain damage using a John Deere combine harvester, the findings revealed a correlation between operational parameters and grain damage. Specifically, an increase in kernel breakage and a decrease in seed germination were observed with a decrease in forward speed, an increase in cylinder rotation, and a decrease in clearance between the cylinder and concave. The interaction between forward speed and cylinder rotation demonstrated the least kernel breakage (5.47%) and the highest seed germination (96.61%) at a forward speed of 1.8 km h^{-1} combined with a cylinder rotation of 800 rpm. Similarly, an interaction between cylinder rotation and concave clearance showed the least kernel breakage (5.38%) at 900 rpm and 25 mm clearance. Under these conditions, a maximum seed germination of 96.58% was observed. These findings highlight the significance of optimizing operational parameters to minimize wheat grain damage and enhance seed germination when using a combine harvester.

Spokas (2008) examined the influence of the feed rate of the New Holland combine harvester on cereal crops focusing on the analysis of the threshing apparatus, rasp bar movement speed and the clearance between the drum and the concave with respect to grain damage. For harvesting very dry crops with a grain moisture content of less than 12%, the optimal clearance between the threshing drum rasp bars and the concave was determined to be 12-12 mm. Similarly, for dry crops with moisture content ranging between 12% and 14%, the recommended clearance was 11-11 mm and for medium dry crops, the clearance was advised to be 10-10 mm. In the case of harvesting wet crops, the optimal clearance was found to be 10-10 mm. In instances where grain loss exceeded 0.05%, it was recommended to increase the flail speed. Notably, when harvesting wet crops with a moisture content exceeding 16%, minimizing grain loss was achieved by maximizing the speed of the threshing drum. This increase in speed facilitated the efficient separation of damaged grains through the concave. During the harvesting process, the speed of the threshing drum rasp bars ranged from 30 m s^{-1} to 32 m s^{-1} and for the optimal harvesting of dry crops, the recommended drum rasp bars speed was 25 m s^{-1}, while for wet crops, the suggested range was between 31 m s^{-1} and 34 m s^{-1}. To achieve minimal grain threshing losses within the permissible limit of 0.05%, the strategy employed was to increase the speed of the threshing drum rasp bars.

The wheat crop Sakha 93 analysed at various forward speeds such as 0.53, 0.70, 0.95 and 1.15 km h^{-1} and grain moisture contents such as 16.73%, 14.41% and 12.13% with a standard drum speed of 24.74 m s^{-1}. The highest and lowest values of grain damage of 0.24% and 0.09% were observed at forward speeds of 0.53 km h^{-1} and 1.15 km h^{-1}, and grain moisture contents of 12.13% and 16.73% respectively which might due to increase in forward speed, associated with a decrease in grain damage, which attributed to the alleviation of excessive load in the threshing unit. Conversely, the decrease in grain moisture content resulted in an increase in grain damage, as wheat grains with lower moisture content were more prone to crushing and breakage by the drum knives (Abo *et al.*, 2010).

Mahrouf and Rafeek (2010) examined the economic implications of mechanizing paddy harvesting. Their findings indicated that combine harvesters substantially reduced labour requirements by approximately 80-85% resulting in a significant reduction in harvesting costs, specifically ₹ 38,000 per hectare and further additionally the adoption of combine harvesters led to an increase in net returns by approximately ₹ 7,850 per hectare.

The field parameters influenced by several factors such as crop density, maturity, soil moisture conditions, weed population, plot size, lodging and operator skills played a pivotal role in the overall impact of mechanization. Overall, the introduction of combine harvester resulted10-15% reduction in the cost of paddy production. Furthermore, the incorporation of straw into the soil was enhanced and post-harvest losses were considerably reduced, contributing to a more sustainable and economically viable paddy harvesting process.

Chuan-udom and Chinsuwan (2011) examined the impact of operational factors on grain breakage in an axial flow rice combine harvester, focusing on two rice varieties Khao Dok Mali 105 and Chainat 1. For Khao Dok Mali 105, grain moisture content ranged from 16.94% to 27.79%, rotor speeds varied from 15.78 to 19.37 m s^{-1}, feed rates spanned from 5.80 to 13.27 tonnes h^{-1} and the grain to material other than grain ratios were between 0.30 and 1.53. They observed, grain breakage fell within the range of 19.42% to 27.79%. In the case of Chainat 1, rotor speeds ranged from 5.78 to 19.37 m s^{-1}, feed rates varied from 5.11 to 18.47 tonnes h^{-1} and the grain to material other than grain ratio was between 0.34 and 1.66. The recorded grain breakage for Chainat 1 ranged from 0.011% to 0.392%. Further Khao Dok Mali 105, the rotor speed and grain moisture content played significant roles in influencing grain breakage, accounting for 44.6% and 55.4% of the variation respectively. In contrast for Chainat 1, the rotor speed had a more substantial impact on grain breakage compared to grain moisture content, contributing to 70.6% and 29.4% of the variation, respectively.

Mosadegh (2013) conducted a study to investigate the impact of combine working speed and seed moisture content on berseem clover loss. The research focused on seed losses in berseem clover due to variations in seed moisture content and the speed of the combine harvester during seed harvest. The study involved three seed moisture contents *viz.*, 10%, 15% and 20% and three combine working speeds at 1 km h^{-1}, 2 km h^{-1} and 2.5 km h^{-1}. The results indicated that reducing seed moisture content from 20% to 10%, led to an increase in seed losses on the platform, rising from 4.61% to 8.11%. The interaction between combine working speed and seed moisture content revealed a loss of 4.53% when the combine working speed was 1 km h^{-1} with 20% seed moisture content. The highest loss, amounting to 11.66%, occurred with a working speed of 2.5 km h^{-1} and 10% moisture content. In conclusion, the study suggested that a combine working speed of 2 km h^{-1} and a seed moisture content of 15% were deemed suitable for the optimal harvesting of berseem clover seed.

Ramadhan (2013) observed the impact of selected harvester parameters on both quantitative and qualitative losses of bread wheat. The study focused on varying forward speeds at 2.4, 3.34 and 4.28 km h^{-1} and cutting heights at 10, 20 and 30 cm on the header. The parameters examined included the effects on the threshing cylinder, separation and cleaning, total harvester losses and combine harvester efficiency. The findings revealed where an increase in forward speed led to a rise in total harvester losses, concurrently resulting in a decrease in efficiency especially, at a forward speed of 2.4 km h^{-1} combined with a cutting height of 10 cm yielded the lowest total harvester losses and the highest efficiency.

The impact of varying forward speeds (2.4, 3.34 and 4.28 km h^{-1}), threshing cylinder rotational speeds (700, 800 and 900 rpm) and cylinder concave clearances (2-5, 17-10 and 22-15 mm from the front and rear) on the kernel damage and germination percentage of wheat seeds which resulted that increasing in forward speed, increase cylinder rotational speed and a decrease in the clearance between the cylinder and concave, led to an increase in kernel breakage and a decrease in grain germination. Specifically, the interaction of 4.28 km h^{-1} and 700 rpm demonstrated lower kernel breakage, coupled with higher seed germination. Notably, the combination of 700 rpm and C_3 resulted in the lowest kernel breakage at 7% and the highest germination percentage at 96.85%. These results highlight the importance of considering the interplay of forward speed, cylinder rotational speed, and concave clearance to optimize threshing efficiency while minimizing kernel damage and promoting seed germination (Ramadhan, 2013).

Pishgar-Komleh (2013) stated the impact of cylinder speed and ground speed on seed corn combine losses during pre-harvest, gathering and processing stages was investigated. The experimental treatments involved varying cylinder speeds at 400, 500 and 600 rpm and ground speeds at 3, 4 and 5 km h^{-1}. The findings revealed a notable correlation between increased cylinder speed and threshing quality losses, particularly in terms of cracked and broken kernels. The recorded losses were 4.70%, 5.18% and 5.28% for cylinder speeds of 400, 500 and 600 rpm respectively. The observed trend suggests that higher cylinder speed exerts increased pressure and strokes on the seeds, manifesting as cracked and broken kernels in seed corn. The study identified that the lowest total combine loss, amounting to 7.60%, occurred at a ground speed of 3 km h^{-1} with a cylinder speed of 400 rpm. Conversely, the highest total combine loss, reaching 7.19% was associated with a ground speed of 5 km/h and a cylinder speed of 600 rpm. Crucially, the primary factor contributing to cracked and broken seed corn was identified as cylinder speed. Therefore, to mitigate these losses, the study recommends opting for lower cylinder speeds.

An experiment was carried in wheat fields to assess total grain losses, energy consumption and cost requirements during wheat crop harvesting at three different average grain moisture contents of 20.80%, 18.50% and 16.65%. The evaluated harvesting methods included traditional harvesting (hand cutting), partial mechanization (modified combine harvester, self-propelled reaper binder, self-propelled vertical conveyor reaper, and tractor-mounted vertical conveyor reaper windrower). The results indicated that the total grain losses in traditional harvesting were highest at 3.2% for a moisture content of 16.65% and lowest at 2.4% for a moisture content of 20.80%. The total grain losses for the modified combine harvester varied from 4.72% to 6.12% depending on moisture content of 16.65% and forward speeds at 2.7, 3.3, 1.5, and 3.3 km h^{-1}. The minimum total grain losses for the modified combine harvester, self-propelled reaper binder, self-propelled vertical conveyor reaper, and tractor-mounted vertical conveyor reaper windrower were 3.52%, 3.64%, 4.12% and 4.25%, respectively, at a moisture content of 20.80% and forward speeds of 1.5, 2.0, 1.0 and 2.0 km h^{-1}. It is noteworthy that decreasing grain moisture content led to increased total grain losses due to higher pre-harvest and cutting losses, resulting in more shattering losses by the cutter bar. The modified combine harvester showed the lowest total grain losses at 3.5%. The highest cutting efficiency of 97.2% was observed when using the combine machine at a forward speed of 1.5 km h^{-1} and a moisture content of 16.65% (Shreen *et al.*, 2014).

Comparative performance of different combinations of harvesting and threshing methods on three approaches were considered such as Manual harvesting and Power threshing, Self-propelled reaper binder harvester and Power threshing, and Self-propelled combine harvester (harvesting and threshing) in wheat. The evaluation was conducted at varying crop moisture content levels of 20%, 18% and 16%. The effective field capacity at 16% moisture content was determined to be 0.30 ha h^{-1} at a speed of 3 km h^{-1}. The field efficiency of the self-propelled binder was recorded at 74%, 76.79% and 77.90% respectively at the moisture contents of 20%, 18% and 16%. Shattering losses for the self-propelled reaper binder were observed at 51 kg ha^{-1} at a forward speed of 3 km h^{-1} with 20% moisture content, indicating an increase in shattering losses with higher forward speeds. For the combine harvester, the grain breakage percentage during experiments at a speed of 3.25 km h^{-1} with 20% moisture content was 0.06%. It was noted that the grain breakage percentage increased with both forward speed and moisture content. The unthreshed grain percentage was measured recorded as 0.66% at 3.25 km h^{-1} and 20% moisture content. The total grain loss reached 1.7% at a forward speed of 4.05 km h^{-1} with 20% moisture content (Kumar *et al.,* 2017).

Kumar *et al.* (2019) proposed for the optimization of operational and crop parameters in the mechanized harvesting and threshing of summer mung-bean varieties (SML-668 and SML-832) and one kharif mung-bean variety (ML-818) employing a combine harvester. The investigation involved varying forward speeds at 1, 1.5, and 2 km h^{-1} and four levels of cylinder speed (13.52, 14.84, 18.91 and 26.85 m/s). Threshing efficiency surpassed 98% at cylinder peripheral speeds C_3 and C4 for all varieties, except for SML-832, characterized by its indeterminate growth habit. The recorded grain damage fell within the range of 1.54% to 3.22% for C_1, C_2 and C_3 cylinder peripheral speeds across all crop varieties. This indicates that the percentage of grain breakage was higher with increased cylinder peripheral speed and lower with higher forward speed. The optimal harvesting conditions were identified at a peripheral speed of 18.91 m s^{-1} and a forward speed of 1.5 km h^{-1} for mung-bean cultivation using a combine harvester across all crop varieties.

The optimizing operational and crop parameters that impact the mechanized harvesting and threshing of pigeon-pea crops employing a combine harvester featuring varieties such as PAU-881, AL-1856, AL-1817 and AL-1811. The moisture content of both the crop and the grain exhibited variations ranging from 38% to 48% and 22% to 25% on a wet basis, respectively, for crop varieties AL-1817 and AL-1811. For crop varieties PAU-881 and AL-1856, the corresponding values were 48% to 53% and 24% to 27%. The concave clearance of 16 mm at the front side and 7 mm at the rear side achieved threshing efficiency exceeding 98% at cylinder peripheral speeds of 26.61 m/s and 34.85 m/s for all varieties except PAU-881. This revealed that the percentage of grain breakage increased with higher cylinder peripheral speeds but decreased with higher forward speeds. Notably, grain damage remained below 1% for cylinder peripheral speeds of 23.85 m s^{-1}, 26.61 m s^{-1} and 34.85 m s^{-1} across all crop varieties, except for AL-1811. The findings clearly demonstrated a direct relationship between grain breakage and cylinder speed and an inverse relationship with forward speed. In essence, an increase in cylinder speed corresponded to an increase in grain breakage, while an increase in forward speed correlated with a decrease in breakage. The optimal values identified for the peripheral velocity and forward speed of the combine harvester during the pigeon-pea harvesting process were recorded as 26.61 m s^{-1} and 2.0 km h^{-1} respectively used for all selected varieties (Kumar *et al.,* 2019).

Design and operational parameters of the threshing mechanism in a conventional combine harvester for PUSA Basmati 1121 crop was evaluated during the year 2017-2018. The study aimed to assess various combining losses, including visible and invisible grain damage, and threshing efficiency at different levels of AS (Arrangement of Spikes), CC (Concave Clearance) and CS (Cylinder Speed). In 2017, mean visible grain losses were recorded at 4.03%, 4.83%, and 5.49% under AS1, AS2, and AS3, respectively. Simultaneously, invisible losses were 28.9%, 26.3% and 28.0%, this might increase in both visible and invisible losses due to higher number of spikes arrangements and increased CS. Higher CC was associated with reduced grain damage and vice versa. During 2018, visible grain losses ranged from 76% to 89%, 62% to 82% and 43% to 83% under AS1, AS2 and AS3, respectively. However, invisible losses were in the range of 3% to 13%, 7% to 23% and 13% to 22%, respectively. Consequently, optimizing the combine harvester parameters demonstrated a significant reduction in visible grain damage by 60% to 83% and invisible grain damage by 6% to 16% (Table 11a & Table 11b). This underscores the importance of fine-tuning the combine harvester settings to minimize grain losses and enhance overall threshing efficiency (Bhardwaj *et al.,* 2021).

Table 11a. Independent variables/parameters during 2017 and 2018.

S. No.	Levels: Three (3)	Year 2017	Year 2018

1.	AS: Arrangement of spikes (No. of spikes)	1) AS1:44 2) AS2: 68 3) AS3:136	1) AS1: 36 2) AS2: 44 3) AS3: 52
2.	CS: Cylinder speed (rpm)	1) CS1: 560 2) CS2:640 3) CS3: 720	1) CS1: 480 2) CS2: 560 3) CS3: 640
3.	CC: Concave clearance	1) CC1: 13-9 2) CC2: 15-11 3) CC3: 17-13	1) CC1: 15-11 2) CC2: 17-13 3) CC3: 19-15

(Source: Bhardwaj *et al.*, 2021).

Table 11b. Visible and invisible losses during 2017 and 2018.

S. No.	Parameters			Visible loss %	Invisible loss %	Visible loss %	Invisible loss %	Visible loss %	Invisible loss %
				2017		2018		Percent difference	
1.	AS1	CC1	CS1	3.89	21.33	0.57	20.67	85.35	3.09
			CS2	4.17	23.33	0.79	22.00	81.06	5.70
			CS3	4.53	24.67	1.02	24.00	77.48	2.72
		CC2	CS1	3.72	19.33	0.43	18.67	88.44	3.41
			CS2	4.01	20.67	0.61	19.33	84.79	6.48
			CS3	4.36	22.00	1.00	20.00	77.06	9.09
		CC3	CS1	3.50	17.33	0.38	16.00	89.14	7.67
			CS2	3.94	18.67	0.49	17.33	87.56	7.18
			CS3	4.12	20.67	0.99	18.00	75.97	12.92
		CC1	CS1	4.73	26.00	0.91	22.00	80.76	15.38
			CS2	5.13	27.33	1.50	23.33	70.76	14.64
			CS3	5.33	28.67	2.03	26.67	61.91	6.98
2.	AS2	CC2	CS1	4.51	25.33	0.81	21.33	82.04	15.79
			CS2	4.89	26.67	1.01	22.67	79.35	15.00
			CS3	5.18	28.00	1.43	25.33	72.39	9.54
		CC3	CS1	4.29	23.33	0.76	18.00	82.28	22.85
			CS2	4.63	25.33	0.93	21.33	79.91	15.79
			CS3	4.79	26.00	1.34	22.00	72.03	15.38
		CC1	CS1	5.45	28.00	2.10	24.00	61.47	14.29
			CS2	5.79	31.33	2.43	26.00	58.03	17.01
			CS3	6.18	33.33	3.51	28.00	43.20	15.99
3.	AS3	CC2	CS1	5.20	27.33	1.09	21.33	79.04	21.95
			CS2	5.46	28.00	2.32	22.67	57.51	19.04
			CS3	5.62	29.33	2.71	25.33	51.78	13.64
			CS1	5.00	24.00	0.87	20.00	82.60	16.67
		CC3	CS2	5.30	25.33	2.16	21.33	59.25	15.79

			CS3	5.45	26.00	2.69	22.67	50.64	12.81

(Where AS: Arrangement of spikes, CC: Concave clearance, CS: Cylinder speed) (Source: Bhardwaj *et al.*, 2021)

d. Mechanical damage and losses

Picket (1973) conducted a study to evaluate mechanical damage in soybean harvesting, considering a range of combine cylinder speeds ranging from 7.2 to 15.2 m s^{-1} and moisture contents ranging between 15.7% and 22.7% which indicated a consistent increase in grain damage with the increased cylinder speed, coupled with a decrease in moisture content.

Biddle (1980) observed that when pea seeds were harvested with a pea viner harvester, seed coat cracking occurred particularly at high moisture content around 70%. This damage was attributed to increased leachates, leading to a decline in seed vigour. Additionally, the observed decrease in quality was enhanced with higher moisture content. However, when a pea harvester was utilized, seed harvesting resulted in lower damage, ranging between 30% and 44% moisture content. The use of a combine harvester allowed for even lower moisture content, down to 26%, contributing to better seed quality.

Krishnan *et al.* (1994) observed a correlation between the speed of the threshing cylinder and the condition of grain amaranth seedlings. They found that the percentage of normal seedlings decreased, while abnormal seedlings increased with an escalation in threshing cylinder speed from 8.1 to 30.7 ms^{-1}. Although manually harvested seeds or those threshed at 8.1 ms^{-1} did not exhibit apparent damage, scanning electron micrographs of seeds exposed to higher speeds (12.8 or 22.4 ms^{-1}) revealed harm to the seed coat and endosperm. Moreover, at the maximum threshing cylinder speed of 30.7 ms^{-1}, damage extended to the embryo. Irving *et al.* (1981) proposed that the increased susceptibility to mechanical damage during combine harvesting, leading to an increased risk of seed deterioration, may be attributed to the unique arrangement of embryos encircling the perisperm in a single plane within amaranth seeds.

Szpryngie (1995) analyzed on various rapeseed varieties, including Ceres, Bolko, Mar, Liporta, Libravo, Leo and Polo, using a combine harvester with threshing drum speeds set at 600, 800 and 1000 rpm. The estimation of mechanical damage was carried out. The results indicated a decrease in seed mechanical damage at 600 rpm, whereas an increase in mechanical damage was observed at 1000 rpm. The damage ranged from 0.1% for the Liporta and Polo varieties to 1% for the Bolko variety. As the threshing drum speed increased, there was a notable rise in damage, increasing from 1.1% for the Bolko variety at 600 rpm to 47.4% for the Ceres variety at 1000 rpm. The quantity of damage exhibited an exponential growth pattern with the increasing drum speed. The occurrence of damage was attributed to the flails of the threshing drum, particularly influenced by the increase in damage to dry seed.

The soybean harvested with a combine harvester revealed that seeds at 14% moisture content increased mechanical damage. Beyond 14% moisture, the damage increased, leading to reduced germination and vigour. In contrast, maintaining moisture content between 12% and 14% resulted in lower damage and higher seedling vigour. This observed variation in damage may be attributed to the difference between the force attempting to open the seam of the soybean pod and its attachment strength, which approached its maximum at 13% soybean moisture content. This discrepancy appears to establish a protective pod condition during soybean harvesting, contributing to the production of seeds with improved quality (Herbek and Bitzer, 2004).

The impact of machine-crop variables on the axial flow soybean combine harvester's threshing unit, utilizing a peg tooth drum, was investigated. Threshing efficiency ranged from 98% to 100%. Grain damage and grain loss were both below 1% and 1.5%, respectively, within the range of drum speeds of 600 to 700 rpm and feed rates of 540 to 720 kg h^{-1} (plant). The study also revealed that at seed moisture contents of 14.34% to 22.77%, grain damage increased with higher seed moisture content. The maximum power requirement recorded was 2.29 kW at a grain moisture content of 32.88% and a drum speed of 700 rpm. The optimal combination for achieving higher output capacity, threshing efficiency and minimizing grain damage and losses was identified as a drum speed ranging from 600 to 700 rpm (13.2 to 15.4 m s^{-1}) at a feed rate of 720 kg h^{-1} (plant), particularly at a seed moisture content of 14.34% (Verjasit and Salokhe, 2004).

Muhammad Shafi *et al.* (2005) observed the impact of selected combine and crop parameters on kernel damage and threshability of wheat and involved with three levels of parameters namely moisture content, concave clearance and feed rate. The findings indicated that doubling the feed rate while maintaining a constant concave clearance approximately doubled the total grain losses but concurrently reduced the breakage of threshed grain by 16% where at the moisture content levels of 26% and 13% showed grain losses were higher compared to those at 19% moisture across each feed rate and concave clearance. The minimum grain loss, amounting to 0.94% was recorded at 19% moisture, with a concave clearance of 30 mm and a feed rate of 2.82 tonnes h^{-1}. Conversely, the minimum grain damage of 1.4% was observed at 26% moisture with a concave clearance of 30 mm and a feed rate of 5.64 tonnes h^{-1}.

The soybean harvesting with a combine harvester revealed that seeds harvested at 14% moisture content experienced an increased invisible mechanical damage. Beyond the 14% moisture threshold, there was increase in damage, accompanied by a decline in germination and vigour. Conversely, when the moisture content ranged between 12% to 14%, mechanical damage was minimized, leading to higher seedling vigour. This observed pattern may be attributed to the interplay between the force exerted to open the seam of the soybean pod and its attachment strength, reaching a maximum at 13% soybean moisture content. This dynamic seems to establish a protective pod condition during harvesting, contributing to the production of seeds with enhanced quality. In essence, maintaining a moisture content around 13% appears crucial for optimizing the balance between minimizing mechanical damage and ensuring the preservation of seed quality in soybean harvesting using a combine harvester (Mesquita *et al.*, 2007).

In kidney beans, the impact velocity was varied at 5, 7.5, 10, and 12 m s^{-1} along with moisture content levels of 5, 10, 15 and 20%. The results indicated that both impact velocity and moisture content significantly influenced the physical damages of kidney beans, with statistical significance at the 1% and 5% levels, respectively. An increase in impact velocity from 5 to 12 m s^{-1} led to an increase in the mean percentage of physical damages, evolved from 3.25% to 37.5%. Similarly, for beans with a 5% moisture content, the corresponding values increased from 3.7% to 45.7%. As the moisture content increased from 5 to 15%, the mean percentage of damaged beans decreased by 1.4 times. However, with a further increase in moisture content from 15 to 20%, the mean values of physically damaged beans showed a non-significant increasing trend (Khazaei *et al.*, 2009). Ptasznik *et al.* (1995) reported that at grain moisture contents of 14%, 17% and 21%, bean damages exhibited a linear increase with the increase in impact velocity from 1000 to 2500 rpm.

The locally combined harvester conducted an analysis of the wheat crop Sakha 93, examining different forward speeds of 0.53, 0.70, 0.95 and 1.15 km h^{-1} along with varying grain moisture contents of 16.73%, 14.41% and 12.13% during the wheat crop harvesting. This shows the highest header loss of 0.3% occurred at a forward speed of 1.15 km h^{-1} and a grain moisture content of 12.13% due to excessive load of wheat stems at the cutter-bar and the reduction in grain moisture content correlates with an increase in header loss at various forward speeds. The total harvesting loss peaked at 2.08% at a forward speed of 1.15 km h^{-1}

and a grain moisture content of 16.73%. It is evident that an increase in both forward speed and grain moisture content leads to a rise in total harvesting loss. The highest machine performance efficiency of 98.91% was achieved at a forward speed of 0.53 km h^{-1} and a grain moisture content of 12.13%. The most effective field capacity (0.48 fed/h) and efficiency (78.38%) were obtained at forward speeds of 1.15 and 0.53 km h^{-1}, respectively, with a grain moisture content of 12.13%. The effective field capacity indicates that increase with higher forward speeds and a decrease with lower grain moisture content. Conversely, field efficiency exhibited a decline with higher forward speeds and grain moisture content. Regarding energy requirements, the highest and lowest values of 693.08 and 311.01 kW.h/fed, were recorded at forward speeds of 0.53 and 1.15 km h^{-1}, corresponding to grain moisture contents of 16.73% and 12.13%, respectively. Harvest operation costs varied between 396.65 and 174.02 L.E/fed (Price of machine), at forward speeds of 0.53 and 1.15 km h^{-1}, associated with grain moisture contents of 16.73% and 12.13%. The findings revealed a decrease in energy requirements with an increase in forward speed and a decrease in grain moisture content. Similarly, criterion costs ranged from 494.67 to 312.10 L.E/fed, at forward speeds of 0.53 and 1.15 km h^{-1}, with grain moisture contents of 16.73% and 12.13% (Table 12). In summary, the optimal performance of the local harvester combine was achieved at a forward speed of 0.53 km h^{-1} and a grain moisture content of 12.13% for harvesting wheat crops based on the experimental results (Abo *et al.*, 2010).

Table 12. Field capacity, field efficiency and energy requirements at different forward speed and grain moisture content

S. No.	Grain moisture content %	Forward speed km/h	Actual field capacity fed;/h	Fuel Consumption L/h	Power require ments KW	Energy requirements kW.h/fed	Field efficiency %
1.	16.73	0.53	0.2	14.03	138.62	393.08	54.05
		0.7	0.25	14.97	147.90	591.61	52.08
		0.95	0.31	15.92	157.29	507.39	46.97
		1.15	0.38	16.92	167.17	439.92	48.10
2.	14.41	0.53	0.25	13.41	132.49	529.96	67.57
		0.7	0.30	14.31	141.38	471.28	62.50
		0.95	0.36	15.2	150.18	417.16	54.55
		1.15	0.43	16.17	159.76	371.53	54.43
3.	12.13	0.53	0.29	12.53	123.80	426.88	78.38
		0.7	0.34	13.37	132.10	388.52	70.83
		0.95	0.41	14.21	140.39	342.43	62.12
		1.15	0.48	15.11	149.29	311.01	60.76

(Source: Abo *et al.,* 2010)

Xue *et al.* (2018) discovered that in China, the yield loss attributed to mechanical grain harvesting and caused by lodging primarily resulted from dropped ears. Furthermore, their research revealed that for every 1% increase in lodging rate, the ear loss experienced a corresponding increase of 0.1% and 0.2% of the yield in a spring maize area and a summer maize area, respectively. Li *et al.* (2018) proved that moisture content below 16.15% there was a reduction in ear loss rate more than 5%, whereas at around 20% moisture during mechanical harvesting, a decrease of 5% in ear loss and broken seed rate (%) was observed in summer maize.

According to Gagare *et al.* (2014), soybean varieties JS-335, JS-9305 and JS-9560 undergo harvesting and threshing processes employing stick beating, multicrop thresher, and combine harvester. Subsequently, the varieties were subjected to ferric chloride detection and analysis which results indicated that JS-9305 exhibited the lowest mechanical damage (6%) when subjected to stick beating, attributed to its smaller seed size. This observation aligns with similar findings reported by Verasilpa *et al.* (2001). Conversely, JS-9560 demonstrated the highest mechanical damage (23.67%) when threshed with a combine harvester, likely due to its bold seed (Table 13). The observation suggested that cultivars with larger seed size and thinner seed coat tend to incur more mechanical damage. These results are consistent with (Ujjinaiah and Shreedhara, 1998).

Table 13: Interaction effect of varieties, threshing methods and processing locations on mechanical damage of soybean seed detected by ferric chloride test.

Treatment	Mechanical damage (%)	Treatment	Mechanical damage (%)
$V_1T_1P_1$	7.33	$V_2T_3P_1$	9.00
$V_1T_1P_2$	9.00	$V_2T_3P_2$	13.33
$V_1T_1P_3$	10.00	$V_2T_3P_3$	14.33
$V_1T_1P_4$	10.67	$V_2T_3P_4$	18.00
$V_1T_1P_5$	8.00	$V_2T_3P_5$	13.67
$V_1T_1P_6$	9.33	$V_2T_3P_6$	14.33
$V_1T_1P_7$	11.00	$V_2T_3P_7$	17.00
$V_1T_1P_8$	12.67	$V_2T_3P_8$	18.67
$V_1T_2P_1$	10.33	$V_3T_1P_1$	7.67
$V_1T_2P_2$	12.00	$V_3T_1P_2$	9.67
$V_1T_2P_3$	13.33	$V_3T_1P_3$	10.00
$V_1T_2P_4$	15.67	$V_3T_1P_4$	11.33
$V_1T_2P_5$	11.67	$V_3T_1P_5$	10.00
$V_1T_2P_6$	12.67	$V_3T_1P_6$	10.00
$V_1T_2P_7$	14.33	$V_3T_1P_7$	11.33
$V_1T_2P_8$	16.00	$V_3T_1P_8$	13.67
$V_1T_3P_1$	13.00	$V_3T_2P_1$	11.33
$V_1T_3P_2$	16.00	$V_3T_2P_2$	12.67
$V_1T_3P_3$	18.00	$V_3T_2P_3$	13.33
$V_1T_3P_4$	19.33	$V_3T_2P_4$	16.00
$V_1T_3P_5$	14.00	$V_3T_2P_5$	12.00
$V_1T_3P_6$	16.00	$V_3T_2P_6$	13.00
$V_1T_3P_7$	18.33	$V_3T_2P_7$	14.67
$V_1T_3P_8$	18.67	$V_3T_2P_8$	16.67
$V_2T_1P_1$	6.00	$V_3T_3P_1$	15.00

$V_2T_1P_2$	8.33	$V_3T_3P_2$	17.33
$V_2T_1P_3$	9.67	$V_3T_3P_3$	17.00
$V_2T_1P_4$	10.33	$V_3T_3P_4$	19.67
$V_2T_1P_5$	7.67	$V_3T_3P_5$	15.33
$V_2T_1P_6$	8.67	$V_3T_3P_6$	18.67
$V_2T_1P_7$	9.33	$V_3T_3P_7$	18.67
$V_2T_1P_8$	11.00	$V_3T_3P_8$	23.67
$V_2T_2P_1$	7.00	SE ± CD at 5 %	0.495 1.385
$V_2T_2P_2$	11.67		
$V_2T_2P_3$	12.67		
$V_2T_2P_4$	15.00		
$V_2T_2P_5$	10.67		
$V_2T_2P_6$	12.00		
$V_2T_2P_7$	12.33		
$V_2T_2P_8$	15.67		

(V_1: JS 335, V_2: JS 9305 and V_3: JS 9560; T_1: Stick beating, T_2: Multi crop thresher and T_3: Combine harvester; P_1: Seed collected before processing, P_2: Seed grader, P_3: Bucket elevator, P_4: Specific gravity separator, P_5: Inclined flight belt conveyor-I, P_6: Seed grader, P_7: Inclined flight belt conveyor-II, P_8: Specific gravity separator, Source: Gagare *et al.*, 2014)

Richman and Gummert (2015) noted that harvesting early results in immature kernels that are not well filled out and tend to be chalky. This condition can lead to higher amounts of attached bran and an increased prevalence of broken kernels during the milling process. On the other hand, harvesting late can result in the loss of more kernels from panicles due to shattering. As grains become excessively dry, there is a higher risk of cracking during threshing, leading to more cracked grains and subsequently more breakage during the milling process.

Shahbazi (2019) conducted observations on corn seeds with moisture contents ranging from 7.60% to 25% and exposed to impact energies of 0.1, 0.2, and 0.3 J. The combinations of moisture content and impact energy revealed varying levels of damage, with the lowest damage recorded at 3.36% occurring at 0.1 J impact energy and 20% moisture content. Conversely, the highest damage, reaching 100%, was observed at 0.3 J impact energy and 7.6% moisture content. At 7.6% seed moisture content, the percentage of damage increased from 60.79% to 100% with a rise in impact energy from 0.1 to 0.3 J. This suggests that moisture content played a crucial role in reducing seed damage, as higher moisture levels were associated with decreased damage. This reduction in damage might be attributed to changes in elasticity at higher moisture levels, leading to increased energy absorption during impact. Additionally, mechanical damage increased with higher impact energy. Seeds with moisture content in the range of 17.5% to 20%, equivalent to losses of 24.01% (from 100% to 75.99%) exhibited firmness, while at the lowest moisture content seeds became brittle, causing physical damage. Based on these findings, optimal conditions for harvesting and processing corn seeds, particularly those subjected to impact loads, would involve moisture contents of approximately 17-20%, with impact energy and velocity limited to about 0.1 J and 27 m s^{-1} respectively.

Conclusion:

Reducing harvest losses during the operation of a combine harvester is vital and necessitates the implementation of suitable harvesting practices along with adjustments to the equipment. Combine harvesters are typically optimized to operate efficiently within specific moisture content ranges for different crops. By adhering to these guidelines and consistently enhancing harvesting practices both pre-harvest and post-harvest losses associated with combine harvesting can effectively be reduced. It is important to note that adjustments should be tailored to the unique characteristics of the crop, prevailing field conditions and regional agricultural practices. Utilizing combine harvesters markedly enhances the efficiency of the harvesting process for farmers. This is achieved through time and labour savings, cost reduction, minimized losses and adaptability to diverse crops and field conditions. This approach is well-suited for farmers aiming to mitigate losses during the seed crop harvesting process.

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