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Soybean yield, seed quality and thresh efficiency by mechanisation at different harvesting stages and postharvest ripening

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Abstract:

This study determined the most appropriate and earliest soybean harvesting stage and the number of days of postharvest ripening with minimal effects on seed losses and quality when mechanical harvest and threshing were applied. Harvesting stages at four physiological maturities (60, 70, 80, and 90%) and various days of postharvest ripening treatment (1, 2, and 3 days) were applied for two soybean varieties DT12 and DT26. Harvesting at physiological maturity of 90% recorded the highest seed-shattering loss but the least seed damage (<5%) and highest seed quality, followed by a physiological maturity of 80%. There were no significant differences in seed yields between harvesting stages of 80 and 90% maturity. Harvesting soybeans at a physiological maturity of 60 and 70% resulted in no seed losses but a significant reduction in seed quality. To avoid adverse weather, an early harvest stage at a physiological maturity of 80% is suggested. Although postharvest ripening of soybeans for early harvest caused seed shattering losses (2-5%), it was necessary to ensure seed quality. These results indicate effective and practical methods for farmers at small households to use in early mechanical harvesting of soybeans.

Keywords: **early harvest, mechanical, physiological maturity, postharvest ripening.**

Classification numbers: **3.1, 3.4**

1. Introduction

Harvesting time is critical to seed quality in soybean seed production since the seeds deteriorate either in the field, during harvesting, or after harvesting [1, 2]. Therefore, appropriate harvesting stages of soybeans are important to minimize losses at harvest and to ensure seed quality for the next growing season. Seed yield and quality largely depend on the stage of maturity. Physiological maturity in soybeans reached the reproductive development stage R7 with pods yellowing and 50% of leaves yellowing [3]. The seed moisture content at that physiological maturity ranged from 54-62% [1, 4], which is unsuitable for mechanical harvesting and threshing. The R8 stage was featured by 95% of pods reaching the mature pod colour [5].

Common practice is to harvest soybeans when 90% of the pods on the plant turn brown [6]. Early harvest often results in very poor seed quality due to a greater number of immature and undeveloped seeds [7], high seed moisture content (e.g., 60.9% for soybean seed harvest early at R7), and a low percentage of seed germination (<75%) [1]. In addition, the study by D.F. Miles, et al. (1988) [8] on harvested pods at four developmental stages (full seed, mid-pod fill, expanded pod, and yellow pod) showed that near maximum radicle protrusion occurred at only 35% seed dry weight accumulation, and maximum germination did not occur until physiological maturity. Soybean seeds harvested too early, such as less than 34 days after flowering, were still able to germinate before maximum seed dry weight was reached; but seeds harvested at less than one-half their full size had very little potential to withstand desiccation [9].

Delayed harvesting by one to two weeks after physiological maturity can result in significant seed yield loss [6, 10] and low seed germination and vigour [1, 11-13]. Germination and vigour were reduced in seeds harvested at 15 and 30 days after the R8 stage (when 95% of pods have typical coloration of mature pods) [11]. Oil

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contents of seeds harvested at R8 stage or 1 to 4 weeks after physiological maturity were not significantly different from and even lower after 1-2 months of storage than that of seeds harvested early at the R7 stage [1, 6]. Maximum protein content was obtained at physiological maturity and decreased with delaying harvest [14]. Total protein was not significantly affected by four harvest times (R7, R7+5 days, R7+10 days (R8), and R7+20 days) [15].

In addition, soybean seed quality is also affected by the field weather environment during harvest dates. Adverse weather, especially highly humid and wet weather or even alternating periods of wet and dry weather during harvest dates, accelerated seed deterioration and shatter loss [13, 16]. Additionally, shrinking and breaking of seeds were some of the physical changes that occurred in soybean seeds after harvesting [17].

Soybean seeds are quite susceptible to mechanical damage, especially at high seed moisture content. One way to minimize the negative effects of harvesting high moisture soybeans on seed viability and vigour is to harvest and dry the seeds within intact pods [18]. Indeed, N.H. Samarah, et al. (2009) [19] found that harvesting and drying soybeans within intact pods helped maintain soybean seed quality (viability and vigour). Drying the seeds within intact pods can also reduce the seed moisture, which consequently reduces seed damage during mechanical threshing. Drying soybean seeds of 9-cm-high seed layer using a prototype dryer showed that seed quality was maintained by drying high moisture seeds (22%) with an average temperature of 34^{o}C and relative humidity of 24.6% [20].

Several studies on soybean harvesting time have been done with emphasis given to effects on commercial values and storage, but not on the use of seeds for the next crop [1, 21]. Additionally, there have been many studies on effects of early harvesting stages and postharvest ripening treatment on seed losses and quality in soybeans. In practice and on small household scales in developing countries like Vietnam [22], farmers are continually faced with the challenge of loss of seed viability and germination. Winter soybeans are a common crop after summer rice - an important rotation sequence in the rice-based cropping system in North Vietnam. However, adverse weather such as high humidity and wet conditions on harvest days in the Vietnamese winter season place pressure on farmers to harvest soybeans early. Moreover, mechanisation at harvest should be increasingly applied for more efficient soybean production. Moreover, there have not yet been any studies providing information on possible early harvesting stages for small farmers to apply in practice with mechanical harvesting to minimize seed losses and quality.

Thus, this study aims to determine the most appropriate stage for early soybean harvesting and number of days of postharvest ripening on seed loss, yield recovery, and seed quality in aspects of seed germination and vigour. This will provide valuable and useful information for small farmers in Vietnam to apply mechanical harvesting and seed threshing to avoid adverse weather at harvest dates.

2. Materials and methods

2.1. Plant materials

Two soybean varieties, DT12 and DT26, were sown in Hung Ha district, Thai Binh province (Northern Vietnam) during the winter season (from September 2019 to January 2020). Soybean varieties suitable for mechanical harvest should have the first pod insertion height ≥10cm, a resistance to logging, and pod shattering [23-25]. DT12 has a short growth duration of 75-80 days, is commonly grown by farmers here, and thus was used as the control variety. DT26 has a growth duration of 85-95 days and is suitable for the winter crop in Thai Binh [25].

2.2. Cultural details and experimental design

The field experiment was a randomised complete block design with three replications. Each experimental plot area was 100 m^2 with a plant density of 45 plants/m^2 and 4 plant rows per plot with row spacing at 15x30x15 cm. Irrigation was provided to ensure plants had sufficient water access, especially around 7-10 days after germination and at flowering and pod filling stages. Chemical sprays were applied to mostly control stem and pod borers. At harvest, the entire plant was mechanically cut and collected in the field. The harvested whole plants with intact pods were mechanically threshed after drying depending on particular treatments. The methods used in this study attempted to approach the real farmers' practice of drying the soybean seeds within intact pods under the sun.

Experiment 1. Determination of appropriate harvesting stages.

Two soybean varieties (DT12 and DT26) were harvested at four stages, viz., when 60, 70, 80 and 90% of pods on the plant turned brown (designated as T1, T2, T3, and T4, respectively). These four stages were between the R7 and R8 reproductive stages of the soybean [3, 5]. The harvested whole plants with intact pods were left to dry for one day under the sun before being mechanically threshed. Before mechanical harvest, the shattered seeds on the ground were collected from 5 sites that were 2 m^2 each per experimental plot, counted and weighted (number of seed loss, No.SL1 and weight of seed loss, WSL1 prior to harvest). After the mechanical harvest, the seeds that fell to the ground on the 5 2m^2 sites per experimental plot were counted and weighted (number of seed loss, No.SL2 and weight of seed loss, WSL2 after harvest). From those same sites, seed yield (g/m^2) was determined from the total weight of harvested seeds taken off the weight of seed loss WSL1 and WSL2.

Five kilograms of harvested plants (including leaves, stem, and pods) of each harvesting stage were threshed mechanically. Seeds were then examined for seed damage and germination. The percentage of damaged seeds (SD1) (thresh efficiency) was calculated from the weight of broken or damaged seeds out of 500 g with three replications. The standard germination test was conducted in the laboratory. Seeds were arranged in 5 replicates of 50 seeds on each petri dish with moistened filter paper. The percentage of seed germination (PG1), hypocotyl length (HL1), and root length (RL1) were evaluated after 7 days. One hundred seed weights (P100) were determined in three replicates

Experiment 2. Evaluation of early harvesting stages and postharvest ripening.

The plants were mechanically cut when 60, 70, and 80% of pods on the plant turned brown (T1, T2, and T3, respectively). Harvested whole plants with intact pods were left for one day at ambient temperature before beginning the 1, 2, and 3 days of postharvest ripening (D1, D2, and D3, respectively) under the sun.

Measurements consisted of (1) percentage of seed-shattering loss during ripening (SL1); (2) percentage of seed loss by mechanical threshing (SL2); (3) total percentage of seed loss (SL3); (4) percentage of damaged seeds (SD2); (5) percentage of seed germination (PG2) after 7 days; (6) seedling hypocotyl length (HL2) and (7) root length (RL2) after 7 days of germination; (8) and weight of 100 seeds (P100).

Five kilograms of harvested plants (including leaves, stem, and pods) from each treatment were used for seed loss measurements. The percentage of seed-shattering losses (SL1) was determined by the ratio between weight of all loose seeds collected on the ground at postharvest ripening over the total weight of seeds from 5 kg of harvested plants. Percentage of seed loss by threshing (SL2), indicating thresh efficiency, was determined by the ratio between weight of seed left in the pods after threshing over the total weight of seeds from 5 kg of harvested plants. SL3 was the sum of SL1 and SL2.

$$\text{Seed loss (\%)(SL1, SL2)} = \frac{\text{Weight of collected seeds}}{\text{Total weight of seeds collected of harvested plants (5 kg)}} \times 100$$

SD2, PG2, HL2, RL2, and P100 were measured as described in Experiment 1.

2.3. Data analysis

The analysis of variance was done by R version 4.0.2 software to determine the effects of harvesting stages and days of postharvest ripening of soybean on seed yield and quality characteristics when applying mechanical harvest and seed threshing. All experiments were performed with three replications.

3. Results

3.1. Yield, seed quality, and thresh efficiency by mechanisation at different harvesting stages

Seed-shattering occurred at a physiological maturity of 80% (T3) and 90% (T4) for both DT12 and DT26 and caused seed loss (Table 1, Supplement Table 1). Seed shattering loss (No.SL1) occurred at T3 for DT12 and DT26 with 9.87 seeds/m^2 (1.33 g/m^2) and 2.47 seeds/m^2 (0.35 g/m^2) respectively. The loss increased nearly double at T4 with 22.80 seeds/m^2 (3.17 g/m^2) and 5.40 seeds/m^2 (0.80 g/m^2) for DT12 and DT26, respectively.

Table 1. Effects of harvesting stages on seed shattering loss before and at harvest, and yield when applying mechanical harvest.

Variety	Harvesting stages	Seed-shattering loss before harvest		Seed-shattering loss at harvest		P100 (g)	Seed yield (g/m^2)
		No.SL1 (seeds/m^2)	*WSL1 (g/m^2)*	*No.SL2 (seeds/m^2)*	*WSL2 (g/m^2)*		
DT12	T1	0^{e}	0^{e}	0^{d}	0^{d}	13.22	23.67^{ab}
	T2	0^{e}	0^{e}	0^{d}	0^{d}	13.41	27.33^{a}
	T3	9.87^{b}	1.33^{b}	9.07^{c}	1.23^{c}	13.62	23.67^{ab}
	T4	22.80^{a}	3.17^{a}	21.20^{a}	2.96^{a}	13.91	18.67^{b}
DT26	T1	0^{e}	0^{e}	0^{d}	0^{d}	13.49	27.0^{a}
	T2	0^{e}	0^{e}	0^{d}	0^{d}	13.42	26.33^{a}
	T3	2.47^{d}	0.35^{d}	9.20^{c}	1.31^{c}	14.36	27.33^{a}
	T4	5.40^{c}	0.80^{c}	12.47^{b}	1.79^{b}	14.43	25.0^{a}
	SE	0.80	0.11	0.89	0.13	0.44	1.12
Mean for variety	DT12	8.17^{f}	1.13^{f}	7.56^{e}	1.05^{e}	13.54	23.33^{d}
	DT26	1.97^{g}	0.29^{g}	5.42^{f}	0.78^{f}	13.93	26.42^{c}
	SE	0.40	0.05	0.46	0.07	0.22	0.56
Mean for harvesting stages	T1	0^{j}	0^{i}	0^{i}	0^{i}	13.36	25.33^{e}
	T2	0^{j}	0^{i}	0^{i}	0^{i}	13.42	26.83^{e}
	T3	6.2^{i}	0.84^{h}	9.13^{h}	1.27^{h}	13.99	25.5^{e}
	T4	14.1^{h}	1.99^{h}	16.83^{g}	2.38^{h}	14.17	21.83^{f}
	SE	0.56	0.08	0.63	0.09	0.31	0.79

Note: T1, T2, T3, T4: harvesting stages at physiological maturity of 60, 70, 80, and 90% respectively; No.SL1: number of seed-shattering loss before harvest; No.SL2: number of seed shattering loss at harvest; WSL1: weight of seed shattering loss before harvest; WSL2: weight of seed shattering loss at harvest. Mean within a column followed by the same superscript letter are not significantly different at p=0.05 according to Tukey test.

Under mechanical harvesting, there were additional seed-shattering losses (No.SL2). The loss for DT12 at harvest was quite similar to that before harvest. However, the loss for DT26 at harvest was nearly four times greater at 80% maturity (9.20 seeds/m^2) and two times greater at 90% maturity (12.47 seeds/m^2) compared to those before harvest. Across varieties, DT12 had higher seed-shattering loss than DT26. Across harvesting stages, number and weight of seed shattering loss at physiological maturity of 90% were highest and significantly different from other earlier harvesting stages (T1-T3).

Seed loss, harvesting stages and varieties significantly affected the yield. The yield was least at 90% maturity for both DT12 (18.67 g/m^2) and DT26 (25.0 g/m^2) and for the

Supplement Table 1. ANOVA for effects of harvesting stages on seed shattering loss and quality when applying mechanical harvesting.

Traits	Source of variation	df	SS	MS	F-value	p
No.SL1	Var	1	813.39	813.39	62.3818	7.31E-11***
	T	3	2891.17	963.72	73.9114	<2.20E-16***
	Var:T	3	1187.17	395.72	30.3494	4.59E-12***
No.SL2	Var	1	122.7	122.72	3.996	0.05014
	T	3	4464.3	1488.11	48.4551	4.93E-16***
	Var:T	3	423.2	141.06	4.593	0.00584***
WSL1	Var	1	14.942	14.9422	63.8999	5.02E-11***
	T	3	57.285	19.095	81.6591	<2.20E-16***
	Var:T	3	22.232	7.4107	31.6918	2.10E-12***
WSL2	Var	1	2	2	3.1685	0.080133
	T	3	88.049	29.3496	46.4979	1.17E-15***
	Var:T	3	8.084	2.6948	4.2693	0.008472**
Seed yield	Var	1	57.04	57.04	13.535	0.00248**
	T	3	82.12	27.38	6.496	0.00558**
	Var:T	3	41.46	13.82	3.279	0.05269
SD1	Var	1	58.86	58.86	66.772	2.00E-11***
	T	3	280.95	93.65	106.235	<2E-16***
	Var:T	3	1.44	0.48	0.543	0.654
P100	Var	1	2.64	2.645	1.621	0.208
	T	3	9.02	3.0056	1.841	0.149
	Var:T	3	1.32	0.4409	0.27	0.847
PG1	Var	1	158.7	158.7	29.815	3.06E-07***
	T	3	996.1	332	62.379	<2.00E-16***
	Var:T	3	46.5	15.5	2.912	0.0378*
HL1	Var	1	30.4	30.36	10.05	0.00164**
	T	3	298.1	99.38	32.896	<2.00E-16***
	Var:T	3	49.9	16.64	5.508	0.00103**
RL1	Var	1	0.5	0.53	0.328	0.567
	T	3	252.2	84.07	52.525	<2.00E-16***
	Var:T	3	117.3	39.12	24.437	1.67E-14***

Note: significant codes: 0$^{(***)}$: 0.001; $^{(**)}$: 0.01; $^{(*)}$: 0.05; '.': 0.1; ' ': 1. Var: variety; T: harvesting stages at physiological maturity of 60, 70, 80, and 90%; No.SL1: number of seed-shattering loss before harvest; No.SL2: number of seed-shattering loss at harvest; WSL1: weight of seed-shattering loss before harvest; WSL2: weight of seed-shattering loss at harvest; SD1: percentage of seed damage; P100: weight of 100 seeds; PG1: percentage of germination; HL1: hypocotyl length; RL1: root length.

overall (21.83 g/m^2). No seed losses at early harvest of 60-70% maturity (T1 and T2) resulted in higher seed yield. However, there were no significant differences in the weight of 100 seeds (P100) between the two soybean varieties and among harvesting stages (Table 1).

Both variety and harvesting stages had significant effects on seed damage (SD1) (Table 2). SD1 varied from 5.27-10.73% for DT12 and 3.92-8.88% for DT26. DT26 also had lower seed damage than DT12 (6.63 compared to 8.43% respectively). Harvesting at earlier stages resulted in a higher percentage of seed damage with the mean ranging from 6.98 (80% maturity) to 9.81% (60% maturity). Thus, harvest at a physiological maturity of 90% caused the least percentage of seed damage with an average of 4.59%.

Seed quality is indicated through seed germination and development of seedlings after 7 days of germination. The analysis showed that there were significant differences in the percentage of germination (PG1), hypocotyl length (HL1), and root length (RL1) between DT12 and DT26 and among the four harvesting stages (Table 2). Seed germination varied from 87.33 at 60% maturity to 95.60 at 90% maturity for DT12. DT26 had higher seed germination than DT12 with a range of 90.67-96.53%. In general, seed germination at the harvesting stage of 90% maturity was the highest but not significantly different from that of 80% maturity. Similarly, harvesting time closer to physiological maturity resulted in higher vigour of seedlings, which was indicated by the longer hypocotyl and root lengths. There seemed to be no significant differences between 80 and 90% maturity for germination, hypocotyl, and root length.

Table 2. Effects of harvesting stages on soybean seed quality after mechanical seed threshing.

Variety	Harvesting stages	SD1 (%)	PG1 (%)	HL1 (cm)	RL1 (cm)
DT12	T1	10.73^a	87.33^c	10.34^d	6.54^d
	T2	9.76^b	90.53^b	11.55^{bc}	6.53^d
	T3	7.99^d	95.20^a	12.30^{ab}	8.45^{ab}
	T4	5.27^e	95.60^a	12.54^{ab}	8.91^a
DT26	T1	8.88^c	90.67^b	9.97^d	6.29^d
	T2	7.73^d	94.27^a	10.82^{cd}	8.04^{bc}
	T3	5.97^e	96.40^a	12.73^a	8.46^{ab}
	T4	3.92^f	96.53^a	11.01^{cd}	7.37^c
	SE	0.22	0.60	0.25	0.19
Mean for variety	DT12	8.43^g	92.17^e	11.68^e	7.61^e
	DT26	6.63^h	94.47^d	11.13^f	7.54^e
	SE	0.11	0.30	0.14	0.11
Mean for harvest	T1	9.801^i	89.0^h	10.15^i	6.42^h
	T2	8.74^j	92.4^g	11.19^h	7.29^g
	T3	6.98^k	95.8^f	12.51^g	8.46^f
	T4	4.59^l	96.07^f	11.78^h	8.14^f
	SE	0.15	0.42	0.18	0.14

Note: T1, T2, T3, T4: harvesting stages at physiological maturity of 60, 70, 80, and 90% respectively; SD1: percentage of seed damage; P100: weight of 100 seeds; PG1: percentage of germination; HL1: hypocotyl length; RL1: root length. Mean within a column followed by the same superscript letter is not significantly different at p=0.05 according to Tukey test.

3.2. Seed loss and quality, and thresh efficiency by mechanisation at early harvesting stages and postharvest ripening

Generally, variety, early harvesting stages, and number of days of postharvest ripening had significant effects on seed losses depending on cases. There were significant differences between DT12 and DT26 for seed loss at threshing (SL2), but no differences for seed shattering loss (SL1) and total seed loss (SL3). Harvesting stages significantly affected all seed losses (SL1-SL3). The number of days of postharvest ripening also caused significant differences in all seed losses except for seed loss at threshing (Supplemental Table 2).

Seed losses occurred with higher percentages at postharvest ripening (around 2-5%) than at threshing (around 1-2%) (Table 3). The total seed losses across varieties, early harvesting stages, and number of days of postharvest ripening varied from 2.45 to 7.87%. Early harvest resulted in fewer total seed losses, such as 4.06% at 60% maturity (T1), 6.21% at 70% maturity (T2), and 7.16% at 80% maturity (T3). Similarly, fewer days of postharvest ripening provided significantly fewer total seed losses at 1-day than those at 2- and 3-days.

There were significant differences in seed damage (SD2) among the three early harvesting stages and number of days of postharvest ripening (Supplemental Table 2). Obviously, later harvest at physiological maturity of 80% and 3 d of postharvest ripening resulted in the least seed damage with 5.36 and 6.19%, respectively. Seed damage was not different between DT12 and DT26. Similar to Experiment 1, the weight of 100 seeds was not affected by variety, harvesting stages, or number of days of postharvest ripening.

Supplement Table 2. ANOVA for effects of early harvesting stages and postharvest ripening on seed losses and quality when applying mechanical harvesting and threshing.

Traits	Source of variation	df	SS	MS	F-value	P
SL1	Var	1	0.06	0.056	0.128	0.72288
	T	2	41.82	20.91	47.68	1.36E-10***
	D	2	8.35	4.176	9.522	0.00052***
	Var:T	2	1.84	0.92	2.098	0.13828
	Var:D	2	0.97	0.487	1.11	0.34127
	T:D	4	3.52	0.88	2.006	0.11578
	Var:T:D	4	4.04	1.01	2.304	0.07842
SL2	Var	1	1.4114	1.4114	15.3362	0.000412***
	T	2	9.1983	4.5992	49.9762	7.53E-11***
	D	2	0.4227	0.2114	2.2967	0.115992
	Var:T	2	0.0602	0.0301	0.3273	0.723105
	Var:D	2	1.0633	0.5317	5.7772	0.006921***
	T:D	4	2.2107	0.5527	6.0055	0.00091
	Var:T:D	4	2.454	0.6135	6.6666	0.00045***
SL3	Var	1	2.132	2.132	2.9257	0.096293
	T	2	90.898	45.449	62.3657	4.21E-12***
	D	2	12.635	6.318	8.6692	0.000907***
	Var:T	2	1.828	0.914	1.2542	0.29816
	Var:D	2	4.019	2.009	2.7574	0.077666
	T:D	4	8.436	2.109	2.8941	0.036501*
	Var:T:D	4	12.073	3.018	4.1417	0.007708**
SD2	Var	1	0.0541	0.0541	0.3621	0.55136
	T	2	18.5777	9.2889	62.1064	4.45E-12***
	D	2	5.2804	2.6402	17.6526	5.52E-06***
	Var:T	2	0.1874	0.0937	0.6267	0.540436
	Var:D	2	0.4724	0.2362	1.5791	0.220904
	T:D	4	3.1664	0.7916	5.2928	0.002007**
	Var:T:D	4	1.3995	0.3499	2.3393	0.074868

Traits	Source of variation	df	SS	MS	F-value	P
P100	Var	1	3.276	3.2757	2.0934	0.15709
	T	2	1.388	0.6941	0.4436	0.64541
	D	2	1.263	0.6313	0.4034	0.67117
	Var:T	2	0.209	0.1047	0.0669	0.93538
	Var:D	2	2.975	1.4877	0.9508	0.39648
	T:D	4	16.046	4.0116	2.5637	0.05591
	Var:T:D	4	19.963	4.9908	3.1894	0.02505*
PG2	Var	1	4.3	4.3	0.359	0.549364
	T	2	1496.6	748.28	62.4449	<2.20E-16***
	D	2	124	62.01	5.1748	0.006017**
	Var:T	2	116.3	58.14	4.8521	0.008247**
	Var:D	2	81.6	40.78	3.4033	0.034164*
	T:D	4	130.8	32.7	2.7291	0.028852*
	Var:T:D	4	48.2	12.06	1.0066	0.403713
HL2	Var	1	1465.6	1465.61	311.5935	<2.20E-16***
	T	2	144.9	72.43	15.3997	2.67E-07***
	D	2	11.3	5.65	1.2011	0.301354
	Var:T	2	319.8	159.89	33.993	6.04E-15***
	Var:D	2	67.7	33.85	7.1973	0.000794***
	T:D	4	83.7	20.93	4.4501	0.001449**
	Var:T:D	4	34.2	8.56	1.82	0.122849
RL1	Var	1	93.3	93.251	20.5953	6.46E-06***
	T	2	69.8	34.895	7.7068	0.000481***
	D	2	47.4	23.698	5.2338	0.005501**
	Var:T	2	7.1	3.543	0.7826	0.457556
	Var:D	2	10.3	5.171	1.1421	0.319609
	T:D	4	91.9	22.976	5.0744	0.00048***
	Var:T:D	4	59.8	14.943	3.3002	0.010716*

Note: significant codes: 0(***): 0.001; (**): 0.01; (*): 0.05; '.': 0.1.; ' ': 1. Var: variety; T: harvesting stages at physiological maturity of 60, 70, and 80% respectively; D: days of postharvest ripening of 1, 2, and 3 days; SL1: percentage of seed-shattering loss when applying postharvest ripening; SL2: percentage of seed loss by threshing; SL3: percentage of total seed loss; SD2: percentage of seed damage after threshing; PG2: percentage of seed germination; HL2: hypocotyl length; RL2: root length; P100: weight of 100 seeds.

Table 3. Effects of early harvesting stages and days of postharvest ripening on seed losses of soybean when applying mechanical harvesting and threshing.

Variety	Harvesting stages	Days of postharvest ripening	SL1 (%)	SL2 (%)	SL3 (%)	SD2 (%)	P100 (g)
DT12	T1	D1	1.89^{d}	0.90^{de}	2.45^{f}	10.30^{a}	14.1
		D2	3.08^{abcd}	1.30^{cde}	4.44^{def}	7.97^{bcde}	13.2
		D3	3.82^{abcd}	1.46^{bcde}	5.33^{abcdef}	7.33^{bcdef}	13.1
	T2	D1	3.19^{abcd}	1.51^{bcde}	4.75^{cdef}	7.10^{cdefg}	14.5
		D2	4.23^{abc}	1.77^{abcd}	6.00^{abcd}	8.47^{abcd}	13.2
		D3	4.8^{a}	2.1^{abc}	6.89^{abcd}	6.47^{defgh}	12.9
	T3	D1	4.13^{abc}	1.93^{abc}	6.30^{abcd}	6^{efgh}	12.6
		D2	5.25^{a}	2.61^{a}	7.87^{a}	5.53^{fgh}	13.8
		D3	4.26^{abc}	2.20^{abc}	6.46^{abcd}	5.1^{gh}	13.0
DT26	T1	D1	2.4^{bcd}	0.90^{ab}	4.78^{bcdef}	9.10^{abc}	14.8
		D2	2.07^{cd}	0.76^{e}	2.85^{ef}	9.33^{ab}	13.6
		D3	2.96^{abcd}	1.46^{bcde}	4.49^{def}	6.9^{defg}	13.7
	T2	D1	3.81^{abcd}	1.51^{abc}	5.7^{abcde}	8.23^{abcd}	12.2
		D2	5.17^{a}	2.54^{a}	7.66^{abc}	8.23^{abcd}	13.8
		D3	4.13^{abc}	2.09^{abc}	6.28^{abcd}	6.9^{defg}	15.6
	T3	D1	4.48^{ab}	1.93^{abc}	6.78^{abcd}	5.77^{fgh}	13.7
		D2	5.25^{a}	2.57^{a}	7.78^{a}	5.3^{fgh}	15.1
		D3	5.16^{a}	2.20^{a}	7.76^{ab}	4.47^{h}	12.2
	SE		0.44	0.18	0.56	0.41	0.74
Mean for variety	DT12		3.87^{e}	1.75^{g}	5.61^{f}	7.14^{i}	13.4
	DT26		3.93^{e}	2.08^{f}	6.0^{f}	7.14^{i}	13.9
	SE		0.15	0.06	0.19	0.14	0.25
Mean for harvesting stages	T1		2.70^{h}	1.37^{j}	4.06^{i}	8.49^{j}	13.8
	T2		4.22^{g}	2.0^{j}	6.21^{h}	7.57^{j}	13.7
	T3		4.79^{f}	2.37^{h}	7.16^{g}	5.36^{k}	13.4
	SE		0.18	0.08	0.23	0.17	0.30
Mean for postharvest ripening	D1		3.35^{j}	1.80^{k}	5.13^{k}	7.75^{l}	13.6
	D2		4.17^{j}	1.93^{k}	6.10^{j}	7.47^{l}	13.8
	D3		4.19^{i}	2.01^{k}	6.20^{j}	6.19^{m}	13.4
	SE		0.18	0.08	0.23	0.17	0.30

Note: T1, T2, T3: harvesting stages at physiological maturity of 60, 70, and 80% respectively; D1, D2, D3: 1, 2, and 3 days of postharvest ripening respectively; SL1: percentage of seed shattering loss when applying postharvest ripening; SL2: percentage of seed loss by threshing; SL3: percentage of total seed loss; SD2: percentage of seed damage after threshing. Mean within a column followed by the same superscript letter are not significantly different at p=0.05 according to Tukey test.

Table 4. Effects of early harvesting stages and days of postharvest ripening on soybean seed quality.

Variety	Harvesting stages	Days of postharvest ripening	PG2 (%)	HL2 (cm)	RL2 (cm)
DT12	T1	D1	87.5^{fg}	10.7^{de}	6.6^{bcd}
		D2	87.0^{g}	10.8^{cd}	7.0^{abcd}
		D3	90.4^{bcdefg}	10.5^{def}	7.1^{abcd}
	T2	D1	91.3^{abcde}	8.8^{g}	6.9^{bcd}
		D2	90.7^{abcdef}	9.1^{fg}	6.9^{abcd}
		D3	92.0^{abcde}	9.2^{efg}	5.8^{d}
	T3	D1	93.9^{a}	10.8^{d}	6.0^{cd}
		D2	93.2^{abc}	12.6^{ab}	8.0^{ab}
		D3	93.4^{ab}	10.8^{de}	7.9^{ab}
DT26	T1	D1	89.3^{efg}	13.1^{ab}	6.8^{bcd}
		D2	89.8^{defg}	13.2^{ab}	7.8^{ab}
		D3	90.2^{bcdefg}	12.9^{ab}	7.4^{abc}
	T2	D1	91.5^{abcde}	13.1^{ab}	7.5^{ab}
		D2	89.8^{cdefg}	12.3^{bc}	7.3^{abc}
		D3	91.1^{abcde}	13.9^{a}	7.4^{abc}
	T3	D1	93.2^{abc}	12.4^{b}	7.6^{ab}
		D2	92.8^{abcd}	12.4^{b}	7.8^{ab}
		D3	92.7^{abcd}	12.9^{ab}	8.3^{a}
	SE		0.7	0.3	0.3
Mean for variety	DT12		91.1^{h}	10.4^{i}	6.9^{f}
	DT26		91.2^{h}	12.9^{h}	7.5^{e}
	SE		0.2	0.1	0.1
Mean for harvesting stages	T1		89^{k}	11.9^{j}	7.1^{h}
	T2		91.1^{j}	11.1^{k}	6.9^{h}
	T3		93.2^{i}	12^{j}	7.6^{g}
	SE		0.3	0.1	0.1
Mean for postharvest ripening	D1		91.1^{l}	11.5^{l}	6.9^{j}
	D2		90.6^{l}	11.7^{l}	7.4^{i}
	D3		91.6^{l}	11.7^{l}	7.3^{ij}
	SE		0.3	0.1	0.1

Note: T1, T2, T3: harvesting stages at physiological maturity of 60, 70, and 80% respectively; D1, D2, D3: 1, 2, and 3 days of postharvest ripening respectively; PG2: percentage of seed germination after 7 days; HL2: hypocotyl length after 7 days of germination; RL2: root length after 7 days of germination; P100: weight of 100 seeds. Mean within a column followed by the same superscript letter are not significantly different at p=0.05 according to Tukey test.

There were significant differences in seed germination and seedling development after 7 days of germination (Table 4).

DT12 and DT26 had a similar percentage of germination (PG2) (91.1 and 91.2%, respectively) but DT26 had the vigour of seedlings with longer hypocotyl length HL2 (12.9 cm) and root length RL2 (7.5 cm). Seed germination significantly increased from 89.0% at 60% maturity to 93.2% at 80% maturity. Hypocotyl and root lengths were also longest at 80% maturity with 12.0 and 7.6 cm, respectively. Two or three days of postharvest ripening also resulted in better seedling development (Table 4).

4. Discussion

Harvesting time is a critical step in soybean seed production because it affects both yield losses and seed quality. The common practice is to harvest soybeans at a physiological maturity of 90% when 90% of the pods on the plant turn brown. This harvesting time results in the highest yield, germination percentage, vigour, and fat content than a delayed one and two weeks after physiological maturity [1, 6, 13]. Soybeans are also suggested to be harvested as soon as seed moisture is suitable for mechanisation (12-14% moisture content) [1]. Early harvest stage, such as R7 (beginning maturity - one normal pod on the main stem reaching mature colour) also caused low seed germination percentage (76%) and vigour. In addition, the seed quality of various varieties responded differently to harvesting stages. Similar to previous studies, both experiments in this study generally showed a lower seed germination percentage at early harvesting (60-70%) than that at physiological maturities of 80 or 90%. Seedling development was also less vigorous with shorter hypocotyl and root length (Table 2, Table 4). Interestingly, there seemed to be no significant differences between harvesting stages of 80 and 90% for those measured characteristics (Table 2).

Yield losses due to seed-shattering losses in nature can be significant from 49.4 to 63.2%. Seed-shattering losses when delaying harvesting by one and two weeks after physiological maturity could reach 20 and 31.22% of the total seed weight, respectively [6]. These experiments also indicated that seed-shattering losses started occurring at early harvest stages of 80% and occurred not only on the field before harvest but also at harvest, during drying and postharvest ripening, and seed threshing (Table 1, Table 3). As a consequence, seed yield was reduced with later harvest stages of 80 and 90% maturity. A. Toledo, et al. (2008) [26] summarised the causes for losses from the action of mechanical harvesting of soybean such as losses due to deficiency of cutting height (remaining lodged to the stalk), the threshing system for grains maintained inside residuals, and the separation system. With different sizes of sample areas (1, 2, and 3 m^2) for quantifying soybean losses in mechanical harvesting, [27] found total losses of 3.61-3.77 kg/ha^1. This study also showed similar losses at harvest of 1.27-2.38 g/m^2 at harvest stages of 80 and 90% physiological maturity, respectively, for sample areas of 2 m^2 (Table 2).

Early harvest for soybeans is sometimes necessary for soybean production to avoid adverse conditions, especially humid and wet conditions in winter seasons in northern Vietnam. This study showed that early harvest stages required postharvest ripening treatment to minimize adverse effects on seed damage and quality. The number of the postharvest ripening days increased as soybeans were harvested earlier. Soybeans harvested early at 60% maturity required at least 3 days of postharvest ripening so that pods and stems turned brown and became drier with the leaves dried and dropping off the stem. This is preferred for mechanical seed threshing since green leaves and stems cause clogs in the machine. Soybeans harvested at 70% maturity required 1-2 days of postharvest ripening for plants to be sufficiently dried before threshing. Similarly, soybeans harvested at 80% maturity only required 1 day of postharvest ripening to reach the ideal physiological maturity of 90%.

Comparable to Experiment 1, seed losses increased as the soybeans were harvested at stages closer to physiological maturity. However, the total percentage of seed losses was much lower (2.16-3.57%) than in other studies (Table 3) [6]. In contrast, seed damage significantly decreased at harvesting stages of 80 and 90% maturity (Table 2) and with more days of postharvest ripening (Table 4). Thus, postharvest ripening treatment is an effective method to reduce seed damage and ensure seed quality if early harvest stages of soybeans are necessary.

5. Conclusions

In conclusion, harvesting stages affect seed-shattering losses and seed quality. Harvesting stages of 90% maturity provide the best seed quality. However, early harvest at a physiological maturity of 80% can also be practical to avoid adverse weather conditions. In that case, at least one day of postharvest ripening should be applied. Thus, careful monitoring of the harvest stages and ripening of different soybean varieties should help to minimize seed damage and ensure seed quality, especially in a practice where farmers apply mechanical harvesting and threshing.

CRediT author statement

Thi Thuy Hang Vu: Writing and Editing the manuscript, Data analysis; Ngoc Thang Vu: Data collection, Data analysis; Thi Tuyet Cham Le: Experimental design, Writing manuscript; Thi Ngoc Pham: Data collection, Data analysis.

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COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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