



Agronomic Modulation through Sowing Time and Spacing Adjustments for Enhanced Seed Yield and Quality in Pea

Khushboo ^a, Rajender Sharma ^a and Kamrul Nissa ^{a*}

^a Department of Seed Science and Technology, Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh-173230, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Enhancing seed yield and quality in pea (*Pisum sativum*) requires careful optimization of agronomic practices. To investigate this, a study was carried out during 2020-21 at the Department of Seed Science and Technology, Dr YS Parmar University of Horticulture and Forestry, Nauni, Solan (HP), focusing on the effects of various sowing dates and plant spacing on seed production in pea. The experiment involved twelve treatment combinations, including three sowing dates (10th, 20th and 30th November) and four spacing levels (60 × 7.5 cm, 60 × 10 cm, 60 × 12.5 cm and 60 × 15.0 cm), arranged in a factorial Randomized Block Design (RBD) with three replications in the field and a Completely Randomized Design (CRD) with four replications for laboratory analysis. Sowing on 10th November led to earlier emergence and flowering, along with improved plant height, pod characteristics, seed yield (20.33 q ha⁻¹), germination (94.38%), and seed vigour. Among the

*Corresponding author: E-mail: kamrulnissa579@gmail.com;

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spacing treatments, the widest spacing (60 × 15.0 cm) proved most effective in enhancing growth and seed quality traits. The interaction treatment D1S4 (10th November sowing with 60 × 15.0 cm spacing) delivered the best performance, achieving the highest seed yield (24.30 q ha⁻¹), 100 seed weight (19.65 g), seed vigour indices and a benefit-cost ratio of 2.56.

Keywords: *Planting density; production; spacing; seed quality.*

1. INTRODUCTION

A diploid (2n=14) herbaceous annual plant in the Fabaceae family, the pea (*Pisum sativum* L.) is commonly referred to be a poor man's vegetable (Zaki et al. 2017; Kharibam et al. 2025). Peas are self-pollinating, high-protein leguminous crops with climbing vines and nitrogen-fixing root nodules. They germinate hypogeally and produce ex-albuminous seeds. Green pods are consumed fresh or processed, while dried peas are used whole, split or as flour (Dahl et al. 2012). In terms of micronutrients, peas supply essential vitamins such as thiamine (B1) and riboflavin (B2), along with minerals like calcium and iron. The fat content in field peas is minimal, typically ranging from 1.2 - 1.8%, making them a low-fat food option (Sachan et al. 2023).

The garden pea (*Pisum sativum*) ranks second in India in terms of production and cultivation (Zaki et al. 2017). In Himachal Pradesh, garden peas make up about 25% of the total area planted to vegetable crops. The states of Himachal Pradesh, Jammu & Kashmir, and Uttarakhand, which have diverse agroclimatic conditions (500 m to 2200 m asl), are among the North-Western Himalayan regions of India where peas are grown. It can also be cultivated in tropical climates that are mild. During the rabi season, it is grown in the low to high hill regions, and in the summer, it is grown in the dry-temperate regions (Thakur et al. 2025).

In addition to a chilly growing season, peas need a steady temperature during that time. Because of its capacity to fix atmospheric nitrogen, it contributes significantly to the enhancement of soil fertility by supplying nitrogen to the next crop (nitrogen fixation by *Rhizobium leguminosarum*) for a minimal cost of additional fertilizers. The ideal temperature range for germination is 18–22°C. and soil composition for growing crops (Dhall 2017).

Numerous factors affect crop yield potential, but one essential component for raising productivity is seed quality (Agrawal 2019). Ensuring the

availability of good quality seed in sufficient quantities is essential for establishing an optimal crop stand. The demand for premium pea seed is growing both locally and in adjacent countries as the amount of land planted to leguminous crops increases. Efficient marketing and timely multiplication are critical to the success of seed production. Crop growth and seed yield are greatly impacted by agronomic methods such as plant spacing and sowing date (Thakur et al. 2025; Rahman et al. 2020; Haque et al. 2020). Plant density is maximized by appropriate timing and spacing, which guarantees sufficient access to nutrients and improves seed output and quality (Batra 1986; Hooda 1991). So present study was conducted to standardized the optimum sowing time and spacing for quality seed production pea.

2. MATERIALS AND METHODS

The current field study was carried out at the Dr. YS Parmar University of Horticulture and Forestry's Pandah Experimental Farm in Nauni, Solan, Himachal Pradesh, India. The experimental farm is situated in the Shivalik range of the northwest Himalayas, 1210 meters above mean sea level. The area's soil was clay loam, with a pH between 6.85 and 7.05. The region has three distinct seasons and is classified as sub-temperate to semi-humid. The current study was conducted during the *Rabi* season, which ran from November 2020 to April 2021. Fig. 1 shows the cropping season's mean monthly temperature and relative humidity.

The Pb-89 cultivar of garden pea was utilized for the research, with seeds sourced from the Department of Seed Science and Technology. A Randomized Complete Block Design (RCBD) comprising 12 treatments with three replications was implemented for the field experiment, while a Completely Randomized Design (CRD) with four replications was employed for the laboratory experiments. There was 36 total plots with each having plot size 3.0×1.8 meter. Treatment details are given in Table 1.

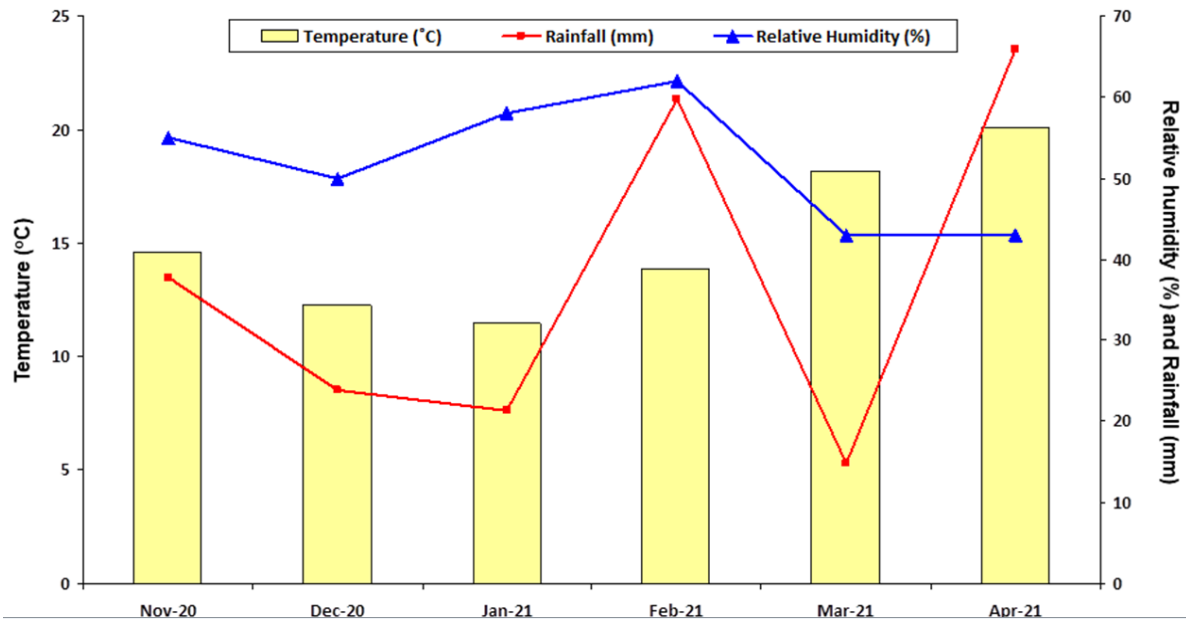


Fig. 1. Agrometeorological Trends Observed at the Experimental Site in 2020-2021

2.1 Agronomic Practices

The cultural practices were carried out as per the standardized guidelines provided in the Package of Practices for Vegetable Crops, issued by the Directorate of Extension Education, Dr. YS Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh, India (Anonymous, 2018).

2.2 Observation Recorded

Various parameters were recorded during the experiment (Table 2). Field parameters include days taken to field emergence & flower initiation, number of flowers & pods/plant, plant height (cm), pod length (cm), days taken to harvesting and seed yield per plant (g), seed yield per plot (g), seed yield (kg/ha), shelling percentage (%) and laboratory parameters include germination (%), seed vigour index-I & II, 100 seed weight (g), electrical conductivity (μSm^{-1}) and accelerated ageing test (%).

Seedling emergence was monitored every other day in each plot until completion, and the average number of days to emergence was recorded. Days to flower initiation were calculated from sowing to the appearance of the first flower in each plot. Flowers and pods were counted from ten randomly selected plants and

the averages were calculated to determine the mean number of flowers and pods per plant. At the end of the season, plant height was measured from the soil surface to the tip using a measuring tape, and the average height was expressed in centimeters. Similarly, the length of ten randomly selected healthy pods was measured from base to tip and averaged to determine mean pod length in centimeters. The number of days to harvest or maturity was calculated from the sowing date to the stage when fully developed mature pods suitable for seed collection were observed in each treatment replication.

Plants from each replication were harvested at full physiological maturity, and the collected seeds were shade-dried, cleaned, and weighed using an electronic balance to obtain the average. Seed yield per plot was calculated based on the total seed harvested from all plants in that plot. Seed yield per hectare was calculated using formula:

$$\text{Seed yield (kg/ha)} = \frac{\text{Seed yield (kg)} \times 8000}{100}$$

where as, Shelling percentage was calculated using formula:

$$\text{Shelling percentage (\%)} = \frac{\text{Weight from 25 pods} \times 100}{\text{Total weight of 25 pods}}$$

Table 1. The table shows the treatments and combination details

Treatments	Combination	Details
Trt-1	D1S1	Sowing time 10th November & Spacing 60 × 7.5 cm
Trt-2	D1S2	Sowing time 10th November & Spacing 60 × 10.0 cm
Trt-3	D1S3	Sowing time 10th November & Spacing 60 × 12.5 cm
Trt-4	D1S4	Sowing time 10th November & Spacing 60 × 15.0 cm
Trt-5	D2S1	Sowing time 20th November & Spacing 60 × 7.5 cm
Trt-6	D2S2	Sowing time 20th November & Spacing 60 × 10.0 cm
Trt-7	D2S3	Sowing time 20th November & Spacing 60 × 12.5 cm
Trt-8	D2S4	Sowing time 20th November & Spacing 60 × 15.0 cm
Trt-9	D3S1	Sowing time 30th November & Spacing 60 × 7.5 cm
Trt-10	D3S2	Sowing time 30th November & Spacing 60 × 10.0 cm
Trt-11	D3S3	Sowing time 30th November & Spacing 60 × 12.5 cm
Trt-12	D3S4	Sowing time 30th November & Spacing 60 × 15.0 cm

Table 2. List of field and laboratory parameters recorded along with methodology and instruments used

S. No.	Parameter	Methodology	Instruments
Field Parameters			
1.	Days to field emergence	Number of days from sowing to 75% emergence of seedlings.	visual observation & calendar
2.	Days to flower initiation	Number of days from sowing to appearance of first flower.	visual observation & calendar
3.	Number of flowers per plant	Average number of flowers counted on five randomly selected plants.	manual counting
4.	Number of pods per plant	Average number of pods counted on five randomly selected plants.	manual counting
5.	Plant height (cm)	Measured from soil surface to tip of main stem at maturity.	measuring scale / meter rod
6.	Pod length (cm)	Average pod length of ten randomly selected pods.	measuring scale / meter rod
7.	Days to harvesting	Days from sowing to physiological maturity (80-85% pod color change).	visual observation & calendar
8.	Seed yield per plant (g)	Weight of seeds obtained from individual plants (average of 5 plants).	electronic weighing balance
9.	Seed yield per plot (g)	Weight of seeds harvested from net plot area.	electronic weighing balance
10.	Seed yield (kg/ha)	Extrapolated from plot yield to per hectare basis.	calculation (plot to hectare conversion)
11.	Shelling percentage (%)	(Weight of shelled seeds / weight of fresh pods) × 100.	electronic weighing balance
Laboratory Parameters			
1.	Germination (%)	100 seeds in 4 replications under controlled lab conditions as per ISTA guidelines.	germination paper, germination chamber
2.	Seed vigour index I	Germination (%) × seedling length (cm).	measuring scale
3.	Seed vigour index II	Germination (%) × seedling dry weight (mg).	hot air oven & electronic weighing balance
4.	100-seed weight (g)	Average weight of 100 randomly selected seeds per replication.	electronic weighing balance
5.	Electrical conductivity ($\mu\text{S m}^{-1}$)	50 seeds soaked in 25 ml distilled water for 24 hours at 25°C, EC measured after soaking.	electrical conductivity meter (ec meter)
6.	Accelerated ageing test (%)	Seeds kept at 40°C and 100% RH for 72 hours; followed by germination test.	accelerated ageing chamber & germination chamber

Seed germination was recorded and calculated as formula given by ISTA 1985:

$$\text{Germination} = \frac{\text{Total number of normal seedling} \times 100}{\text{Total number of seeds used}}$$

Seed vigour index-I & II was calculated as per formula given by Abdul-Baki and Andreson (1973):

$$\text{Seed vigour index- I} = \text{Germination (\%)} \times \text{Seedling length (cm)}$$

$$\text{Seed vigour index- II} = \text{Germination (\%)} \times \text{Seedling dry weight (g)}$$

Fifty clean seeds from each treatment replication were soaked in 250 ml of distilled water at room temperature for 24 hours. After soaking, the seeds were removed, and the remaining water, referred to as leachate, was collected. The electrical conductivity (EC) of both the distilled water and the leachate was then measured using a conductivity meter ($\mu\text{S cm}^{-1}$), and the sample's conductivity was recorded and calculated using formula:

$$\text{Actual EC of seed sample } (\mu\text{S cm}^{-1}) = \text{EC of leachate} - \text{EC of distilled water}$$

The accelerated aging test was carried out in accordance with the protocol described by Islam et al. (1973). 400 seeds from each treatment were knotted in muslin fabric and put in a sealed desiccator with a KOH (22.25%) solution at the bottom for this purpose. For 72 hours, the desiccator was maintained within the incubator at 40 to 45 degrees Celsius and 75% relative humidity. To determine the germination percentage, the aged seeds were removed and a germination test was conducted.

2.3 Statistical Analysis

The data were analyzed using two-factor ANOVA in a Completely Randomized Design (CRD) for laboratory trials and a Randomized Complete Block Design (RCBD) for field experiments, following Panse and Sukhatme (2000). A significance level set at 0.05, was used to determine the statistical significance of the main effects and their interaction. The error mean square from the ANOVA output was used to compute the standard error (SE) of treatment means. Additionally, analyses can be efficiently performed using the OPSTAT web-based agricultural statistics software from CCS Haryana Agricultural University, which supports two-factor

CRD and RBD factorial designs, provides ANOVA results and computes critical differences along with interaction effects.

3. RESULTS AND DISCUSSION

3.1 Days taken to Field Emergence and Flower Initiation

Table 3 data showed that the dates of sowing had a significant impact on the number of days needed for full emergence. Regarding the impact of varying sowing dates, D1 (10 November) had the shortest time (18.33 days) to field emergence, which was significantly less than all other treatments. On the other hand, D3 recorded the longest time to field emergence (22.50 days) on November 30. Days to field emergence showed statistically non-significant results for spacing. On the other hand, S2 (60 x 10 cm) had the fewest days to field emergence (19.78), while S1 (60 x 7.5 cm) had the most days (20.78).

For days to field emergence, the interaction between plant spacing and sowing dates was determined to be statistically non-significant. However, D1S2 (10th November sowing with 60 x 10 cm spacing) had the shortest time to field emergence (17.33 days), while D3S1 (30th November sowing with 60 x 7.5 cm spacing) had the longest time (23.33).

Late-sown crops experienced slower emergence than earlier sowings, likely due to cooler soil and air temperatures in mid to late November and December conditions that delay germination and extend emergence time (Sharma 2014). Sen et al. (2016) reported similar results in pea.

Flower initiation occurred fastest when sowing early (D1: 10 November), taking 84.75 days, and slowest with the late sowing (D3: 30 November) at 97 days. Wider spacing (60 x 15 cm) also advanced flowering significantly, with the earliest response seen in the combined D1S4 treatment (79.33 days), and the latest in the D3S1 combination (99 days). The earlier sowing date (10 November) had the shortest time to flower initiation, while the last sowing date (30 November) had the longest. This could be because low temperatures delayed the emergence and growth of late-planted crops, which in turn caused them to take longer to enter the vegetative growth phase before flowering. As a result, late-planted crop plants took longer to flower.

The widest spacing (60 × 10.0 cm) showed the earliest flowering, while the closest spacing (60 × 7.5 cm) generally had delayed flowering. Because there is more competition among the plants for sunlight, moisture, nutrients, space, and other metabolites, a high plant density may be the reason why flower formation is decreased. Rehman et al. (2020) reported similar results in pea.

Early-planted, widely spaced plants (10 Nov, 60 × 15 cm) flowered earlier, probably because they could spread out richly and use nutrients effectively in the right conditions. Conversely, plants that were sown later grew more slowly because of the cooler weather and delayed emergence, which resulted in a longer time before flowering.

3.2 Number of Flowers and Pods per Plant

The number of flowers per plant was significantly influenced by both sowing date and spacing. Maximum flowers were observed with early sowing (D1: 10 Nov) and widest spacing (S4: 60 × 15 cm), with the highest recorded in combination D1S4 (32.40). Delayed sowing reduced flower count, likely due to shorter growing periods and less favorable conditions. Wider spacing enhanced flowering by improving access to light, moisture, and nutrients. Plants sown early and spaced widely produced the most flowers per plant, likely because they faced less competition for light, moisture, and nutrients, which promoted robust vegetative growth under optimal early-season conditions.

Sowing date and spacing significantly affected the number of pods per plant, with the highest count (24.52) recorded in early sowing (D1: 10 Nov) and the lowest (20.57) in late sowing (D3: 30 Nov). Among spacings, the widest (S4: 60 × 15 cm) produced the most pods (25.29), while the narrowest (S1: 60 × 7.5 cm) had the fewest (20.82). The D1S4 combination resulted in the maximum pods per plant (29.87), whereas D3S1 recorded the minimum (19.07). Early sowing gives plants an extended vegetative phase and stronger source capacity, allowing them to build more reserves and thereby set more pods per plant. This outcome aligns with previous reports by Singh & Singh (2011) and Sirwaiya et al. (2018), who similarly observed higher pod counts in peas sown earlier than usual.

Closely spaced plants (60 × 7.5 cm) had the fewest pods, while wider spacing (60 × 15 cm) greatly increased pod production, probably as a result of improved access to light, nutrients, and less competition. Early sowing (10 November) with wide spacing (60 × 15 cm) produced the highest pod counts, while late sowing with narrow spacing produced the lowest. These results are consistent with those of Hooda (1991) in pea and Bhatt (2020) in black gram, who noted comparable advantages of greater spacing.

3.3 Pod Length and Plant Height (cm)

Pod length was significantly influenced by sowing date and spacing (Table 3). The longest pods (10.08 cm) were observed in early sowing (D1: 10 Nov) with wide spacing (S4: 60 × 15 cm), while the shortest (7.77 cm) occurred with late sowing (D3: 30 Nov) and narrow spacing (S1: 60 × 7.5 cm). Early sowing allowed more time for vegetative and reproductive growth, enhancing pod development. In contrast, late sowing reduced the growth period and pod formation time, resulting in smaller pods. These findings align with Sharma et al. (2014) and Sirwaiya (2015) in pea.

Pod length significantly increased at wider spacing (60 × 15 cm) compared to closer spacing (60 × 7.5 cm), likely due to reduced competition for light, space, and nutrients allowing for more robust growth. The longest pods occurred with early sowing (10 Nov) combined with wide spacing, as plants benefited from enhanced vegetative and reproductive development under favorable conditions. Conversely, late sowing with narrow spacing resulted in smaller pods due to limited growth time and increased interplant competition.

Table 4 represents the data on plant height at maturity and significant influence of both sowing date and spacing was observed. The tallest plants (55.87 cm) were recorded under early sowing (D1: 10 Nov), while the shortest (50.50 cm) occurred with late sowing (D3: 30 Nov). Among spacings, the widest (S4: 60 × 15 cm) produced the tallest plants (56.62 cm), and the narrowest (S1: 60 × 7.5 cm) the shortest (50.62 cm). The tallest plants overall (63.60 cm) were seen in the D1S4 combination. Early sowing likely promoted better growth due to favorable temperatures and longer development time. Wider spacing allowed improved access to resources like light, moisture, and nutrients, resulting in greater plant height. These findings

are consistent with earlier studies by Mandal (1998), Sirwaiya (2015), and Sibhatu et al. (2016). Early-sown plants (10 November) with wide spacing (60 × 15 cm) achieved the greatest height, likely due to reduced competition for soil moisture, nutrients, and light. This combination provided more time and optimal temperatures for growth, enabling taller, healthier plants under favorable early-season conditions.

3.4 Days taken to Harvesting

The date and spacing of sowing had a significant impact on the number of days until harvest (Table 4). Due to the longer cool-season development of early-planted crops, the time to harvest was shortened to approximately 130.4 days by late sowing (30 Nov, D3), whereas it was extended to approximately 143.9 days by early sowing (10 Nov, D1). Plants with a wider spacing (60 × 15 cm, S4) reached maturity more quickly (~134.9 days), probably as a result of improved light and nutrient availability and less mutual shading. The longest maturity was under D1S1 (143.92 and closest spacing), and the shortest was under D3S4 (130.42 and widest spacing), despite the fact that the interaction was not statistically significant. These results demonstrate that early sowing increases crop duration while late sowing decreases it, which is consistent with Joshi & Rahevar (2015).

3.5 Seed Yield (g plant⁻¹, kg plot⁻¹ and q ha⁻¹)

Seed yield was significantly affected by sowing date, spacing and their interaction (Table 4). Early sowing (10 Nov, D1) produced the highest yields - 20.57 g/plant, 1.372 kg/plot, and 20.33 q/ha - while late sowing (30 Nov, D3) yielded the least. Among spacings, wide spacing (60×15 cm, S4) maximized yields: 24.93 g/plant, 1.239 kg/plot, and 18.36 q/ha, compared to narrow spacing (S1), which gave the lowest. The combination D1S4 achieved the highest yields overall (31.18 g/plant, 1.640 kg/plot, 24.30 q/ha), whereas D3S1 resulted in the lowest (8.29 g/plant, 0.757 kg/plot, 11.22 q/ha). Early sowing with optimal spacing extends the growing period under favorable conditions, enhancing plant growth and resource accumulation, and has been consistently shown to improve yield in pea crops. Similar results were reported by Sharma et al. 2014 and Sirwaiya et al. 2015 in pea.

The highest seed yields per plant, per plot, and per plot hectare were shown by plants spaced at

a wider spacing of 60 × 15.0 cm, and these yields decreased as plant spacing decreased. Because there is less competition for sunlight, moisture, aeration, and plant nutrients when plants are spaced farther apart than when they are spaced closer together, this may be the reason why wider spacing offers the necessary conditions for vigorous growth and yield. Plants sown on November 10th at 60 × 15.0 cm spacing recorded the highest seed yields, likely due to favorable conditions and reduced competition, which promoted better growth, flowering, and pod formation.

3.6 Shelling Percentage

Shelling percentage was not significantly affected by sowing dates or their interaction with spacing. However, the highest shelling percentage (61.03%) was observed with the November 20th sowing (D2), and the lowest (59.80%) with November 30th (D3). Plant spacing had a significant effect, with the highest shelling percentage (64.08%) recorded at 60 × 15.0 cm (S4), and the lowest (57.59%) at 60 × 7.5 cm (S1). Among combinations, D2S4 showed the highest (64.58%) and D3S1 the lowest (56.28%) shelling percentage. The highest shelling percentage was recorded with 60 × 15.0 cm spacing and lowest in 60 × 7.5 cm spacing. This could be due to the fact that wider spacing provided better opportunities for growth and development of individual plants by ensuring sufficient availability of sunlight, soil moisture and nutrients. Higher value of shelling percentage may also be because of more seed weight due more number of leaves, branches and plant height of wider spaced crop plants as a consequence of efficient translocation of photosynthates into economical organ. Vankeswaran and Vijaykumar (2005) reported similar results in pea.

3.7 Seed Quality Parameters

Sowing dates, spacings and their interaction significantly affected seed quality traits (Table 5). The highest germination (94.38%) was recorded from seeds of the 10th November sowing (D1), while the lowest (88.44%) was from the 30th November sowing (D3). Among spacings, 60 × 15.0 cm (S4) resulted in the highest germination (92.58%), and 60 × 7.5 cm (S1) the lowest (89.25%). The best interaction was D1S4 with 96.25% germination, whereas D3S1 showed the minimum (86.50%). Sowing dates, spacings, and their interaction significantly affected seed

germination. The highest germination (94.38%) was recorded from seeds of the 10th November sowing (D1), while the lowest (88.44%) was from the 30th November sowing (D3). Among spacings, 60 × 15.0 cm (S4) resulted in the highest germination (92.58%), and 60 × 7.5 cm (S1) the lowest (89.25%). The best interaction was D1S4 with 96.25% germination, whereas D3S1 showed the minimum (86.50%). Better seed quality from early sowing was likely due to improved vegetative and reproductive growth. Sirwaiya (2015) in garden pea reported similar results. The percentage of seeds that germinated was found to be highest when the spacing was wider and to decrease as the spacing decreased. Because there was less competition for nutrients, more reserves were deposited in widely spaced crop plants, which eventually produced higher-quality seeds. Vankeswarm and Vijakumar in pea reported similar results.

Dates of sowing, spacing, and their combination had a significant impact on the seed vigor index-I. The 10th November sowing (D1) and 60 × 15.0 cm spacing (S4) produced the highest value (2483.04), while the D1S4 combination produced the highest value (3102.20). The 30th November sowing and 60 × 7.5 cm spacing produced the lowest index (1773.38) (D3S1). The seed vigor index-I was greatly increased by early sowing on November 10th, most likely as a result of favorable conditions that improved plant growth and dry matter accumulation, which resulted in longer seedlings and higher germination. The production of bolder, higher-quality seeds with improved access to sunlight, moisture, and nutrients was made possible by wider spacing (60 × 15.0 cm), which also increased the seed vigor index-I. The most robust seedlings, a sign of superior seed quality, were produced by combining early sowing with wider spacing.

The interaction between sowing dates and spacings significantly influenced seed vigor index-II. Seeds from the November 10th sowing (D1) recorded the highest index (3391.46), whereas those from the November 30th sowing (D3) showed the lowest (2835.77). Among the spacings, the highest value (3418.38) was noted at 60 × 15.0 cm (S4), and the lowest (2826.66) at 60 × 7.5 cm (S1). The D1S4 combination produced the maximum seed vigor index-II (4092.12), while D3S1 recorded the minimum (2660.29).

The highest seed vigor index-II from the 10th November sowing was likely due to better plant

growth, resulting in bolder, higher-quality seeds with increased 100-seed weight and seedling dry weight. Wider spacing significantly increased seed vigor index-II, likely due to reduced competition allowing better access to water, sunlight, and nutrients, leading to healthier plant growth and improved seed quality. Similar findings were reported by Batra (1986) and Vankeswaran & Vijyakumar (2005) in pea. The highest seed vigor index-II was displayed by seeds sown on November 10th with the widest spacing. This was probably because bolder seeds with more dry matter produced healthier seedlings with higher dry weight.

Seed electrical conductivity was significantly influenced by sowing dates, spacings, and their interaction. The lowest conductivity ($14.301 \mu\text{S cm}^{-1}$) was recorded for seeds from the 10th November sowing (D1), and the highest ($18.894 \mu\text{S cm}^{-1}$) from the 30th November sowing (D3). Among spacings, 60 × 15.0 cm (S4) showed the lowest ($14.680 \mu\text{S cm}^{-1}$), while 60 × 7.5 cm (S1) showed the highest ($18.021 \mu\text{S cm}^{-1}$). The D1S4 combination recorded the minimum conductivity ($11.672 \mu\text{S cm}^{-1}$), and D3S1 the maximum ($19.957 \mu\text{S cm}^{-1}$). The lowest electrical conductivity was found in seeds sown on November 10th, most likely as a result of robust plant growth and superior seed quality, which preserved cell membrane integrity and decreased electrolyte leakage. In a similar vein, seeds from plants that were farther apart exhibited lower conductivity, presumably as a result of less competition resulting in less environmental stress and better seed development.

Seed germination after ageing was notably affected by sowing dates, spacing, and their interaction. Seeds from the 10th November sowing (D1) showed the highest germination rate (77.50%), while those from the 30th November sowing (D3) had the lowest (71.94%). Among the different spacings, the widest spacing of 60 × 15.0 cm (S4) resulted in the highest germination (77.75%), whereas the closest spacing of 60 × 7.5 cm (S1) had the lowest (72.33%). The best performance was observed in the D1S4 combination with 84.25% germination, while D3S1 recorded the lowest (71.00%). The superior germination in early sown crops was likely due to greater seed vigor, higher dry matter, and lower electrolyte leakage. Murthy et al. (2003), artificial aging causes the biochemical deterioration of seed reserves, which lowers seed vigor. Wider spacing, however, may allow

Table 3. Effect of sowing time and spacing on vegetative parameters of pea

Parameters	Spacings Sowing dates	S ₁ (60 × 7.5 cm)	S ₂ (60 × 10.0 cm)	S ₃ (60 × 12.5 cm)	S ₄ (60 × 15.0 cm)	Mean	CD _{0.05}
Days taken to field emergence	D ₁ (10 th November)	18.67	17.33	18.67	18.67	18.34 ± 0.34	D : 1.28
	D ₂ (20 th November)	20.33	20.00	20.67	20.33	20.33 ± 0.14	S : NS
	D ₃ (30 th November)	23.33	22.00	22.33	22.33	22.50 ± 0.29	D × S : NS
	Mean ± SE	20.78 ± 1.36	19.78 ± 1.35	20.56 ± 1.06	20.44 ± 1.06		
Days taken to flower initiation	D ₁ (10 th November)	89.67	87.00	83.00	79.33	84.75 ± 2.03	D : 1.40
	D ₂ (20 th November)	91.33	89.00	88.67	87.00	89.00 ± 0.97	S : 1.62
	D ₃ (30 th November)	99.00	97.67	96.33	95.00	97.00 ± 0.82	D × S : 2.80
	Mean ± SE	93.33 ± 2.87	91.22 ± 3.27	89.33 ± 3.86	87.11 ± 4.52		
Number of flowers per plant	D ₁ (10 th November)	24.00	25.33	26.13	32.40	26.97 ± 1.95	D : 1.25
	D ₂ (20 th November)	22.93	23.73	24.80	26.00	24.37 ± 0.56	S : 1.44
	D ₃ (30 th November)	20.40	21.20	22.53	23.87	22.00 ± 0.59	D × S : 2.50
	Mean ± SE	22.44 ± 1.30	23.42 ± 1.35	24.49 ± 1.41	27.42 ± 2.19		
Number of pods per plant	D ₁ (10 th November)	22.07	22.73	23.40	29.87	24.52 ± 2.98	D : 1.22
	D ₂ (20 th November)	21.33	21.40	23.13	23.53	22.35 ± 0.76	S : 1.41
	D ₃ (30 th November)	19.07	19.87	20.87	22.47	20.57 ± 0.81	D × S : 2.45
	Mean ± SE	20.82 ± 1.13	21.33 ± 1.14	22.47 ± 1.11	25.29 ± 1.75		
Pod length (cm)	D ₁ (10 th November)	8.11	8.23	8.57	10.08	8.75 ± 0.87	D : 0.40
	D ₂ (20 th November)	8.02	8.18	8.41	8.51	8.28 ± 0.25	S : 0.46
	D ₃ (30 th November)	7.77	7.98	8.05	8.16	7.99 ± 0.16	D × S : 0.80
	Mean ± SE	7.97 ± 0.19	8.13 ± 0.17	8.35 ± 0.27	8.92 ± 0.83		

Table 4. Effect of sowing time and spacing on productivity of pea

Parameters	Spacings Sowing dates	S ₁ (60 × 7.5 cm)	S ₂ (60 × 10.0 cm)	S ₃ (60 × 12.5 cm)	S ₄ (60 × 15.0 cm)	Mean	CD _{0.05}
Plant height (cm) at harvest	D ₁ (10 th November)	52.20	53.27	54.40	63.60	55.87 ± 3.86	D : 1.95
	D ₂ (20 th November)	51.13	51.60	53.40	53.67	52.45 ± 1.04	S : 2.26
	D ₃ (30 th November)	48.53	50.00	50.87	52.60	50.50 ± 0.74	D × S : 3.91
	Mean ± SE	50.62 ± 2.28	51.62 ± 1.17	52.89 ± 1.21	56.62 ± 3.23		
Days taken to harvesting	D ₁ (10 th November)	147.00	144.33	143.67	140.67	143.92 ± 2.35	D : 1.98
	D ₂ (20 th November)	141.67	139.33	137.67	136.33	138.75 ± 1.61	S : 2.28
	D ₃ (30 th November)	132.33	131.67	130.00	127.67	130.42 ± 1.15	D × S : NS
	Mean ± SE	140.33 ± 2.20	138.44 ± 2.21	137.11 ± 2.20	134.89 ± 2.02		
Seed yield per plant (g)	D ₁ (10 th November)	12.24	16.64	22.23	31.18	20.57 ± 4.28	D : 1.26
	D ₂ (20 th November)	10.33	15.38	19.18	23.33	17.06 ± 3.13	S : 1.45
	D ₃ (30 th November)	8.29	11.66	15.75	20.29	13.99 ± 3.27	D × S : 2.25
	Mean ± SE	10.29 ± 1.58	14.56 ± 2.15	19.06 ± 2.43	24.93 ± 3.45		
Seed yield per plot (kg)	D ₁ (10 th November)	1.232	1.289	1.329	1.640	1.372 ± 0.17	D : 0.06
	D ₂ (20 th November)	0.984	1.077	1.132	1.165	1.090 ± 0.08	S : 0.07

Parameters	Spacings Sowing dates	S ₁ (60 × 7.5 cm)	S ₂ (60 × 10.0 cm)	S ₃ (60 × 12.5 cm)	S ₄ (60 × 15.0 cm)	Mean	CD _{0.05}
	D ₃ (30 th November)	0.757	0.816	0.864	0.912	0.837 ± 0.07	D × S : 0.12
	Mean ± SE	0.991 ± 0.12	1.060 ± 0.12	1.108 ± 0.11	1.239 ± 0.16		
Seed yield per hectare (q)	D ₁ (10 th November)	18.25	19.09	19.68	24.30	20.33 ± 2.48	D : 0.90
	D ₂ (20 th November)	14.58	15.95	16.78	17.26	16.14 ± 1.06	S : 1.04
	D ₃ (30 th November)	11.22	12.09	12.80	13.51	12.41 ± 0.96	D × S : 1.80
	Mean ± SE	14.68 ± 1.62	15.71 ± 1.58	16.42 ± 1.57	18.36 ± 2.17		
Shelling percentage	D ₁ (10 th November)	58.01	59.84	60.91	64.25	60.75 ± 1.29	D : NS
	D ₂ (20 th November)	58.47	59.81	61.25	64.58	61.03 ± 1.10	S : 2.21
	D ₃ (30 th November)	56.29	59.09	60.41	63.42	59.80 ± 0.97	D × S : NS
	Mean ± SE	57.59 ± 0.90	59.58 ± 0.42	60.86 ± 0.46	64.08 ± 0.71		

Table 5. Influence of sowing time and plant spacing on seed quality characteristics in pea

Parameters	Spacings Sowing dates	S ₁ (60 × 7.5 cm)	S ₂ (60 × 10.0 cm)	S ₃ (60 × 12.5 cm)	S ₄ (60 × 15.0 cm)	Mean	CD _{0.05}
1000 seed weight	D ₁ (10 th November)	15.79	16.55	17.15	19.65	17.29 ± 1.26	D : 0.44
	D ₂ (20 th November)	13.65	14.65	15.89	16.37	15.14 ± 0.65	S : 0.51
	D ₃ (30 th November)	12.78	13.03	13.86	14.15	13.45 ± 0.41	D × S : 0.88
	Mean ± SE	14.07 ± 1.04	14.74 ± 0.88	15.63 ± 0.86	16.72 ± 0.98		
Germination (%)	D ₁ (10 th November)	92.50 (9.67) ± 0.62	93.75 (9.73) ± 0.62	95.00 (9.79) ± 0.62	96.25 (9.86) ± 0.62	94.38 ± 0.74 (9.77)	D : 0.06
	D ₂ (20 th November)	88.75 (9.47) ± 0.55	89.50 (9.51) ± 0.55	90.75 (9.58) ± 0.55	91.50 (9.62) ± 0.55	90.13 ± 0.64 (9.55)	S : 0.07
	D ₃ (30 th November)	86.50 (9.35) ± 0.78	88.00 (9.43) ± 0.78	89.25 (9.50) ± 0.78	90.00 (9.64) ± 0.78	88.44 ± 0.90 (9.46)	D × S : NS
	Mean ± SE	89.25 ± 1.77 (9.50)	90.42 ± 1.69 (9.56)	91.67 ± 1.79 (9.62)	92.58 ± 1.89 (9.71)		
Seed vigour index-I (length)	D ₁ (10 th November)	2076.30	2205.38	2548.28	3102.20	2483.04 ± 145.50	D : 64.57
	D ₂ (20 th November)	1897.33	2097.23	2405.10	2630.60	2257.56 ± 103.30	S : 74.56
	D ₃ (30 th November)	1773.38	2050.00	2238.68	2477.75	2134.95 ± 105.20	D × S : 129.14
	Mean ± SE	1915.67 ± 102.30	2117.53 ± 71.70	2397.35 ± 110.10	2736.85 ± 160.00		
Seed vigour index- II (mass)	D ₁ (10 th November)	2983.19	3142.79	3347.74	4092.12	3391.46 ± 212.50	D : 176.09
	D ₂ (20 th November)	2836.52	2898.64	3078.31	3145.99	2989.87 ± 120.80	S : 203.33
	D ₃ (30 th November)	2660.29	2803.95	2861.79	3017.04	2835.77 ± 106.50	D × S : 352.18
	Mean ± SE	2826.66 ± 106.30	2948.46 ± 107.10	3095.95 ± 117.40	3418.38 ± 193.90		
Electrical conductivity (µS cm ⁻¹)	D ₁ (10 th November)	16.069	15.069	14.393	11.672	14.30 ± 1.02	D : 0.363
	D ₂ (20 th November)	18.037	17.037	16.287	15.163	16.63 ± 0.53	S : 0.419
	D ₃ (30 th November)	19.957	19.457	18.957	17.204	18.89 ± 0.39	D × S : 0.726
	Mean ± SE	18.02 ± 0.96	17.19 ± 0.95	16.55 ± 0.96	14.68 ± 1.12		
Accelerated ageing test (%)	D ₁ (10 th November)	72.50 (8.571)	75.25 (8.73)	78.00 (8.89)	84.25 (9.23)	77.50 ± 2.46 (8.86)	D : 0.12
	D ₂ (20 th November)	73.50 (8.63)	74.00 (8.66)	75.50 (8.75)	76.00 (8.77)	74.75 ± 0.54 (8.70)	S : 0.13
	D ₃ (30 th November)	71.00 (8.49)	71.50 (8.51)	72.25 (8.56)	73.00 (8.60)	71.94 ± 0.57 (8.54)	D × S : 0.23
	Mean ± SE	72.33 ± 0.72 (8.56)	73.58 ± 1.10 (8.63)	75.25 ± 1.64 (8.73)	77.75 ± 2.73 (8.87)		

Table 6. Effect of sowing time and plant spacing on economics of production in pea

Treatment	Gross return (Rs)	Total Expenditure (Rs)	Net return (Rs)	B:C ratio
T ₁	273750	107290	166460	1.55
T ₂	286350	104852	181497	1.73
T ₃	295200	103390	191810	1.86
T ₄	364500	102415	262085	2.56
T ₅	218550	107290	111260	1.04
T ₆	239250	104852	134397	1.28
T ₇	251550	103390	148160	1.43
T ₈	258900	102415	156485	1.53
T ₉	168150	107290	60860	0.57
T ₁₀	181200	104852	76347	0.73
T ₁₁	192000	103390	88610	0.86
T ₁₂	202650	102415	100235	0.98

seeds to accumulate more metabolites and photosynthates, which will improve germination and vigor as they age. Probably as a result of producing bolder seeds with higher dry matter content, higher seed weight, and improved vigor, which in turn improved resilience to ageing stress, the seeds from the 10th November sowing with the widest spacing had the highest germination after aging.

3.8 Economics of Production

The economic evaluation presented in Table 6 highlights the significant impact of sowing date and plant spacing on the profitability of pea cultivation. Among the treatments, T₄ (10th November sowing with 60 × 15.0 cm spacing) achieved the highest net returns of Rs 2,62,085 and a benefit-cost (B:C) ratio of 2.56, indicating that early sowing combined with wider spacing creates favorable conditions for optimal plant growth, higher yield and better economic returns. T₃ (10th November sowing with 60 × 12.5 cm spacing) also performed well, with net returns of Rs 1,91,810 and a B:C ratio of 1.86, though slightly lower than T₄ due to increased plant competition at narrower spacing. Conversely, T₉ (30th November sowing with 60 × 7.5 cm spacing) recorded the lowest net returns (Rs 60,860) and B:C ratio (0.57), demonstrating that delayed sowing and higher plant density adversely affect economic viability.

4. CONCLUSION

The treatment combination of sowing on November 10th with a spacing of 60 × 15.0 cm (D1S4) proved to be the most successful, according to the results of this study. In terms of important metrics like days to flower initiation (79.33), number of flowers per plant (32.40), number of pods per plant (29.87), pod length

(10.08 cm), plant height (63.60 cm), seed yield (31.18 g per plant, 1.640 kg per plot, and 24.30 q/ha), 100-seed weight (19.65 g), seed vigour indices I and II (3102.20 and 4092.12, respectively), electrical conductivity (11.672 μS cm⁻¹), germination after accelerated ageing (84.25%) and benefit-cost ratio (2.56) were all outperformed by this combination. Thus, based on multi-location trials conducted in Himachal Pradesh's mid-hill sub-humid conditions, it can be concluded that planting peas during the second week of November at a spacing of 60 × 15.0 cm can yield a profitable and high-quality seed yield.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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