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Research article

Optimization of vine killing date for maximum seed-tuber yield and minimum exposure to late-season aphid vectors in potato

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A R T I C L E I N F O

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A B S T R A C T

Short-duration and early-bulking potato varieties are well-suited for commercial cultivation in the subtropical Indo-Gangetic plains of India. To maximize seed tuber yield, prevent late-season exposure to aphid vectors, and facilitate the timely planting of wheat crops during the *rabi* season, it is essential to cut the haulms (vines) of seed potatoes at the earliest possible time. A study was conducted to standardize the optimal vine-killing date for two popular potato varieties in the north-western plains of India, *Kufri Pukhraj* and *Kufri Jyoti*, by examining variations in seed yield across different vine-killing dates and assessing the incidence of aphid vectors transmitting potato viruses. Tubers were planted on 15 October for two consecutive seasons, and haulms were cut at 70, 80, and 90 days after planting (DAP), with continuous monitoring of aphid populations. Results showed that total tuber yield and tuber numbers increased with delayed vine-killing. Similarly, the yield and number of oversized tubers significantly rose as the vine-killing date was extended. However, seed-size and undersized tuber yields were largely unaffected, while the number of undersized tubers decreased between 70 and 90 DAP. Further, the gain in total tuber yield and yield of over-sized tubers occurred mainly during 70–80 DAP for *Kufri Pukhraj* in contrast to *Kufri Jyoti* where maximum increase occurred between 80 and 90 DAP. Therefore, it is concluded that the optimum time of vine killing for maximum seed tuber yield is directly linked to the tuber growth cycle of individual variety. The period of maximum incidence of aphid vectors varied between the two years. Based on the incidence of *Myzus persicae*, the seed crops in north-western plains of India should not be extended beyond last week of December although real time monitoring of the aphid incidence is recommended.

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1. Introduction

The subtropical Indo-Gangetic plains contribute nearly 90 % of India's potato production [1], where the crop is grown under short-day conditions during the winter season [2,3]. Since both potato and wheat are cultivated during the *rabi* season (October to March), only early and medium-duration potato varieties are well-suited for this cropping system due to their shorter growing period. Early potato varieties allow growing potato-wheat as sequential crops hence the early harvest of potatoes ensures remunerative price to farmers for their produce [3]. The introduced European varieties which are long-day adapted and mostly longer duration do not fit well in to the system [1]. Hence the aim of potato breeding program in India is to develop short duration early bulking varieties, among other desirable traits [4,5]. Other than growing of short duration varieties, the major crop husbandry technique to realize highest returns in shortest duration is the timing of vine killing or haulm cutting, which is linked to the tuber growth cycle. Potato tuber formation is a multifaceted process involving various distinct and interrelated stages, each regulated independently [6,7]. These stages include induction, initiation, set, bulking, and maturation [8,9]. It is important to note that the number of tubers initiated often exceeds the number that grow to a commercially viable size. Some tubers may be entirely reabsorbed, while others remain small until the plant's foliage matures, with some reaching varying sizes [10]. Following tuber initiation, there is an initial rapid increase in tuber dry matter, known as the bulking stage. Subsequently, a prolonged period of nearly linear growth, termed maturation, ensues. This is succeeded by a decrease in growth rate, culminating in cessation of growth upon senescence of the shoot. The pattern of dry matter accumulation in tubers follows a similar trend to that of average tuber weight, tuber number, cell diameter, and the number of cells per tuber. The resource storage and nutrient transfers to the underground tuber occur during the bulking stage [11,12]. For long duration long day potato varieties, the period of tuber bulking (exponential tuber growth) lasts from 90 to 130 days after planting [13]. The potato crops cultivated in the subtropical Indo-Gangetic plains normally belong to early and medium maturing varieties, suited to the local growing conditions and cropping system [1]. During the tuber growth cycle, the stage of tuber bulking needs to be manipulated in such as way so as to achieve maximum fraction of desirable tubers. For early and medium bulking varieties, the period of tuber bulking stage lasts from 70 to 90 days after planting [14]. In potato cultivation, the grade-wise yield of tubers is a key factor with significant implications for marketing, as different markets demand varying tuber sizes based on their intended use as seed or table potatoes. In India, potato tubers are categorized into three grades viz. < 25 g (<30 mm; taken as mean of length and two widths at the middle of the tuber) as under-sized; 25–125 g (30–55 mm) as seed size and >125 g (>55 mm) as over-sized [15]. In seed potato crops, the tuber bulking stage is usually manipulated during the early phase so as to have maximum seed tuber yield by cutting of haulms (vines) on specific dates [16,17].

In addition to having an eight decades old breeding program with as many as 72 released varieties suited for specific growing conditions, India boasts a robust domestic production system for seed potatoes [18], employing the 'seed plot technique' to cultivate crops during periods of low aphid activity. This approach is guided by the population dynamics of the peach potato aphid, *Myzus persicae* (Sulzer). It is recommended to cut the haulms promptly once the *M. persicae* population exceeds 20 aphids per 100 compound leaves [19,20]. Primarily located in sub-tropical plains, India's seed potato production minimally involves hilly regions [21]. Early vine termination regulates tuber size and mitigates the spread of virus diseases, particularly during late-season aphid infestations [22,23]. Notably, *Potato virus Y* (PVY), *Potato leaf roll virus* (PLRV), *Potato virus A* (PVA), *Potato virus S* (PVS), and *Potato virus M* (PVM) are the key viruses transmitted by aphids in India [24–27], contributing to significant yield losses ranging from 20 % to 50 % [28]. PVY and PLRV account for approximately 80 % of seed degeneration in the country [20]. Furthermore, more than seventeen aphid species have been documented on potato crops across various regions of India [29]. However, the farmers tend to extend the crop growth cycle for getting higher tuber yield with longer crop growth period which not only leads to undesirable results *vis-à-vis* seed tuber yield, but also leads to higher incidence of debilitating virus diseases. Since the ideal time of vine killing to achieve the desirable yield of seed size tubers is likely to vary among the varieties with different maturation periods, the growers often find it difficult to tune the crop growth periods for best economic results. In light of these considerations, the current studies examined the tuber growth cycle of the most popular potato varieties in the western Indo-Gangetic plains. The aim was to provide clear recommendations on optimal vine-killing dates to achieve maximum seed yield and facilitate early potato production. Further, the incidence of aphid vectors was also studied to understand if the recommendations go hand-in-hand with the principles of 'Seed Plot technique'. It was found that the optimum date of vine killing would actually depend on the tuber bulking category of the varieties (early, medium or long) and is likely to vary from variety to variety.

2. Materials and methods

2.1. Experimental site, soil physico-chemical properties and climatology

The field experiment was carried out at the Research Farm of ICAR - Central Potato Research Institute, Regional Station, Jalandhar, Punjab, India (31.16°N, 75.32°E) from October to January over two consecutive seasons, 2018-19 and 2019-20, using a fixed, homogenous plot. Homogenous plot was created by growing exhaustive preceding single crop of pearl millet, *Cenchrus americanus* (*Pennisetum glaucum*) (L.) Morrone and succeeding was kept fallow. Prior to potato planting, soil samples from 0 to 15 cm depth at five random sites were collected and composited and analyzed for physico-chemical properties. The soil of experimental location is predominantly alluvial and with sandy loam texture.

The soil in the experimental plot showed a moderately alkaline reaction, with a pH of 7.9. It had low levels of organic carbon (0.42 %) and available nitrogen (246.0 kg/ha), while available phosphorus (18.0 kg/ha) and potassium (184.0 kg/ha) were present at medium levels. The climate of the study area ranges from sub-humid to semi-arid and is generally dry, except during the monsoon season. Meteorological data were collected from a local observatory located approximately 200 m from the fields, as shown in Table 1.

2.2. Yield trials

2.2.1. Land preparation, planting and crop husbandry

The field was prepared to a fine tilth using a disc plough, followed by a tiller with a leveler. Well-sprouted seed-size tubers, weighing 40–50 g, were planted on October 15th in both years. Phosphorus (as diammonium phosphate) @ 100 kg/ha and potassium (as muriate of potash) @ 150 kg/ha were applied entirely at planting. Nitrogen @ 175 kg/ha was applied in two splits: half as urea and diammonium phosphate at planting as a basal application, and the remaining half as urea during earthing-up, 25 days after planting, as a top dressing. Hand weeding was conducted to control weeds, and plant protection measures were taken as needed to manage pests and diseases. The pre-emergence herbicide, metribuzin 70 WP @ 0.75 kg/ha, was sprayed 6 days after planting. All intercultural operations were carried out as required [30]. The crop was harvested manually.

2.2.2. Experimental treatments and design

The investigation was carried on two most popular varieties of the region namely *Kufri Pukhraj* and *Kufri Jyoti*. *Kufri Pukhraj* is an early bulking variety while as *Kufri Jyoti* is an early to medium bulking variety. The experiment consisted of three haulm (vine) killing dates or vine cutting dates; 70 days, 80 days, and 90 days after planting (DAP), replicate three times with both the selected varieties. The experiment was conducted using a randomized block design. The treatments involved cutting the vines on specific dates—70, 80, or 90 days after planting (DAP) with tubers harvested 20–25 days after each vine-killing date. Each plot comprised six rows, each 4 m long, resulting in a net plot size of 14.4 m^2. Tubers were planted 20 cm apart, with a row spacing of 60 cm. A footpath 60 cm wide was maintained between the plots, and a 100 cm path was left between the blocks.

2.2.3. Data collection

Emergence was recorded 30 days after planting, and additional morphological assessments were carried out by tagging ten randomly selected plants from each plot. Tuber initiation was observed on multiple plants at random. The main stem count, leaf count per stem, and plant height were evaluated at the time of vine termination, specifically at 70, 80, and 90 days after planting (DAP). After harvest, tubers were categorized into three grades within each plot: those weighing less than 25 g were considered under-size, those between 25 and 125 g were classified as seed size, and those exceeding 125 g were designated over-size [15]. The tubers were quantified, weighed, and expressed in terms of per-hectare count and yield.

2.2.4. Economic analysis

The cost of cultivation and gross income were calculated based on the prevailing market rates for various inputs and the sale prices of different grades of seed potatoes. Net income for each treatment was then determined by subtracting the cost of cultivation from the gross income. Benefit cost ratio (B: C ratio) was calculated by dividing net income by the cost of cultivation (Table S1, Supplementary Information).

2.2.5. Statistical analysis

The selected varieties have different yield potential and tuber growth patterns; therefore, data on yield by number and weight were analyzed separately for the two varieties. Data on percent emergence, plant height, number of shoots per stem, number of leaves per shoot, and tuber number and yield were analyzed using analysis of variance (ANOVA) following appropriate transformations. Treatment means were compared using the least significant difference test (LSD) at a significance level of 5 % [31].

2.3. Monitoring of vector incidence

The incidence of aphid vectors, specifically the peach-potato aphid, *Myzus persicae* (Sulzer), was monitored in two adjacent plots of the *Kufri Jyoti* variety, each approximately 0.1 ha. These monitoring plots were planted alongside yield trials during both seasons in the second week of October. The experimental plots were prepared following established agronomic practices, including fertilization and irrigation methods recommended for the local area to facilitate vector population monitoring. Pesticides were not applied to the experimental plots, except for a pre-emergence herbicide application of metribuzin 70 WP @ 0.75 kg/ha, administered six days after

Table 1
Monthly average weather parameters at the experimental site (Jalandhar) during 2018-19 and 2019-20.

Season	Month	Max. Temp. (°C)	Min. Temp. (°C)	Relative Humidity (%)	Rainfall (mm)	Sun Shine (hrs.)
2018–2019	October	31	16	70	0	5.6
	November	25	10	69	0	4.6
	December	19	5	71	0	4.7
	January	17	5	73	92.9	5.3
2019–2020	October	29	18	71	0	4.5
	November	23	13	70	23.1	4.2
	December	13	6	76	58.9	4.4
	January	14	5	75	40.9	4.1

planting. Crop emergence occurred within 10–20 days post-planting, with vector incidence monitoring beginning immediately after emergence and continuing until the third week of January. The presence of winged morphs of *M. persicae*, a common aphid species, was assessed using the leaf turn method, which involved examining three leaves per plant for adult aphids—one leaf from the plant's upper, middle, and lower sections. During each sampling event, 34 plants (equivalent to 100 compound leaves) were monitored in each selected field to determine the presence of winged aphids. Counts were conducted before 8:00 a.m. on each sampling occasion [3,22,23]. The incidence of winged morphs of *M. persicae* indicated vector pressure, defined as the product of the aphid species' virus transmission efficiency and the number of adults captured on plants or traps within a specified time frame. This approach adheres to the 'Seed Plot Technique' guidelines for monitoring aphid vectors to ensure the production of healthy seed potatoes in the subtropical plains of India [19,20]. Numerous aphid samples infesting the potato crops were collected and identified using morphological and molecular techniques for species verification.

3. Results

3.1. Yield trials

The crop emergence started 10 days after planting (DAP) and by 14 DAP, more than 90 % crop emerged during both seasons. Total crop emergence averaged over all the plots was (mean ± SE) 93.85 ± 0.55 % for *Kufri Pukhraj* and 93.87 ± 0.75 % for *Kufri Jyoti* during 2018-19, and 94.20 ± 0.35 % and 93.26 ± 0.89 % respectively during 2019-20, with no significant variation between the two seasons. The average number of shoots per plant (measured at the time of haulm cutting) did not show significant variation with the delay in vine-killing dates for either variety ($F = 0.04$, $d.f. = 2, 10$, $p \leq 0.95$ for *Kufri Pukhraj*; $F = 0.48$, $d.f. = 2, 10$, $p \leq 0.62$ for *Kufri Jyoti*), with no significant differences observed between years. The average number of shoots per plant ranged from 3.5 to 4.9 for *Kufri Pukhraj* and from 3.3 to 4.9 for *Kufri Jyoti*. In contrast, a significant impact of the vine-killing date was noted on average plant height and the average number of compound leaves per shoot in both varieties (Fig. 1). The average plant height increased as the date of vine killing was delayed, while the average number of compound leaves per shoot decreased after 70 DAP. The average plant height increased from 62.25 ± 1.06 cm at 70 DAP to 63.80 ± 1.08 cm at 80 DAP and 69.45 ± 1.36 cm at 90 DAP for *Kufri Pukhraj* (averaged over both seasons). For *Kufri Jyoti*, the average plant height increased from 58.78 ± 0.59 cm at 70 DAP to 63.59 ± 2.01 cm at 80 DAP and 68.30 ± 1.10 cm at 90 DAP. Opposite to this, the average number of compound leaves decreased from 13.12 ± 0.37 cm at 70 DAP to 8.98 ± 0.22 cm at 80 DAP and 5.52 ± 0.30 cm at 90 DAP for *Kufri Pukhraj*, and from 13.05 ± 0.37 cm at 70 DAP to 9.60 ± 0.10 cm at 80 DAP and 5.72 ± 0.07 cm at 90 DAP for *Kufri Jyoti*.

The total tuber yield significantly increased with progressive delay in the date of vine killing for both varieties (Fig. 2). The total tuber yield for *Kufri Pukhraj* increased from 32.05 ± 0.39 t/ha at 70 DAP to 42.14 ± 0.64 t/ha at 80 DAP (31.49 ± 1.94 % increase over 70 DAP), and 43.52 ± 0.52 t/ha at 90 DAP (3.32 ± 2.28 % increase over 80 DAP). In contrast, for *Kufri Jyoti*, the total tuber yield increased from 27.22 ± 0.26 t/ha at 70 DAP to 29.28 ± 1.11 t/ha at 80 DAP (7.50 ± 3.13 % increase over 70 DAP), and 33.87 ± 0.46 t/ha at 90 DAP (16.09 ± 5.44 % increase over 80 DAP). For *Kufri Jyoti*, no significant year-to-year variation was noticed in total tuber yield averaged over the three vine killing dates (mean ± SE) (30.43 ± 1.07 t/ha during 2018-19, and 29.81 ± 1.17 t/ha during 2019-20), with but for *Kufri Pukhraj*, the variation in total yield over the two seasons was statistically significant ($F = 8.73$, $d.f. = 1, 10$, $p \leq 0.01$); 40.15 ± 1.54 t/ha during 2018-19, and 38.32 ± 2.14 t/ha during 2019-20. Similarly, the total tuber number increased with progressive delay in the date of vine killing for both varieties (Fig. 2). For both varieties, no significant year-to-year variation was noted in the total tuber number. For *Kufri Pukhraj*, the total tuber number averaged over the three vine killing dates (mean ± SE), was 605.27 ± 6.60 thousand/ha during 2018-19 and 599.55 ± 7.85 thousand/ha during 2019-20, and for *Kufri Jyoti*, the total tuber number averaged over the three vine killing dates was recorded as 461.24 ± 8.06 thousand/ha during 2018-19, and 461.89 ± 10.11 thousand/ha during 2019-20. The total tuber number for *Kufri Pukhraj* increased from 579.71 ± 7.69 thousand/ha at 70 DAP to 607.24 ± 7.76

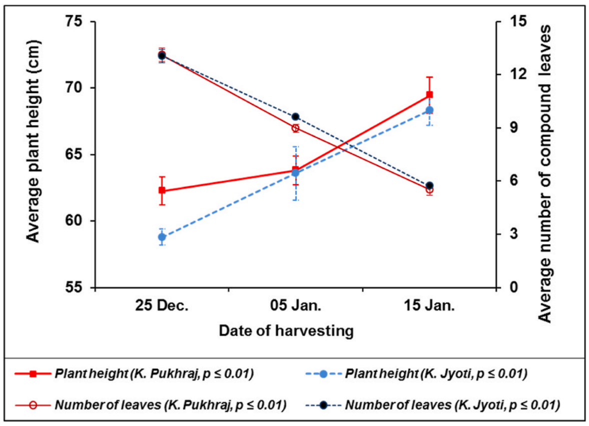

Fig. 1. Effect of delay in date of vine killing on average plant height and number of compound leaves in *Kufri Pukhraj* and *Kufri Jyoti*.

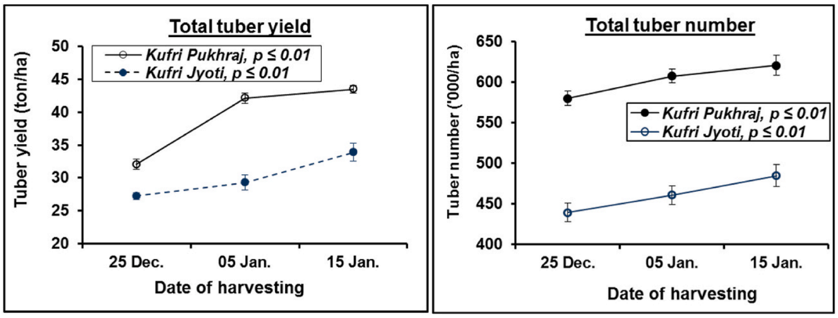

Fig. 2. Effect of vine killing date on total tuber yield and total tuber number in *Kufri Pukhraj* and *Kufri Jyoti* (date of planting 15 October).

thousand/ha at 80 DAP (4.80 ± 2.34 % increase over 70 DAP), and 620.30 ± 0.52 thousand/ha at 90 DAP (2.19 ± 1.41 % increase over 80 DAP). In contrast, for *Kufri Jyoti*, the total tuber number increased from 439.24 ± 8.14 thousand/ha at 70 DAP to 460.90 ± 8.50 thousand/ha at 80 DAP (4.94 ± 0.60 % increase over 70 DAP), and 484.56 ± 2.24 thousand/ha at 90 DAP (5.22 ± 2.31 % increase over 80 DAP). The yield of over-sized tubers also increased significantly with delay in date of vine killing for both the varieties, with non-significant year-to-year variation (Fig. 3). The yield of over-sized tubers for *Kufri Pukhraj* increased from 14.22 ± 0.16 t/ha at 70 DAP to 24.50 ± 1.01 t/ha at 80 DAP (72.48 ± 8.80 % increase over 70 DAP), and 26.08 ± 0.56 t/ha at 90 DAP (6.63 ± 2.38 % increase over 80 DAP). In contrast, for *Kufri Jyoti*, the yield of over-sized tubers increased from 14.21 ± 0.23 t/ha at 70 DAP to 15.60 ± 0.92 t/ha at 80 DAP (9.98 ± 7.65 % increase over 70 DAP), and 20.12 ± 0.05 t/ha at 90 DAP (29.89 ± 7.61 % increase over 80 DAP).

Conversely, the yield of seed-size tubers did not show significant variation across the three vine-killing dates for both varieties. (Fig. 3). The seed yield was comparatively lower during the second year, and the seasonal variation was statistically significant for *Kufri Pukhraj* only. The yield of seed-sized tubers for *Kufri Pukhraj* was recorded as 13.46 ± 0.26 t/ha at 70 DAP, 13.23 ± 0.24 t/ha at 80 DAP, and 13.12 ± 0.67 t/ha at 90 DAP, and for *Kufri Jyoti*, the yield of seed-sized tubers was recorded as 10.00 ± 0.28 t/ha at 70 DAP, 10.86 ± 0.59 t/ha at 80 DAP, and 11.24 ± 0.36 t/ha at 90 DAP. The yield of under-sized tubers showed different trends for both varieties by varying the date of vine killing. For *Kufri Pukhraj* no significant variation in the yield of under-sized tubers was recorded ($F = 0.02$, $d.f. = 2, 10$, $p \leq 0.97$). In contrast, as for *Kufri Jyoti*, a significant decrease was recorded over the three vine-killing dates ($F = 5.63$, $d.f. = 2, 10$, $p \leq 0.02$) (Fig. 3). The yield of under-sized tubers for *Kufri Pukhraj* was recorded as 4.37 ± 0.38 t/ha at 70 DAP, 4.40 ± 0.45 t/ha at 80 DAP, and 4.31 ± 0.25 t/ha at 90 DAP. In contrast, for *Kufri Jyoti*, the yield of under-sized tubers decreased from 3.01 ± 0.05 t/ha at 70 DAP to 2.81 ± 0.05 t/ha at 80 DAP (6.50 ± 1.74 % decrease over 70 DAP), and 2.51 ± 0.11 t/ha at 90 DAP (10.77 ± 4.85 % decrease over 80 DAP). Similar to tuber yield, the number of over-sized tubers also increased significantly with a delay in the date of vine killing for both the varieties, with non-significant year-to-year variation (Fig. 4). The number of over-sized tubers for *Kufri Pukhraj* increased from 147.50 ± 9.98 thousand/ha at 70 DAP to 195.84 ± 6.70 thousand/ha at 80 DAP (33.79 ± 8.38 % increase over 70 DAP), and 214.19 ± 1.94 thousand/ha at 90 DAP (9.56 ± 4.78 % increase over 80 DAP). In contrast, for *Kufri Jyoti*, the number of over-sized tubers increased from 100.40 ± 0.23 thousand/ha at 70 DAP to 126.28 ± 0.92 thousand/ha at 80 DAP (26.12 ± 4.75 % increase over 70 DAP), and 159.52 ± 1.40 thousand/ha at 90 DAP (26.32 ± 1.07 % increase over 80 DAP).

As for the number of seed-size tubers, no significant variation was recorded for both the varieties with vine killing date, with non-significant variation over the two years (Fig. 4). The number of seed-sized tubers for *Kufri Pukhraj* was recorded as 216.41 ± 6.37 thousand/ha at 70 DAP, 207.15 ± 3.83 thousand/ha at 80 DAP, and 203.17 ± 2.75 thousand/ha at 90 DAP, and for *Kufri Jyoti*, the number of seed-sized tubers was recorded as 168.62 ± 5.45 thousand/ha at 70 DAP, 175.13 ± 1.40 thousand/ha at 80 DAP, and 177.38 ± 3.26 thousand/ha at 90 DAP, averaged over both the seasons. The number of under-sized tubers also followed a similar trend where no significant variation was recorded for number of under-sized tubers in case of *Kufri Pukhraj* while as for *Kufri Jyoti*, significant decrease was recorded over the three vine killing dates, with non-significant variation over the two seasons in both the cases (Fig. 4). The number of under-sized tubers for *Kufri Pukhraj* was recorded as 215.80 ± 3.28 thousand/ha at 70 DAP, 204.25 ± 1.66 thousand/ha at 80 DAP, and 202.95 ± 4.95 thousand/ha at 90 DAP. For *Kufri Jyoti*, the yield of under-sized tubers decreased from 170.22 ± 6.71

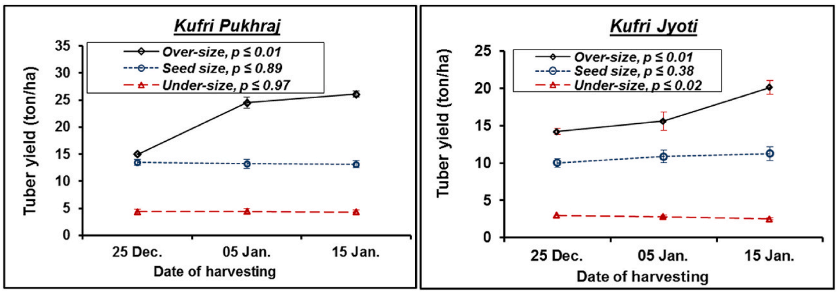

Fig. 3. Effect of vine killing date on grade-wise tuber yield in *Kufri Pukhraj* and *Kufri Jyoti* (date of planting 15 October).

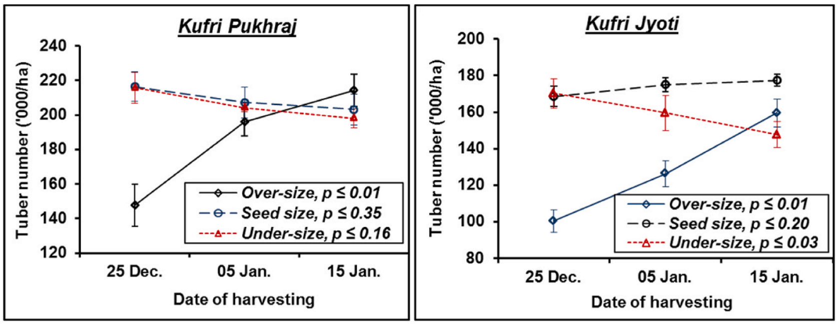

Fig. 4. Effect of vine killing date on grade-wise tuber number in *Kufri Pukhraj* and *Kufri Jyoti*, date of planting 15 October for both the seasons.

thousand/ha at 70 DAP to 159.49 ± 8.14 thousand/ha at 80 DAP (6.39 ± 1.14 % decrease over 70 DAP), and 147.66 ± 1.38 thousand/ha at 90 DAP (6.95 ± 4.64 % decrease over 80 DAP).

The proportion of seed size tuber yield out of the total yield decreased from 42.00 to 30.16 % for *Kufri Pukhraj* while it decreased from 36.76 to 33.19 % for *Kufri Jyoti* with progressive delay in the date of vine killing from 70 to 90 DAP. Similarly, the proportionate yield of under-sized tubers also decreased for both varieties (from 13.62 to 9.90 % for *Kufri Pukhraj*, and 11.05 to 7.40 % for *Kufri Jyoti*). In contrast, the proportionate yield of over-size tubers exhibited a significant increase over the three vine-killing dates for both varieties (from 44.38 % at 70 DAP to 58.15 % at 80 DAP, and 59.95 % at 90 DAP for *Kufri Pukhraj*, and from 52.20 % at 70 DAP to 53.29 % at 80 DAP, and 59.41 % at 90 DAP for *Kufri Jyoti*). Analysis of the cost of cultivation revealed that the gross economic returns significantly increased with delay in the date of vine killing ($F = 39.44$, $d.f. = 2, 4$, $p \leq 0.01$ for *Kufri Pukhraj*; $F = 11.26$, $d.f.=2, 4$, $p = 0.02$ for *Kufri Jyoti*) (Fig. S1, Supplementary Information). However, for *Kufri Pukhraj*, the gross economic returns from vine killing at 80 and 90 DAP were statistically comparable while for *Kufri Jyoti,* the returns from vine killing at 70 and 80 DAP were also statistically similar. However, when considering total seed yield (both seed-size and under-size tubers), no significant differences were observed across the three vine-killing dates ($F = 0.09$, $d.f. = 2, 4$, $p = 0.91$ for *Kufri Pukhraj*; $F = 0.35$, $d.f. = 2, 4$, $p = 0.71$ for *Kufri Jyoti*) (Table S2, Supplementary Information).

3.2. Vector incidence

Myzus persicae first appeared on the potato plants during the 2nd week of November in 2018-19 and the 1st week of November in 2019-20, exceeding the economic threshold of 20 winged *M. persicae* per 100 compound leaves on December 22 and January 12, respectively, during the two consecutive seasons (Fig. 5). The population of *M. persicae* gradually increased until interrupted by rainfall events, showing exponential growth after the second week of January. In 2018-19, population growth was halted in the first week of January due to rainfall, while in 2019-20, multiple rainfall events occurred from November to January, significantly affecting the aphid population build-up. As a result, the economic threshold was crossed only after the second week of January.

4. Discussion

The two most popular potato varieties in the Indo-Gangetic plains viz., *Kufri Pukhraj* and *Kufri Jyoti* are typically classified as early

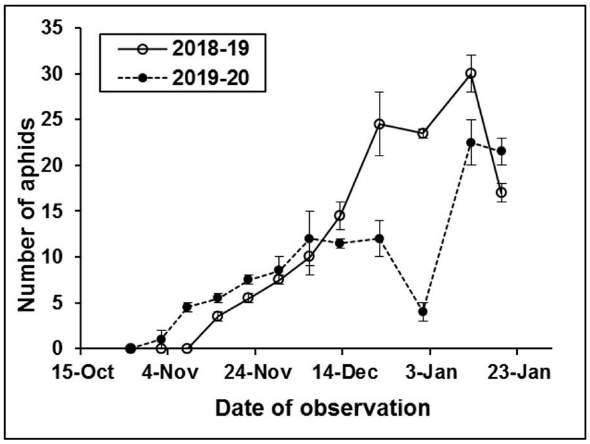

Fig. 5. Incidence of winged *Myzus persicae* in potato crop during 2018-19 and 2019-20 at Jalandhar.

bulking and early-medium bulking varieties, respectively [14]. The results of the current study indicated that the total tuber yield of *Kufri Pukhraj* showed a higher incremental increase from 70 to 80 DAP (31.49 ± 1.94 %) as compared to the period from 80 to 90 DAP (3.32 ± 2.28 %). In the case of *Kufri Jyoti*, the reverse trend was noted: 7.50 ± 3.13 % increase from 70 to 80 DAP, and 16.09 ± 5.44 % increase from 80 to 90 DAP. A similar trend was noted for the total tuber number for both varieties. Therefore, it is plausible to conclude that the tuber bulking phase of *Kufri Pukhraj* lasts till 80 DAP while that of *Kufri Jyoti* continues right up to 90 DAP. The tuber size distribution at the three vine-killing dates showed different trends for the two varieties. Although the yield and number of seed size tubers did not vary significantly among the three vine-killing dates for both varieties, the proportion of seed yield compared to total yield showed a declining trend for both varieties. The yield-wise proportionate distribution of tubers further indicated that the gain in over-size tuber yield, which occurs at the cost of seed size and under-size tubers, occurs more in the period from 70 to 80 DAP for *Kufri Pukhraj* and mainly from 80 to 90 DAP for *Kufri Jyoti*. The non-significant variation in seed yield beyond a certain crop duration has been found in most potato varieties studied worldwide. For example, with significant variation in total yield, the similar yield of desired 25–35 mm diameter tubers in *Bintje* (early to medium maturing) and *Ciklamen* (medium to late maturing) potato cultivars at different vine killing dates was recorded by Boydst et al. (2018) [32]. Roy and Sharma (2000) reported non-significant variation in the yield and number of under-sized tubers when haulms were cut at 70 and 80 DAP in the case of *Kufri Sindhuri* [33]. Krupek et al. (2022) demonstrated that early vine desiccation reduces large-sized tubers in long-day potato varieties [34]. Therefore, it is evident that the extension of potato crops beyond the specific duration does not result in an increased yield of seed tubers. However, the decision of vine killing date should take into consideration the overall market value of the produce including the yield of over-size and under-size tubers. From the seed tuber yield point of view, which is the most important aim of seed potato crops, it is evident that the time of vine killing is the most important crop husbandry practice available to the growers. The seed tuber yield did not vary significantly among the three vine-killing dates for both cultivars. However, the proportionate yield of seed tubers was maximum at 70 DAP for *Kufri Pukhraj* and 80 DAP for *Kufri Jyoti*. Based on the gross economic returns, extending the seed potato crops of *Kufri Pukhraj* beyond 80 DAP does not add to the economic yield. In contrast, expanding the crop beyond 80 DAP for *Kufri Jyoti* may lead to increased gross returns, but returns from total seed yield do not increase.

The effect of vine-killing date on the growth parameters of the potato crops showed that the average number of shoots per plant remained unchanged. In contrast, the average number of compound leaves per shoot decreased, and the average shoot height increased with a progressive delay in the date of vine killing for both varieties. While the plants' general height tends to increase, the senescence sets in during the same period. Both varieties lose 3–4 lower compound leaves from 70 to 80 DAP and by almost the same number during 80–90 DAP. The general yellowing of foliage can be seen followed by browning of the haulm tissue; however, for both the varieties, the lowest leaves were the first to die by the end of trials at 90 DAP. Celis-Gamboa et al. (2003) scaled the senescence process of potato foliage to start from the yellowing of upper leaves followed by the rest of the foliage with gradual browning of the haulm tissue and finally death of the plant [35]. It is pertinent to mention that none of the two varieties progress to any advanced stage of crop senescence by 90 DAP. Generally, the haulms in seed potato crops are cut much before the onset of senescence. For example, early-maturing cultivars grown in the southern USA are harvested before the onset of natural vine senescence as a rule, by chemical or mechanical haulm killing methods [17,36]. Other than achieving a desirable tuber size distribution, haulm or vine killing has numerous other advantages. Harvesting is easier when the vines are dead, and vine killing can help achieve the desired skin set, reduce bruising, and improve the storability of the crop [34]. In Northern Europe, cutting the haulms is considered an essential practice and a key factor in controlling tuber size [37,38]. Haulm cutting is typically performed on immature plants that are still flowering [39]. In regions with short growing seasons, killing the haulms of potato plants is seen as a method for early harvesting, enhancing tuber skin formation before harvest, and ensuring suitable tuber size [40]. Therefore, in the context of the Indo-Gangetic plains of India, where potato crops compete with wheat during the winter season, it is preferable to cultivate potato varieties with shorter growth durations to allow for subsequent wheat planting.

Additionally, haulm killing reduces the spread of viral diseases by aphids, which typically appear in the later stages of the growing season, as well as the spread of fungal diseases [20,41–43]. In the current study, rainfall events were the most significant factor influencing the population build-up of *M. persicae*. This population growth is generally determined by the prevailing average daily temperature and frequent rainfall from the last week of December to the first week of January [3]. Rainfall significantly decreases the aphid population and reduces their flight activity. However, historical records of aphid monitoring in the subtropical plains of India indicate that the population of *M. persicae* gradually increases until the last week of December, crossing the threshold limit around that time, and then experiences exponential growth after the last week of January [3,19,20]. The seed potato crops in the current study (planted on 15th October) were harvested (vine killing) on 25th December (70 DAP), 04 January (80 DAP) and 14 January (90 DAP). Based on the seasonal incidence of *M. persicae* in potato crops, it is not advisable to extend the crop season beyond the second week of January if the aphid build-up is slow and not beyond the last week of December under normal/high aphid incidence to prevent the spread of debilitating potato viruses. This scenario indicates that no confident presumptions can be made about the incidence of virus-vectoring aphids. The only way to check the resulting virus incidence is through continuous monitoring of the aphids and making management decisions based on real-time situations prevailing during a particular season. Hence, it is concluded that the tuber bulking phase of potato varieties is directly linked to the tuber growth cycle, which varies significantly among the varieties, particularly the varieties that belong to different maturity groups. For the varieties under study, the tuber bulking phase for *Kufri Pukhraj* lasts till 80 DAP, while as that of *Kufri Jyoti* continues right up to 90 DAP. Therefore, the decision on the date of vine killing is a direct function of the tuber bulking group of the variety under consideration. Based on the economics of the returns, seed potato crops of *Kufri Pukhraj* should not be extended beyond 80 DAP. In contrast, in case of *Kufri Jyoti,* extending the crop beyond 80 DAP may lead to increased gross returns but returns from total seed yield do not increase. Based on the incidence of *M. persicae*, the seed crops should not be extended beyond last week of December in case of normal aphid incidence and never beyond the second week of January. The population build-up of *M. persicae* depends on the prevailing weather conditions; therefore, the actual time of crossing the economic threshold by *M. persicae* should be ascertained through real-time monitoring and decisions should be taken accordingly to contain the incidence of virus diseases in seed potato crops.

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We have meticulously followed the Guide for Authors to prepare this manuscript, ensuring compliance with the Ethics in Publishing Policy outlined in the Guide for Authors.

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The consent of participants in research

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CRediT authorship contribution statement

Prince Kumar: Investigation, Conceptualization, Writing – original draft. **Raj Kumar:** Writing – review & editing, Resources, Investigation, Formal analysis. **Mohd Abas Shah:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Rajesh Kumar Singh:** Writing – review & editing, Conceptualization. **Ashwani Kumar Sharma:** Writing – review & editing, Conceptualization. **Raj Kumar:** Investigation, Data curation, Conceptualization. **Anil Sharma:** Writing – review & editing. **Jagdev Sharma:** Writing – review & editing. **Brajesh Singh:** Writing – review & editing, Conceptualization. **Ravinder Kumar:** Writing – review & editing, Writing – original draft, Software, Conceptualization, Formal analysis, Resources.

Declaration of competing interest

The authors declare the following financial interests and personal relationships which may be considered as a potential competing interest.

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Appendix A. Supplementary data

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