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Influence of row spacing and weed management practices on growth and productivity of Indian mustard (*Brassica juncea* L.)

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Abstract

In order to assess the impact of various row spacing and weed management techniques on mustard, a field experiment was carried out during *rabi* season the 2021–2022 fiscal year at the Research Farm, Department of Agriculture, R.M.P. (P.G.) College, Gurukul Narsan, Haridwar, Uttarakhand. The experiment was set up in a factorial randomized block design with three replications and included five treatment combinations combining three row spacings (30 x 20 cm, 45 x 20 cm, and 60 x 20 cm) and five weed management techniques. The results showed that the highest seed yield (1822.46 kg ha⁻¹) and recovery yield (3996.50 kg ha⁻¹) were recorded at row spacing of 45×20 cm, whereas wider spacing (60×20 cm) considerably enhanced yield parameters such number of siliquae plant⁻¹ (220.90), siliqua length (4.68 cm), seeds siliqua⁻¹ (14.89), and test weight (4.59g). The highest seed yield 1612.58 kg/ha was recorded with treatment W4: Pendimethalin @ 1.0 kg ha⁻¹ as Pre Emergence + Quizalofop -P- ethyl @ 0.06 kg ha⁻¹ at 20 DAS+ HW and IC at 40 DAS.

Keywords: Mustard, row spacing, weed management, pendimethalin, Quizalofop-P-ethyl

Introduction

Rapeseed and mustard (*Brassica* spp.) is one of the world's most economically important oilseed crops, being the third largest producer of vegetable oil in the world after soybean and oil palm, Indian mustard (*Brassica juncea* (L.)), and small grains (*Brassica napus* (L.)). Czern. & Coss.]. Rapeseed mustard is the second largest oilseed crops in India after groundnut, and is cultivated in an area of about 10% (or half of the total oilseed area) and about 25% (or 40% of the total oilseed production) mainly in the states of Rajasthan, Haryana, Madhya Pradesh, Uttar Pradesh and West Bengal (Kumar *et al.*, 2018; Anonymous 2023) ^[11]. National area between 1950–51 and 2023–24 increased from 2.07 million hectares to 9.18 million hectares while the production increased from 0.76 million tonnes to 13.26 million tonnes but the farm yields were still lagging behind research-station potential by 150 - 600 kg/ha (Kumbhare *et al.*, 2025) ^[12]. In fact, the edible oil imports in India accounted for an estimated ₹1,56,800 crore during 2021–22 alone, which makes it an urgent policy priority in India's edible oil strategy, Atmanirbharta to increase domestic mustard production (Kumbhare *et al.*, 2025; NITI Aayog 2024) ^[12, 14].

Mustard seed is a nutritious and balanced source of oil, protein and minerals whose range of oil content of released varieties is estimated to be around 36.5 – 43.5 per cent and protein content of the seed is around 17.6 – 20.7 per cent, depending on the genotype and growing condition (Verma *et al.*, 2023) ^[19]. The seed and oil are also rich in bioactive compounds, including glucosinolates, which have antioxidant, antimicrobial, and anti-inflammatory properties, and sulphur containing amino acids, which are increasingly being used in functional food formulations, traditional medicine, and food preservation. (Mishra *et al.*, 2024; Saha *et al.*, 2024) ^[13, 18]. The need of the hour is to boost the production of edible oil in the country since India is heavily relying on imports. Achieving this potential requires significant improvement of field level agronomic practices, some of which are simple and readily available for use to boost productivity, such as optimisation of crop geometry and weed management.

Crop geometry (row spacing) affects plant population, light interception, row spread and intra-crop competition, and thus influences canopy development, dry matter accumulation and yield attributes. A wider row spacing tends to have better branching and attributes of yield per plant while sometimes a higher yield of seeds is obtained with narrow spacing under conditions of moisture or inputs limitations but it results in a faster canopy closure, which results in better suppression of early weed growth (Beulah and Umesha 2022; Jangir *et al.*, 2018) [3, 7].

Weeds are one of the most detrimental problems of mustard as they grow slowly during the first 4 to 6 weeks after sowing and mustard does not compete favorably with weeds for light, moisture, nutrients, and space. The losses are reported between 15 to 30%, and up to 70% in severe infested cases (Bista *et al.*, 2023) [4]. The critical period of weed competition for the crop is typically during the first 3 to 7 weeks after sowing, depending on the specific weed species and crop stage; recent studies have determined it to be between 19 and 52 days after sowing, with the most critical time being around 20 days after sowing for early management (Kadu and Korav 2026) [8]. Dominant weed flora is *Chenopodium*, *Anagallis*, *Polygonum* and *Cyperus* species, and (Kumar *et al.*, 2015) [10].

Manual weeding (1 or 2 hand-weedings around 20-45 days after sowing) is highly effective, but labour intensive and is becoming limited by the lack of labour and costs. (Kalita *et al.*, 2023; Bamboriya *et al.*, 2016) [9, 2]. Most common pre-emergence herbicides used are pendimethalin, oxyfluorfen and fluchloralin, as well as post-emergence like quizalofop-ethyl, which do not always perform consistently or do not have acceptable phytotoxic properties and are not as cheap as weeding done by hand throughout the season (Kumar *et al.*, 2015; Bista *et al.*, 2023) [10, 4]. Mixed results validate the Integrated Weed Management (IWM) strategies that incorporate cultural, mechanical and chemical practices for more uniform, economical control (Rao and Chauhan 2015) [16].

The interaction between row spacing and weed management cannot be separated, the narrow spacing will cause close canopy which can result in decrease weed flora, too wide spacing can cause more weed flora which requires weed control as the inter-row space will be exposed longer. Field trials have validated that the efficiency of weed control and final yield and returns is not related to either spacing or weed management, but to a specific combination of both (Jangir *et al.*, 2018) [7].

Integrated weed management combining herbicides and manual methods is essential for effective weed control and yield improvement. Therefore, the present study was undertaken to evaluate suitable row spacing and weed management practices for enhancing productivity of Indian mustard under the agro-climatic conditions of Uttarakhand.

Materials and Methods

During the Rabi season (2021–2022), a field experiment was conducted at the research farm of Raja Mahendra Partap (Post Graduate) college in Gurukul Narsan, Haridwar (Uttarakhand). The farm is located in Uttarakhand's Ganga alluvial belt. Geographically, Gurukul Narsan is located between latitude 29.70240 N and longitude 77.84960 S and has a subtropical, semi-arid climate. Gurukul Narsan is 261 meters above sea level. Gurukul Narsan has an average annual temperature of 23.70°C and an average annual rainfall of 1170 mm. The experimental site's soil had a sandy loam texture, low levels of organic carbon (0.34%), low levels of available nitrogen (174.4 kg/ha), medium levels of available phosphorus (25.8 kg/ha), and medium in available potassium 220.7 kg/ha also pH and Electrical

conductivity was neutral and normal.

The field experiment was laid out in factorial randomized block design with total fifteen treatment combinations consisting of three levels of row spacing and five levels of weed management replicated thrice during rabi season of the year 2021-2022. The treatments were assigned randomly to the respective plots in each replication. The details of the treatments of experiment are given as Planting method (P): Three (3):

P₁: 30 x 20 cm Normal Planting

P₂: 45 cm x 20 cm Normal Planting

P₃: 60 cm x 20 cm Normal Planting

Weed management (W): Five (5)

W₀: Weedy check

W₁: Hand Weeding and Inter Culture at 20 and 40 DAS

W₂: Pendimethalin @ 1.0 kg ha⁻¹ as pre-emergence + Quizalofop-P-ethyl @ 0.06 kg ha⁻¹ at 20 DAS

W₃: Pendimethalin @ 1.0 kg ha⁻¹ as pre-emergence + Hand Weeding and Inter Culture at 40 DAS

W₄: Pendimethalin @ 1.0 kg ha⁻¹ as pre-emergence + Quizalofop-P-ethyl @ 0.06 kg ha⁻¹ at 20 DAS + Hand Weeding and Inter Culture at 40 DAS.

Different characters' observations were documented at various intervals. According to Panse and Sukhatme's (1967) [15] description, the statistical analysis of the data was conducted using the method suitable for the randomized block design with factorial idea of the experiment.

Each net plot's delineated 1 m² area was used to count and record the number of monocots, dicots, and sedges at 20, 40 DAS, and harvest. The weed population was then expressed as plant m². Prior to statistical analysis, the weed population data underwent square root transformation due to significant variation (Gomez and Gomez, 1984) [6]. The weed samples were collected from 1.0 m² area and expressed as g m⁻² and finally at the time of harvest from entire net plot area of each plot and expressed as kg ha⁻¹. After removing the roots, the above ground plant parts and whole weed samples were first sun dried and finally oven dried at 65°C for 72 hours up to constant dry weight.

Results and Discussion

Plant Height

Row spacing had no significant effect on plant height at 30 and 90 days after sowing (DAS), but 60 cm x 20 cm spacing produced significantly taller plants than 30 cm x 20 cm spacing at 60 DAS (125.61 cm vs 121.03 cm) and at harvest (155.93 cm vs 152.10 cm), reflecting reduced inter-plant competition for light and moisture under wider spacing that supports greater internode elongation, particularly as canopy demand peaks and through pod-filling (Beulah & Umesha, 2022; Rathour *et al.*, 2025) [3, 17]. Weed management showed a consistent trend across all stages: the weedy check was significantly the shortest throughout (e.g., 118.39 cm at 60 DAS and 147.53 cm at harvest), while pendimethalin @ 1.0 kg ha⁻¹ (pre-emergence) + hand weeding and interculture at 40 DAS, and pendimethalin @ 1.0 kg ha⁻¹ (pre-emergence) + quizalofop-P-ethyl @ 0.06 kg ha⁻¹ at 20 DAS + hand weeding and interculture at 40 DAS, gave the tallest plants and remained statistically at par with each other from 30 DAS onward, since season-long weed suppression protects nitrogen and moisture availability during the crop's peak vegetative and reproductive growth phases, whereas unmanaged weeds impose compounding, season-long stress that progressively restricts height gain (Kalita *et al.*, 2023; Bista *et al.*, 2023) [9, 4].

Treatments	Plant height (cm)			
	30 DAS	60 DAS	90 DAS	At Harvest
Row spacing				
P1:30 x 20 cm	27.08	121.03	142.94	152.10
P2: 45 cm x 20 cm	27.24	123.01	141.75	152.28
P3: 60 cm x 20 cm	27.50	125.61	144.16	155.93
S.Em. $\pm$	0.12	1.33	1.93	1.93
C.D at 5%	0.43	3.15	3.39	3.04
Weed Management practices				
W0: Weedy check	26.81	118.39	136.44	147.53
W1: HW and IC at 30 DAS and 60 DAS	26.87	120.56	142.90	154.38
W2: Pendimethalin @ 1.0 kg ha ⁻¹ as PE + Quizalofop-P- ethyl @ 0.06 kg ha ⁻¹ at 20 DAS	27.01	123.03	144.95	156.22
W3: Pendimethalin @ 1.0 kg ha ⁻¹ as PE + HW and IC at 40 DAS	27.74	126.48	143.81	154.518
W4: Pendimethalin @ 1.0 kg ha ⁻¹ as PE + Quizalofop -P- ethyl @ 0.06 kg ha ⁻¹ at 20 DAS + HW and IC at 40 DAS	27.92	127.61	146.56	156.01
S.Em. $\pm$	0.23	1.74	3.87	1.595
C.D at 5%	0.55	4.07	4.37	3.93

Number of Branches per Plant

Treatments	No of Branches plant ⁻¹			
	30 DAS	60 DAS	90 DAS	At Harvest
Row spacing				
P1:30 x 20 cm	3.07	10.36	14.85	16.80
P2: 45 cm x 20 cm	2.97	10.57	15.25	17.18
P3: 60 cm x 20 cm	3.88	11.82	16.32	18.37
S.Em. $\pm$	0.29	0.49	0.44	0.47
C.D at 5%	0.33	0.72	0.76	0.62
Weed Management practices				
W0: Weedy check	2.53	9.78	13.69	15.65
W1: HW and IC at 30 DAS and 60 DAS	3.00	10.57	14.88	16.78
W2: Pendimethalin @ 1.0 kg ha ⁻¹ as PE + Quizalofop-P- ethyl @ 0.06 kg ha ⁻¹ at 20 DAS	3.17	10.94	15.67	17.68
W3: Pendimethalin @ 1.0 kg ha ⁻¹ as PE + HW and IC at 40 DAS	3.72	11.85	16.22	18.36
W4: Pendimethalin @ 1.0 kg ha ⁻¹ as PE + Quizalofop -P- ethyl @ 0.06 kg ha ⁻¹ at 20 DAS+ HW and IC at 40 DAS	4.11	11.72	16.89	18.80
S.Em. $\pm$	0.27	0.38	0.55	0.57
C.D at 5%	0.43	0.93	0.99	0.80

Row spacing significantly affected branching at every growth stage; P3: 60 cm x 20 cm consistently produced the most branches, reaching 18.37 plant⁻¹ at harvest versus 16.80 (P1:30 x 20 cm) and 17.18 (P2: 45 cm x 20 cm), the latter two being statistically at par. Weed management also significantly influenced branching throughout, rising from 15.65 (W0: Weedy check) to 18.80 (W4: Pendimethalin @ 1.0 kg ha⁻¹ as PE + Quizalofop -P- ethyl @ 0.06 kg ha⁻¹ at 20 DAS+ HW and IC at 40 DAS) at harvest, about 20% higher, with (W3: Pendimethalin @ 1.0 kg ha⁻¹ as PE + HW and IC at 40 DAS) and (W4: Pendimethalin @ 1.0 kg ha⁻¹ as PE + Quizalofop -P- ethyl @ 0.06 kg ha⁻¹ at 20 DAS+ HW and IC at 40 DAS) forming the highest, statistically similar group from the mid-vegetative stage onward. Wider spacing reduces competition for light and space among neighbouring plants, favouring release of apical dominance and greater axillary bud outgrowth, a typical dicot response to reduced crowding (Beulah & Umesha, 2022) ^[3]. At 30 x 20 cm, dense intra-row planting likely caused mutual shading that suppressed lateral branching in favour of primary-stem elongation. The progressive rise in branching with increasing weed-control intensity mirrors reduced competition for nitrogen and moisture, both essential for axillary meristem activation (Jangir *et al.*, 2018) ^[7]; because branch number underlies the number of silique-bearing sites, this advantage anticipates the corresponding gains later observed in silique number (Kadu & Korav, 2026) ^[8].

Yield Attributes

Number of siliques per plant

With the wider spacings, there was a significant increase in silique

number from 196.93 (P1:30 x 20 cm) to 220.90 (P3: 60 cm x 20 cm) a rise of approximately 12% and all three spacings were different from each other and significant. Weed management resulted in a near-linear increase from 178.18 (W0 Weedy Check) to 231.06 (W4: Pendimethalin @ 1.0 kg ha⁻¹ as PE + Quizalofop -P- ethyl @ 0.06 kg ha⁻¹ at 20 DAS+ HW and IC at 40 DAS) approximately 30% higher with (W3 Pendimethalin @ 1.0 kg ha⁻¹ as PE + HW and IC at 40 DAS) and (W4: Pendimethalin @ 1.0 kg ha⁻¹ as PE + Quizalofop -P- ethyl @ 0.06 kg ha⁻¹ at 20 DAS+ HW and IC at 40 DAS) statistically better than the lowest weed treatment (W0: Weedy check) and the lowest (W3: Pendimethalin @ 1.0 kg ha⁻¹ as PE + HW and IC at 40 DAS) was not significantly different from the highest (W4: Pendimethalin @ 1.0 kg ha⁻¹ as PE + Quizalofop -P- ethyl @ 0.06 kg ha⁻¹ at 20 DAS+ HW and IC at 40 DAS). A strong relationship was observed between developmental traits of branching and silique number and the trends of the two traits were similar (Beulah & Umesha, 2022) ^[3]. The wider spacing increased the amount of available space between plants for radiation during reproductive period, favoring flower retention and pod set, while the closer spacing may have resulted in more flower/pod abortion under mutual shading during the reproductive phase. In the case of integrated weed management, there was a significant increase which reflected on the protection of the reproductive sink capacity of the crop, as competition for nitrogen and moisture is most intense during flowering and early development of pods, with unchecked competition in W0: Weedy check evident by reduced flower to pod conversion of 20% or more, as reported by Kumar *et al.*, (2015) ^[10] and Kadu & Korav (2026) ^[8].

Treatments	No. of siliqua plant ⁻¹	Length of Siliqua (cm)	No. of seeds siliqua ⁻¹	Test weight 1000 (g)
Row spacing				
P1:30 x 20 cm	196.93	3.93	13.57	3.97
P2: 45 cm x 20 cm	204.60	4.47	14.30	4.31
P3: 60 cm x 20 cm	220.90	4.68	14.89	4.59
S.Em. $\pm$	5.77	0.22	0.38	0.18
C.D at 5%	6.67	0.29	0.74	0.31
Weed Management practices				
W0: Weedy check	178.18	3.73	12.95	3.86
W1: HW and IC at 30 DAS and 60 DAS	192.81	4.06	13.94	4.18
W2: Pendimethalin @ 1.0 kg ha ⁻¹ as PE + Quizalofop-P- ethyl @ 0.06 kg ha ⁻¹ at 20 DAS	212.03	4.45	14.23	4.39
W3: Pendimethalin @ 1.0 kg ha ⁻¹ as PE + HW and IC at 40 DAS	223.31	4.61	14.95	4.41
W4: Pendimethalin @ 1.0 kg ha ⁻¹ as PE + Quizalofop -P- ethyl @ 0.06 kg ha ⁻¹ at 20 DAS+ HW and IC at 40 DAS	231.06	4.98	15.18	4.62
S.Em. $\pm$	9.75	0.22	0.32	0.13
C.D at 5%	8.62	0.38	0.96	0.39

Length of Siliqua

Siliqua length increased significantly with increase in spacing, up to (P2: 45 cm x 20 cm) (4.47 cm) and P3: 60 X 20 CM(4.68 cm) which were not statistically different from each other, but both were significantly longer than P1: 30 x 20 cm (3.93 cm). Weed management increased the length from 3.73 cm (W0: Weedy check) to 4.98 cm (W4: Pendimethalin @ 1.0 kg ha⁻¹ as PE + Quizalofop -P- ethyl @ 0.06 kg ha⁻¹ at 20 DAS+ HW and IC at 40 DAS) which was significantly higher than W0 (Weedy Check) and W1: HW and IC at 30 DAS and 60 DAS with W2: pendimethalin @ 1.0 kg/ha as pe + quizalofop-p- ethyl @ 0.06 kg/ha at 20 DAS, W3: pendimethalin @ 1.0 kg/ha as pe + hw and ic at 40 DAS and W4 (Pendimethalin @ 1.0 kg ha⁻¹ as PE + Quizalofop -P- ethyl @ 0.06 kg ha⁻¹ at 20 DAS+ HW and IC at 40 DAS) being a similar group and significantly higher than W0 (Weedy Check). The length of siliqua is mostly dependent on the growth of cells during pod formation, and is influenced by the supply of assimilate and moisture, hence the smaller siliquae at close-row spacing is likely due to assimilate limitation by more intra row competition during pod-filling (Rathour *et al.*, 2025) [17]. A plateau between P2: 45 cm x 20 cm and P3: 60 x 20 cm indicates that there is a genotypic limit upon the attainment of a higher P3: 60 x 20 cm when competition is properly eased. Increasing in siliqua length with increasing weed control indicates the reduction in competition for moisture during the moisture sensitive elongation stage (Kadu & Korav, 2026) [8]; the decline in the difference between W1: HW and IC at 30 DAS and 60 DAS and W0: weedy check indicates that manual weeding alone may not be as effective as a series of herbicides to protect this trait as effectively as a series of herbicides (Kumar *et al.*, 2015) [10].

Number of Seeds per Siliqua

Seed number significantly rose from 13.57 (P1:30 x 20 cm) to 14.89 (P3: 60 x 20 cm); P2: 45 x 20 cm (14.30) was statistically similar to both. Seed number increased significantly from 12.95 (W0: weedy check) to 15.18 (W4: pendimethalin @ 1.0 kg/ha as pe + quizalofop -p- ethyl @ 0.06 kg/ha at 20 DAS + HW and IC at 40 DAS), approximately 17%, indicating a generally similar higher group of W1: HW and IC at 30 DAS AND 60 DAS, W4, with W0: weedy check significantly the lowest. Seeds set per

siliqua are dependent on the number of ovules that are fertilised and retained which is sensitive to assimilate supply around flowering (Beulah & Umesha, 2022) [3]. The higher light competition under the widest spacing probably resulted in higher abortion rates during this period, causing a decrease in net photosynthesis, while the wider spacing maintained a more favourable source/sink ratio. The reduction in seed number under the weedy check is similar to the depression observed in other seed-set components such as nitrogen and sulphur which are important for mustard reproductive development (Verma *et al.*, 2023) [19]; the small range among the four W treatment levels indicates that, by either control method, there is little variation in potential seed-set once weeds are adequately managed.

Test Weight

Spacing had a significant effect on test weight, which rose from 3.97 g (P1:30 x 20 cm) to 4.59 g (P3: 60 x 20 cm); spacing P2: 45 x 20 cm (4.31 g) was statistically similar to P3: 60 x 20 cm, which is significantly heavier than P1:30 x 20 cm. Test weight was significantly higher from 3.86 g (W0: weedy check) to 4.62 g (W4: pendimethalin @ 1.0 kg/ha as pe + quizalofop -p- ethyl @ 0.06 kg/ha at 20 DAS + HW and IC at 40 DAS) with a substantial improvement of approximately 20% in heavier weight in W4: pendimethalin @ 1.0 kg/ha as pe + quizalofop -p- ethyl @ 0.06 kg/ha at 20 DAS + HW and IC at 40 DAS, the weedy check, compared to W0: weedy check. The increased competition for light and moisture during this phase evidently reduced test weight, which indicates seed size and assimilate loading during grain filling in the closer spacing as compared to the wider spacing (Beulah & Umesha, 2022) [3]. This is in accordance to Brassica seed size being more influenced by per plant resource availability rather than population density since the crop adjusts for lower seed size with the increase in plant numbers under close spacing (Rathour *et al.*, 2025) [17]. The slight and steady improvements from W1: HW and IC at 30 DAS and 60 DAS to W4: pendimethalin @ 1.0 kg/ha as pe + quizalofop -p- ethyl @ 0.06 kg/ha at 20 DAS + HW and IC at 40 DAS suggest that protection of resources over time is more important than the control approach for seed weight, with the weedy check having a higher impact.

Yield

Treatments	Seed yield (kg ha ⁻¹)	Stover yield (kg ha ⁻¹)
Row spacing		
P1: 30 x 20 cm	790.37	3018.18
P2: 45 cm x 20 cm	1822.46	3996.50
P3: 60 cm x 20 cm	1311.53	3446.50
S.Em. ±	297.94	283.30
C.D at 5%	158.27	323.84
Weed Management practices		
W0: Weedy check	959.87	3116.02
W1: HW and IC at 30 DAS and 60 DAS	1178.15	3368.05
W2: Pendimethalin @ 1.0 kg ha ⁻¹ as PE + Quizalofop-P- ethyl @ 0.06 kg ha ⁻¹ at 20 DAS	1333.21	3407.83
W3: Pendimethalin @ 1.0 kg ha ⁻¹ as PE + HW and IC at 40 DAS	1456.80	3746.83
W4: Pendimethalin @ 1.0 kg ha ⁻¹ as PE + Quizalofop -P- ethyl @ 0.06 kg ha ⁻¹ at 20 DAS+ HW and IC at 40 DAS	1612.58	3785.77
S.Em. ±	112.60	125.45
C.D at 5%	323.84	418.08

Seed Yield

Seed yield was significantly influenced by row spacing, and P2: 45 x 20 cm produced significantly more yield (1822.46 kg ha⁻¹) than P3: 60 X 20 cm (1311.53 kg ha⁻¹) and P1: 30 x 20 cm (790.37 kg ha⁻¹), which was around 39% and 131% higher, respectively, while all three spacing had significant difference. Increased weed management resulted in an increase in seed yield from 959.87 kg ha⁻¹ (W0: Weedy check) to 1612.58 kg ha⁻¹ (W4: pendimethalin @ 1.0 kg/ha as pe + quizalofop -p- ethyl @ 0.06 kg/ha at 20 DAS + HW and IC AT 40 DAS) (ca. 68%), while W2: pendimethalin @ 1.0 kg/ha as pe + quizalofop-p- ethyl @ 0.06 kg/ha at 20 DAS, W3: pendimethalin @ 1.0 kg/ha as PE + HW and IC AT 40 DAS and W4: pendimethalin @ 1.0 kg/ha as pe + quizalofop -p- ethyl @ 0.06 kg/ha at 20 DAS + HW and IC at 40 DAS being a higher yield group were statistically similar with each other and at par with W1: HW AND IC AT 30 DAS AND 60 DAS and W4: pendimethalin @ 1.0 kg/ha as PE + quizalofop -p- ethyl @ 0.06 kg/ha at 20 DAS + HW and IC at 40 DAS, and W0: Weedy check and W1: HW AND IC AT 30 DAS AND 60 DAS remaining at comparatively lower level and at par with each other. The maximum yield of most yield attributes were recorded at the widest spacing, but the maximum seed yield per hectare was recorded at the intermediate spacing, as final yield depends on the yield performance of plants at a given spacing and plant population per hectare (Kumbhare *et al.*, 2025) [12]. The effects of the density were clearly seen in all the per-plant parameters at 30 x 20 cm, as it was clearly found that the density was having a negative effect on all the per plant parameters, whereas at 60 x 20 cm, the lower density was not compensated by better per plant performances of the crop and thus 45 x 20 cm was found as the optimum row and plant spacing where both the parts of the geometry were balanced which was in accordance with row spacing study in Brassica which suggested that an intermediate row spacing showed the maximum land use efficiency while the widest row spacing showed the least (Beulah & Umesha, 2022) [3]. The advantage in yield with W3: pendimethalin @ 1.0 kg/ha as pe + hw and ic at 40 das/w4: pendimethalin @ 1.0 kg/ha as pe + quizalofop -p- ethyl @ 0.06 kg/ha at 20 DAS + HW AND IC AT 40 DAS when compared to all other practices confirms the synergistic effect of weed competition as earlier reported in studies (Kumar *et al.*, 2015; Jangir *et al.*, 2018) [10, 7] that the integrated weed management (IWM) practices of pre-emergence pendimethalin and need based hand weeding is more effective in controlling the mixed weed flora of mustard than either of the two practices would be used as a single management. The observation that W0: Weedy check and W1: HW and IC AT 30 DAS and 60

DAS were not different suggest that a single hand-weeding/interculture weed management was not enough to outcompete the season-long weed, thereby supporting the integrated weed management rather than single-tactic weed management (Rao and Chauhan, 2015) [16].

Stover Yield

Stover yield was also space-wise, significantly greatest for P2: 45 CM X 20 CM (3996.50 kg ha⁻¹) followed by P3: 60 X 20 CM (3446.50 kg ha⁻¹) and P1: 30 X 20 CM (3018.18 kg ha⁻¹). The stover yield from this was significantly improved with weed management with yields of 3785.77 kg ha⁻¹ (W4: pendimethalin @ 1.0 kg/ha as pe + quizalofop -p- ethyl @ 0.06 kg/ha at 20 das + hw and ic at 40 das) approximately 21% higher than W0: Weedy check, weed-free treatment; W3: pendimethalin @ 1.0 kg/ha as pe + hw and ic at 40 das and w4: pendimethalin @ 1.0 kg/ha as pe + quizalofop -p- ethyl @ 0.06 kg/ha at 20 das + hw and ic at 40 das also significantly outperformed W0: Weedy check, with W1: HW and IC at 30 DAS AND 60 DAS and W2: pendimethalin @ 1.0 kg/ha as pe + quizalofop-p- ethyl @ 0.06 kg/ha at 20 das not significantly different from the weedy check. The seed- and stover-yield response to spacing was consistent; in both cases, 45 x 20 cm spacing was the most efficient combination of plant population and per-plant vegetative production (Rathour *et al.* 2025) [17]. The lower impact of weed management on that stover yield, compared to the LY, indicates that vegetative biomass is less sensitive to weed competition, whereas reproductive yield is more sensitive due to the relatively short window of opportunity to escape weed competition for reproduction (Bista *et al.*, 2023) [4]. The integrated pendimethalin (P) + quizalofop-Ethyl (Q) + hand-weeding (W4: pendimethalin @ 1.0 kg/ha as pe + quizalofop -p- ethyl @ 0.06 kg/ha at 20 das + hw and ic at 40 das) and the very similar pendimethalin (P) + hand-weeding (W3: pendimethalin @ 1.0 kg/ha as pe + HW and IC at 40 das) sequence is the most agronomically effective combination found in this study because of the concordant yield and biomass effects across the two treatments.

Conclusion

Results conclude that the widest spacing (60 cm x 20 cm) had better individual yield attributes, its spacing resulted in the lowest yield (1822.46 kg ha⁻¹) and lowest stover yield (3996.50 kg ha⁻¹), indicating that yield is dependent on plant population and per plant performance. The seed yield of pendimethalin @ 1.0 kg ha⁻¹ (pre-emergence) + quizalofop-P-ethyl @ 0.06 kg ha⁻¹ at 20 DAS + hand weeding and interculture at 40 DAS was about 68% higher

than weed control and was statistically at par with the same treatment without hand weeding and interculture at 40 DAS + hand weeding and interculture at 40 DAS. Hand weeding and interculture was not significantly better than weedy check. The interactions between the two factors were not significant. Mustard sown at 45 cm row x 20 cm spacing and pendimethalin 1.0 kg/ha (pre-emergence) + hand weeding and interculture practices at 40 DAS is recommended as higher yield with better agronomic efficiency and economical significance.

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