JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(4), 71–82
https://doi.org/10.12911/22998993/199731
ISSN 2299–8993, License CC-BY 4.0

Received: 2024.12.17
Accepted: 2025.01.31
Published: 2025.02.17

Optimizing weeding and plant density for improved quinoa yield and seed quality in fluvisol soils

Thiem Thi Tran[1*], Loan Thi Nguyen[1], Duy Hoang Vu[1], Roel Rodriguez Suralta[2]

[1] Faculty of Agronomy, Vietnam National University of Agriculture, Hanoi, Vietnam
[2] DA-Crop Biotechnology Center, Philippine Rice Research Institute (PhilRice), Maligaya, Science City of Muñoz, Nueva Ecija 3119, Philippines
* Corresponding author's e-mail: tranthiem@vnua.edu.vn

ABSTRACT

The eco-friendly weed management is a significant challenge for sustainable crop production because weed interference reduces yield and quality of a crop. Thus, the study was conducted to determine the effect of the frequency of hand weeding and planting densities on weed composition and nutrient uptake, seed yield and quality of quinoa. The field experiments were established in Ha Noi and Hung Yen, Vietnam in a randomized complete block design (RCBD) with three replications. The treatments include combination of hand weeding frequencies (W0: Un-weeded; W1: Hand weeding (HW) once at 20 days after sowing (DAS); W2: HW twice at 20 and 40 DAS; and W3: HW three times at 20, 40 and 60 DAS) and planting densities (D8: 8 plants m^{-2}; D10: 10 plants m^{-2}; D13: 13 plants m^{-2}; and D20: 20 plants m^{-2}, with a row distance of 50 cm and plant distances of 25, 20, 15, and 10 cm, respectively) of quinoa. The results showed that HW significantly reduced weed infestation, enhanced nutrient uptake of quinoa, and ultimately increased yield and quality of quinoa compared to un-weeded plot. The highest actual seed yield was recorded with HW twice or three times in both sites. On the other hand, planting density (PD) significantly reduced the weed composition and thus, enhanced nutrient uptake, yield and yield components of quinoa, and seed protein content in both sites. The optimal PD that effectively suppressed weeds and maximized quinoa yield and improved its seed quality was at 8–10 plant m^{-2}. This study suggests that the HW done at 20 and 40 DAS combined with PD of quinoa at 8–10 plant m^{-2} is the most efficient weed control strategy to improve quinoa production in fluvisol regions of Vietnam.

Keywords: hand weeding, plant density, weed biomass, nutrient uptake, quinoa

INTRODUCTION

Quinoa (*Chenopodium quinoa* Willd.) is considered an excellent source of nutrition and healthy food due to its protein quality, balanced amino acid composition and richness in essential minerals, vitamins and health-promoting compounds (Bertero et al., 2004; Afzal et al., 2023). Quinoa is also highly tolerant to abiotic stresses such as drought and salinity, and adapted to different agroecological zones, making it a good choice for enhancing food security in the face of climate change (Taaime et al., 2023). As a result, the interest in quinoa production and quinoa-derived foods has increased significantly in recent years. In 2022, quinoa was grown in 193.679 hectares of land with a total production of around 159.000 tons, an increase from 66.268 hectares and 55.000 tons in 2002 (FAOSTAT, 2024). Currently, quinoa is grown or being tested in over 125 countries (Bazile, 2023), indicating the global significance of this crop. In Vietnam, quinoa adapts well to different agro-ecological areas (Bertero et al., 2004; Minh et al., 2021a; Tran et al., 2024) and the current focus is to select suitable genotypes (Tran et al., 2024, Minh et al., 2021a) and study agronomic management such as fertilizer application and planting density optimization to improve seed yield (Minh et al., 2021a; Minh et al., 2021b). However, weed management for quinoa production has not been explored fully. The inclusion of quinoa into the agri-food system have many challenges, including weed infestation (Afzal et al., 2023). Heavy weed pressure in the early stages of quinoa growth causes significant growth stunting and substantial yield loss. In addition, some of the predominant weed species in quinoa growing areas belong to the same botanical family as the crop, making selective weed control difficult (Langeroodi et al., 2020). The use of herbicides is effective in controlling weeds and increasing crop yields, but there are concerns on herbicide residues in food, the development of herbicide resistance in weeds and environmental hazards (Jabran and Chauhan, 2018). Besides, there are no herbicides that are currently approved for use in quinoa production or availability of herbicide-tolerant varieties (Hanif et al., 2024).

The increasing emphasis on organic quinoa production created opportunities for research into ecological weed management strategies (Afzal et al., 2023). Manual weeding is a common method in quinoa production, although the frequency of weeding varies with the growing conditions (Taaime et al., 2023). In some cases, manual weeding is more efficient than either mechanical weeding or chemical control (Abbas et al., 2018). In quinoa, manual weeding is usually carried out in the early growth stage to minimize weed competition and is often repeated during the flowering stage (Cruces et al., 2024). Plant density (PD) is also an effective ecological strategy for suppressing weeds by minimizing crop – weed competition (Hanif et al., 2024), which also significantly increase seed yield and quality of quinoa (Eisa et al., 2018; Minh et al., 2021a). High PD suppressed weed growth via faster canopy closure of crop which limits space and light penetration needed for high weed growth (Vu and Ha, 2015; Tran et al., 2020; Hanif et al., 2024). However, higher PD of quinoa often leads to a decrease of its yield and quality due to the intra crop competition (Hanif et al., 2024). Therefore, optimum PD for quinoa must be established to ensure uniform availability of essential factors for the growth and maintaining the yield and quality of crop to minimize intra crop and crop-weed competition.

The trend of eco-friendly crop management practices is increasingly popular to increase crop production without harming the enviroment. Previous studies showed that HW combined with optimal PD suppressed weed growth and increased yield of crop (Kebede et al., 2015; Tran et al., 2020; Hanif et al., 2024). However, the effect of the combination of the weeding frequency and PD on yield and quality of crop is site specific due to the differences on weed species, kind of crops, soil characteristic and the prevailing climate conditions. Hence, this study evaluated the effects of the frequency of HW and PD on weed composition and biomass, and yield and quality of quinoa in different ecological regions of Vietnam, and to determine the optimal combination of the frequency of HW and PD that improved seed yield and quality of quinoa.

MATERIALS AND METHODS

Plant material and experimental site

This study used a quinoa variety, Cahuil, from Chile. This variety was selected as the most adapted cultivar in Ha Noi, Northern Vietnam (Tran et al., 2024). The field experiments were conducted between January 29th and May 18th, 2024, at the open field of Vietnam National University of Agriculture, Hanoi, Vietnam (21°00′18.7″N, 105°56′09.4″E), and at the experimental farm of Yen Phu Agricultural Service Cooperative, Hung Yen Province (20°53′12.1″N, 105°59′19.7″E). During the experiments, Ha Noi and Hung Yen received 349 and 251 mm of rainfall, respectively. Ha Noi and Hung Yen had average temperatures of 23.6 and 23.3 degrees Celsius, respectively. The soil types in two sites were classified as fluvisol, with some soil chemical analyses included in Table 1.

Experimental design and cultivation management

The experiments were laid out in RCBD with three replications for both two sites. The plot size was 30 m^2 (10×3 m). The treatments consisted of a combination of hand weeding frequencies (W0: Un-weeded; W1: hand weeding (HW) once at 20 days after sowing (DAS); W2: HW twice at 20 and 40 DAS; and W3: HW three times at 20, 40 and 60 DAS) and plant densities (D8: 8 plants m^{-2}; D10: 10 plants m^{-2}; D13: 13 plants m^{-2}; and D20: 20 plants m^{-2}, with a row distance of 50 cm and plant distances of 25, 20, 15, and 10 cm, respectively) of quinoa.

Fertilizers containing 1000 kg ha^{-1} microbial organic fertilizer, 120 N kg ha^{-1}, 100 P_2O_5 kg ha^{-1} and 100 K_2O kg ha^{-1} were applied. In both sites, the total amount of microbial organic fertilizer

Table 1. Soil properties of the two site field experiments before cultivation

Sites	pH	OM (%)	Available N (mg kg^{-1})	Available P (mg kg^{-1})	Exchangeable K (mg kg^{-1})
Ha Noi	6.42	2.15	44.8	134.6	98.5
Hung Yen	6.57	2.51	50.6	132.1	119.4

and P fertilizers were applied as basal prior to sowing. The N and K fertilizers were applied at half of the total amount before sowing. The remaining half of N and K fertilizers were applied at the panicle initiation stage. Three seeds per hill were sown manually at a depth of 2 cm and later were thinned to one seedling per hill at the 2–3 true leaves stage. Crop management practices, including irrigation, and pest and disease control, were done whenever necessary.

Data collection and measurements

Weed species composition were determined based on their botanical characteristics (Duong et al., 2022). The weeds were randomly collected within the five quadrats of 50 × 50 cm (0.25 m^2) placed in each plot to estimate the weed density. All weed samples were oven-dried at 70 °C until constant weight to record the weed biomass.

The experiment was terminated at physiological maturity. Five plants of quinoa from each plot were randomly selected and cut at the ground level. The number of panicles per plant, number of seeds per panicle, 1000-grain weight, and the weight of seeds per plant were recorded. The plant samples were oven-dried at 70 °C until constant weight before recording the dry weight. The remaining plant from each plot were harvested for the measurement of actual seed yield and expressed ton ha^{-1} at 14% grain moisture content.

The nutrient concentrations of the plant tissues were also quantified. The total N, P and K concentrations were determined by the Kjeldahl method, the ascorbic acid method using a spectrophotometer, and a flame photometer, respectively. Nutrient uptakes were calculated by multiplying the N, P and K tissue concentrations with their respective dry weights. The protein content of the quinoa seeds was calculated based on the N content, multiplied by a conversion factor of 6.25 (AOAC method). The total sugar content was quantified using the DNS method. The Bertrand method was used to determine the amount of reducing sugars and starch content was calculated based on the reducing sugars and the total sugar content in glucose. The lipid content was measured using Velp solvent extractors unit SER 148/6 (Italy) with Velp cellulose thimbles (33 × 80 mm) for 90 min, using petroleum ether with a boiling range of 40–60 °C, as the extraction solvent.

Statistical analysis

The analysis of variance (ANOVA) were conducted to determine significant effect of treatments ($p < 0.05$) for the measured traits using Minitab ver 16. Differences between treatment means were determined using the Tukey's Honest Significant Difference (Tukey's HSD) test at the 5% probability level.

RESULTS

Effect of weeding frequency and plant density on weed composition

The major weed species present in both experimental sites were *Eleusine indica* (L.) Gaertn, *Echinochloa colona* (L.) Link, *Cyperus rotundus* L., *Ageratum conyzoides* L., *Eclipta prostrata* L., *Physalis angulata* L., *Portulaca oleracea* L., *Alternanthera sessilis* (L.) DC. Additionally, weed species such as *Leptochloa chinensis* (L.) Nees, *Polygonum avicular* and *Rorippa indica* (L.) Hiern were presented only in Ha Noi while *Blumea lacera* (Burm.f.) DC was presented only in Hung Yen.

In both Ha Noi and Hung Yen sites, there was a significant interaction between the frequency of HW and PD on weed density and weed biomass (Table 2). The weed density and weed biomass were also significantly affected by both HW and PD of quinoa. The weed density and weed biomass were lowest in both W3 and D20. The increase in PD significantly reduced weed density and weed biomass in most HW treatments except on W3. In general, the weed density and weed biomass was not significantly different among PDs when HW was done at least twice (W2 and W3).

Table 2. Effect of the frequency of hand weeding and plant density on weed density and weed biomass

Weeding frequency, W/ Plant density, D (plant m^{-2})		Ha Noi		Hung Yen	
		Weed density (number m^{-2})	Weed biomass (g m^{-2})	Weed density (number m^{-2})	Weed biomass (g m^{-2})
W	W0	154.8^{a}	100.0^{a}	133.5^{a}	86.3^{a}
	W1	113.9^{b}	70.9^{b}	99.0^{b}	61.2^{b}
	W2	69.0^{c}	29.0^{c}	57.7^{c}	28.5^{c}
	W3	25.8^{d}	4.6^{d}	21.1^{d}	3.6^{d}
ANOVA		***	**	***	***
D	D8	106.2^{a}	59.8^{a}	89.0^{a}	51.4^{a}
	D10	96.9^{ab}	53.8^{ab}	85.7^{a}	47.6^{a}
	D13	85.9^{b}	47.7^{bc}	73.3^{b}	42.0^{b}
	D20	74.5^{c}	43.2^{c}	63.3^{c}	38.7^{b}
ANOVA		***	***	***	**
W0	D8	176.8^{a}	114.1^{a}	140.8^{ab}	94.6^{a}
	D10	163.7^{a}	105.5^{ab}	149.6^{a}	91.5^{ab}
	D13	149.6^{ab}	94.7bc	128.8^{a-c}	81.1^{a-c}
	D20	129.1^{bc}	86.1^{cd}	114.6^{cd}	78.1^{b-d}
W1	D8	130.4^{bc}	81.7^{cd}	116.5^{b-d}	70.7^{c-e}
	D10	121.9^{b-d}	74.1^{de}	109.1^{cd}	65.3^{de}
	D13	109.9^{c-e}	68.3^{de}	93.9d^{e}	58.9^{ef}
	D20	93.3^{d-f}	59.2^{e}	76.5^{ef}	50.0^{fg}
W2	D8	89.6^{e-g}	38.3^{f}	75.6^{e-g}	36.5^{gh}
	D10	73.3^{f-h}	30.3^{f}	61.9^{fh}	29.9^{h}
	D13	60.3^{gh}	23.9^{f}	51.3^{gh}	24.4^{h}
	D20	52.8^{h}	23.9^{f}	42.9^{h}	23.3^{h}
W3	D8	28.0^{i}	5.1^{g}	22.9^{i}	3.9^{i}
	D10	28.5^{i}	5.3^{g}	22.1^{i}	3.6^{i}
	D13	24.0^{i}	4.1^{g}	19.2^{i}	3.7^{i}
	D20	22.7^{i}	3.7^{g}	20.0^{i}	3.3^{i}
ANOVA		**	*	*	*

Note: *,** and *** indicate significant effect at 0.05, 0.01 and 0.001, respectively. Weeding treatments: W0: un-weeded; W1: hand weeding at 20 days after sowing (DAS); W2: hand weeding twice at 20 and 40 DAS; and W3: hand weeding thrice at 20, 40 and 60 DAS. Planting density treatments: D8: 8 plants m^{-2}; D10: 10 plants m^{-2}; D13: 13 plants m^{-2}; and D20: 20 plants m^{-2}. Means followed by the same letter in each column are not significantly different by Tukey's HSD at 0.05.

Effect of weeding frequency and plant density on nutrient uptake in quinoa

The N, P and K uptake of quinoa as affected by the frequency of HW and PD are shown in Table 3. There was a significant interaction between HW and PD on the nutrient uptakes in both sites. The N, P and K uptake was significantly affected by both the HW and PD treatments. Manual weeding regardless of frequency had higher the N, P and K uptake compared to un-weeded treatment (W0). The N, P and K uptake was the highest when manual weeding was done at least twice (W2 and W3), but no significant difference between W2 and W3. In both Ha Noi and Hung Yen sites, the N uptake in un-weeded (W0) and manually weeded once (W1) was significantly higher at highest planting density (D20) relative to D8 while in weeded plots twice or thrice (W2 or W3), the N uptake was significantly higher at D13 and D20 relative to D8. In Hanoi, the P uptake was significantly increased by PD at D20 in W3 only while in Hung Yen, the uptake was significantly increased in D20 in W1, in D13 and D20 in W2 and D20 in W3. Furthermore, K uptake in Ha Noi was generally and significantly increased in manually weeded plots especially at D13 and D20 while in Hung Yen, the trend was similar to that in

Table 3. Effect of frequency of hand weeding and planting density on nutrient uptake of quinoa

Weeding frequency, W/ Plant density, D (plant m^{-2})		Ha Noi			Hung Yen		
		N uptake (kg ha^{-1})	P uptake (kg ha^{-1})	K uptake (kg ha^{-1})	N uptake (kg ha^{-1})	P uptake (kg ha^{-1})	K uptake (kg ha^{-1})
W	W0	28.5^{c}	2.3^{c}	18.9^{c}	33.2^{c}	2.8^{c}	21.8^{c}
	W1	38.7^{b}	3.9^{b}	32.7^{b}	46.3^{b}	4.7^{b}	37.8^{b}
	W2	59.9^{a}	6.3^{a}	47.8^{a}	67.3^{a}	7.3^{a}	51.9^{a}
	W3	62.6^{a}	7.1^{a}	49.8^{a}	69.3^{a}	7.7^{a}	52.5^{a}
ANOVA		***	**	**	***	***	**
D	D8	37.2^{c}	4.0^{b}	29.0^{d}	41.5^{d}	4.4^{d}	32.1^{d}
	D10	44.2^{b}	4.7^{b}	34.6^{c}	49.0^{c}	5.1^{c}	37.9^{c}
	D13	48.5^{b}	4.8^{b}	38.4^{b}	56.1^{b}	5.9^{b}	41.7^{b}
	D20	59.9^{a}	5.7^{a}	47.1^{a}	69.4^{a}	7.1^{a}	52.2^{a}
ANOVA		***	***	**	***	**	**
W0	D8	22.7^{g}	1.9^{g}	14.6^{i}	24.7^{i}	2.1^{h}	16.2^{h}
	D10	26.9^{fg}	2.4^{g}	17.1^{i}	29.4^{hi}	2.6^{gh}	19.8^{h}
	D13	27.1^{fg}	2.1^{g}	19.6^{i}	34.7^{g-i}	3.0^{gh}	22.3^{gh}
	D20	37.4^{ef}	2.7^{fg}	24.2^{hi}	43.8^{e-g}	3.5^{f-h}	28.8^{fg}
W1	D8	31.2^{fg}	3.3^{e-g}	24.4^{hi}	37.0^{f-h}	3.9^{f-h}	27.9^{fg}
	D10	36.9^{ef}	4.0^{d-g}	29.8^{gh}	44.2^{e-g}	4.0^{e-g}	34.2^{ef}
	D13	39.1^{ef}	3.6^{d-g}	34.5^{fg}	46.7^{e-g}	5.2^{d-f}	38.9^{de}
	D20	47.8^{de}	4.8^{c-f}	42.0^{c-f}	57.2^{cd}	5.7^{de}	50.1^{bc}
W2	D8	46.5^{de}	5.3^{b-e}	37.4^{e-g}	51.3^{c-e}	5.7^{de}	41.2^{d}
	D10	56.8^{b-d}	5.9^{b-d}	45.8^{c-e}	60.2^{c}	6.5^{cd}	48.7^{bc}
	D13	61.3^{bc}	6.6^{bc}	48.9^{cd}	71.4^{b}	7.7^{bc}	52.4^{b}
	D20	75.1^{a}	7.3^{ab}	59.2^{ab}	86.4^{a}	9.4^{ab}	65.4^{a}
W3	D8	48.4^{c-e}	5.5^{b-e}	39.6^{d-g}	53.0^{c-e}	6.2^{cd}	43.3^{cd}
	D10	56.4^{b-d}	6.6^{bc}	45.6^{c-e}	62.2^{bc}	7.7^{bc}	48.8^{bc}
	D13	66.5^{ab}	6.9^{bc}	50.8^{bc}	71.7^{b}	8.0^{a-c}	53.2^{b}
	D20	79.2^{a}	8.2^{a}	63.1^{a}	90.2^{a}	9.1^{a}	64.6^{a}
ANOVA		*	*	*	*	*	*

Note: ns, not significant; *,** and *** indicate significant effect at 0.05, 0.01 and 0.001, respectively. Weeding treatments: W0: un-weeded; W1: hand weeding at 20 days after sowing (DAS); W2: hand weeding twice at 20 and 40 DAS; and W3: hand weeding thrice at 20, 40 and 60 DAS. Planting density treatments: D8: 8 plants m^{-2}; D10: 10 plants m^{-2}; D13: 13 plants m^{-2}; and D20: 20 plants m^{-2}. Means followed by the same letter in each column are not significantly different by Tukey's HSD at 0.05.

Ha Noi except that the increase in PD in W0 also increased P uptake especially at D20.

Effect of weeding frequency and plant density on yield components of quinoa

The yield and yield components of quinoa as affected by the frequency of HW and PD are presented in Table 4. The yield components and seed yield of quinoa was significantly affected by weeding frequency. In both conditions, W2 and W3 had significantly higher values on yield components than W1 and W0, except of the number of panicles per plant in Ha Noi. Similarly, the seed yield was highest at W3 and lowest at W0. There was no significant difference in the seed yield between W3 and W2. The increase in PD significantly reduced the yield components of quinoa such as the number of panicles per plant, number of seeds per panicle, weight of 1000 seeds and individual plant yield in both sites. However, actual yield increased initially from D8 to D10, then reduced gradually as PD increase to D20 and there was significant difference in that value among PDs.

In both Ha Noi and Hung Yen, there was a significant interaction between the HW frequency and PD on weight of 1000 grains, individual plant

Table 4. Effect of hand weeding and plant density on yield components and seed yield of quinoa

Weeding frequency, W/ Plant density, D (plant m^{-2})		Ha Noi					Hung Yen				
		NoP	NoS	W1000	IY	AY	NoP	NoS	W1000	IY	AY
W	W0	23.5^{b}	262.6^{c}	1.8^{c}	11.72^{c}	1.08^{c}	25.2^{c}	273.1^{c}	1.9^{c}	13.0^{c}	1.15^{c}
	W1	25.9^{a}	290.5^{b}	2.1^{b}	17.37^{b}	1.57^{b}	27.4^{b}	307.5^{b}	2.3^{b}	18.5^{b}	1.68^{b}
	W2	26.3^{a}	325.3^{a}	2.5^{a}	22.14^{a}	1.95^{a}	28.7^{a}	335.5^{a}	2.6^{a}	24.7^{a}	2.07^{a}
	W3	26.1^{a}	331.8^{a}	2.6^{a}	22.47^{a}	2.02^{a}	28.9^{a}	339.7^{a}	2.7^{a}	24.9^{a}	2.09^{a}
ANOVA		**	**	***	**	***	**	***	***	**	***
D	D8	27.0^{a}	334.4^{a}	2.5^{a}	23.18^{a}	1.67^{b}	29.4^{a}	343.3^{a}	2.7^{a}	25.2^{a}	1.75^{b}
	D10	26.6^{a}	318.8^{a}	2.4^{a}	21.90^{a}	1.75^{a}	28.5^{a}	330.0^{a}	2.6^{a}	24.2^{a}	1.85^{a}
	D13	24.8^{b}	289.1^{b}	2.2^{b}	16.28^{b}	1.65^{b}	26.7^{b}	298.7^{b}	2.3^{b}	18.1^{b}	1.73^{bc}
	D20	23.7^{c}	267.9^{b}	1.9^{c}	12.34^{c}	1.54^{c}	25.4^{c}	283.3^{b}	2.1^{c}	13.8^{c}	1.66^{c}
ANOVA		**	**	***	**	***	***	**	***	**	***
W0	D8	24.5	285.8	1.9^{fg}	13.48^{e-g}	0.95^{g}	26.5	293.7	2.1^{c-e}	15.0^{cd}	1.06^{ef}
	D10	24.3	281.3	1.9^{fg}	13.64^{e-g}	1.05^{fg}	25.7	288.7	2.1^{de}	14.9^{cd}	1.12^{gh}
	D13	22.9	253.1	1.8^{gh}	11.38^{f-h}	1.11^{fg}	24.5	263.3	2.0^{e}	12.9^{d}	1.16^{gh}
	D20	22.3	230.1	1.6^{h}	8.37^{h}	1.19^{f}	23.9	246.6	1.7^{f}	9.3^{e}	1.28^{g}
W1	D8	27.8	325.5	2.3^{cd}	22.58^{bc}	1.50^{e}	29.5	332.1	2.5^{b}	23.4^{b}	1.60^{ef}
	D10	27.3	315.1	2.2^{de}	20.95^{c}	1.57^{de}	28.6	325.0	2.4^{b-d}	22.0^{b}	1.75^{de}
	D13	25.3	278.9	2.0^{ef}	15.44^{de}	1.72^{cd}	26.6	298.2	2.3^{b-e}	16.7^{c}	1.86^{cd}
	D20	23.5	242.6	1.8^{gh}	10.53^{gh}	1.48^{e}	24.7	274.7	2.2^{b-e}	12.0^{de}	1.52^{f}
W2	D8	27.7	354.6	2.8^{a}	27.92^{a}	2.08^{ab}	30.9	371.9	3.0^{a}	30.7^{a}	2.13^{ab}
	D10	27.4	337.3	2.7^{ab}	26.37^{ab}	2.17^{a}	29.5	348.1	2.9^{a}	30.0^{a}	2.26^{a}
	D13	25.5	313.6	2.5^{bc}	19.23^{cd}	1.86^{c}	27.8	318.3	2.5^{bc}	21.4^{b}	1.98^{bc}
	D20	24.7	295.8	2.1^{d-f}	15.03^{ef}	1.71^{cd}	26.7	301.5	2.3^{b-e}	16.9^{c}	1.91^{cd}
W3	D8	27.8	371.6	2.9^{a}	28.75^{a}	2.16^{a}	30.7	375.3	3.1^{a}	31.6^{a}	2.22^{a}
	D10	27.2	341.5	2.8^{a}	26.63^{a}	2.21^{a}	30.2	358.1	2.9^{a}	29.9^{a}	2.28^{a}
	D13	25.3	310.9	2.5^{bc}	19.06^{cd}	1.92^{bc}	28.1	314.9	2.4^{b-d}	21.6^{b}	1.92^{cd}
	D20	24.2	303.1	2.2^{d-f}	15.45^{de}	1.79^{c}	26.4	310.3	2.3^{b-e}	17.0^{c}	1.94^{b-d}
ANOVA		ns	ns	*	**	***	ns	ns	*	**	**

Note: NoP: number of panicles per plant; NoS: number of seeds per panicle; W1000: weight of 1000 seeds; IY: individual yield (g plant^{-1}); AY: actual yield (ton ha^{-1}). ns, not significant; *,** and *** indicate significant effect at 0.05, 0.01 and 0.001, respectively. Weeding treatments: W0: un-weeded; W1: hand weeding at 20 days after sowing (DAS); W2: hand weeding twice at 20 and 40 DAS; and W3: hand weeding thrice at 20, 40 and 60 DAS. Planting density treatments: D8: 8 plants m^{-2}; D10: 10 plants m^{-2}; D13: 13 plants m^{-2}; and D20: 20 plants m^{-2}. Means followed by the same letter in each column are not significantly different by Tukey's HSD at 0.05.

yield, as well as actual yield, but not on number of panicles per plant and number of seeds per panicle. In un-weeded (W0), actual yield was significantly increased with the highest planting density (D20) at 1.19 and 1.28 tons ha^{-1} in Ha Noi and Hung Yen, respectively. In HW once (W1), actual yield was significant higher at D13 with 1.72 and 1.86 tons ha^{-1} in Ha Noi and Hung Yen, respectively. However, in HW done twice or thrice (W2 or W3), the actual yield was significantly higher at lower PD in D8 and D10, with a yield ranging from 2.08 to 2.21 tons ha^{-1} in Ha Noi and 2.13 to 2.28 tons ha^{-1} in Hung Yen.

Effect of weeding frequency and plant density on seed quality of quinoa

The seed quality of quinoa as affected by the frequency of HW and PD is shown in Table 5. In both sites, there was no significant interaction between the HW and PD on the protein, starch, lipid and sugar contents. The protein, starch, lipid and sugar contents were significantly affected by HW in both sites. These parameters were generally and significantly higher at manually weeded plots (W1, W2 and W3), relative to un-weeded plots (W0) in both sites. On the other hand, in Ha

Table 5. Effect of hand weeding and plant density on seed quality of quinoa

Weeding Frequency, W/ Plant density, D (plant m^{-2})		Ha Noi				Hung Yen			
		Protein (%)	Starch (%)	Lipid (%)	Sugar (%)	Protein (%)	Starch (%)	Lipid (%)	Sugar (%)
W	W0	13.45^{c}	54.32^{b}	2.96^{b}	1.17^{c}	14.16^{c}	56.82^{b}	3.17^{b}	1.22^{b}
	W1	15.18^{b}	57.62^{a}	3.58^{a}	1.26^{b}	16.05^{b}	60.17^{a}	3.60^{a}	1.26^{b}
	W2	15.94^{ab}	57.76^{a}	3.70^{a}	1.34^{a}	16.87^{a}	61.23^{a}	3.70^{a}	1.40^{a}
	W3	16.57^{a}	58.28^{a}	3.67^{a}	1.33^{a}	17.04^{a}	61.49^{a}	3.73^{a}	1.40^{a}
D	D8	16.24^{a}	57.17	3.46	1.30^{a}	16.66^{a}	60.36	3.57	1.34
	D10	15.62^{ab}	57.14	3.53	1.29^{a}	16.35^{ab}	60.39	3.56	1.32
	D13	15.07^{b}	56.66	3.48	1.26^{b}	15.93^{b}	59.71	3.52	1.32
	D20	14.21^{c}	57.01	3.44	1.25^{b}	15.18^{c}	59.25	3.55	1.30
W		*	*	*	*	**	*	*	*
D		*	ns	ns	*	*	ns	ns	ns
W × D		ns	ns	ns	ns	ns	ns	ns	ns

Note: ns, not significant; *,** and *** indicate significant effect at 0.05, 0.01 and 0.001, respectively. Weeding treatments: W0: un-weeded; W1: hand weeding at 20 days after sowing (DAS); W2: hand weeding twice at 20 and 40 DAS; and W3: hand weeding thrice at 20, 40 and 60 DAS. Planting density treatments: D8: 8 plants m^{-2}; D10: 10 plants m^{-2}; D13: 13 plants m^{-2}; and D20: 20 plants m^{-2}. Means followed by the same letter in each column are not significantly different by Tukey's HSD at 0.05.

Noi, PD reduced the protein and sugar contents especially at D20 while in Hung Yen, it was only the protein content which was reduced at higher PDs (D13 and D20).

Relationship between weed biomass and nutrient uptake in plant and seed yield of quinoa

The relationship between weed biomass with N, P and K uptake in quinoa was negative and significant in both sites (Figure 1). The increase in weed biomass generally reduced the N, P and K uptake of quinoa. Furthermore, the weed biomass was negative and significant related to seed yield of quinoa in both Ha Noi and Hung Yen (Figure 2) indicating that an increase in weed biomass can reduce significantly the yield of quinoa.

DISCUSSION

Weed composition

Generally, the weed composition was higher in Ha Noi than in Hung Yen site. This may be due to the differences in crop grown prior to the experiment in Ha Noi (corn) and Hung Yen (bittergourd), and the differences in the total rainfall received (349 mm in Ha Noi versus 251 mm in Hung Yen). Kebede et al. (2015) reported that a higher number of weed species and higher weed density occur with higher rainfall. In addition, altitude, weed seed bank on soil surface, soil type may be some of the reasons for the difference in weed composition between sites (Kebede et al., 2015; Manaswini et al., 2020).

Weed density and biomass were generally affected by the frequency of manual weeding and PD of a crop (Kebede et al., 2015; Tran et al., 2020, Maimunah et al., 2021). In this study, the increase in the frequency of HW have effectively reduced the weed density and biomass in both sites, similar to previous findings by Kebede et al. (2015), Vu and Ha, (2015) and Tran et al. (2020), which showed that one or two manual weeding significantly reduced weed density and biomass relative to un-weeded plot. The growth and development of weeds can be suppressed by PD of a crop if properly done. In this study, the increase in PD reduced weed density and biomass due to the increase in population of quinoa plant per unit area which closed the canopy quickly and thus limit space and reduce light penetration for weed growth. Kebede et al. (2015) reported that weed suppression was effective with narrower plant spacing in bean, since weeds under wider spaced crop planting have more space for growth and development, leading to more accumulation weed biomass as opposed to those under narrow spaced crop planting. In this study, at lower PDs, there

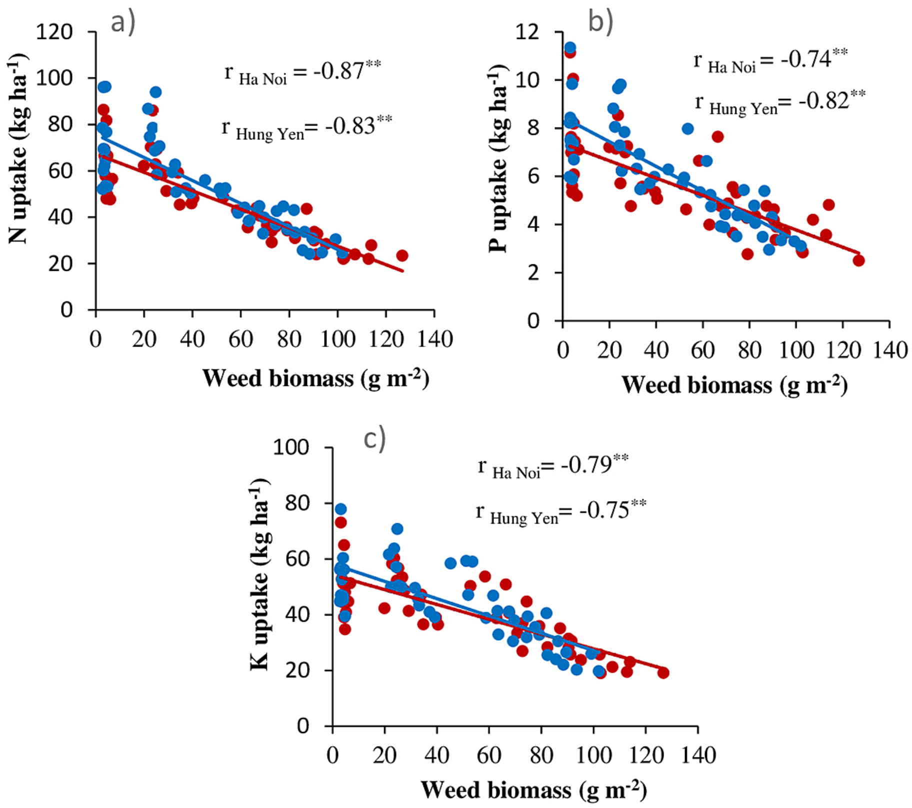

Figure 1. Relationship between nutrient uptake of quinoa and weed biomass

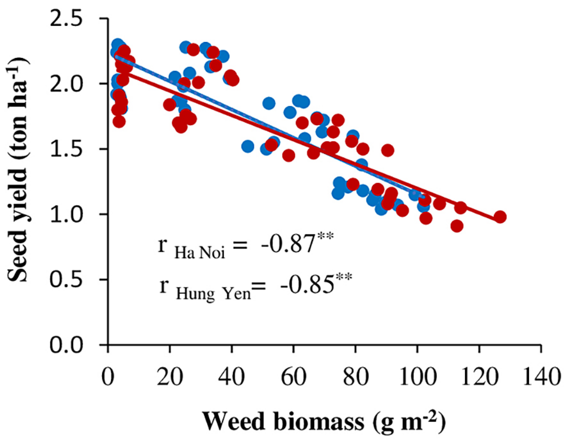

Figure 2. Relationship between seed yield of quinoa and weed biomass

was no significantly difference in weed density and biomass between D8 and D10 maybe due to the slower canopy closure of crop under these PDs that allows weed to receive ample light, and space and nutrients for the weeds' maximal growth.

Nutrient uptake in quinoa

Crop cultural practices such as weeding and optimum PD can reduce weed infestation, and thus the minimize crop–weed competition, resulting in higher nutrients uptake of crop from the soil (Sinchana et al., 2020; Maimunah et al., 2021). In this study, HW significantly improved N, P and K uptake of quinoa compared to un-weeded check, similar to the findings of Sinchana et al. (2020) and Maimunah et al. (2021). Moreover, in un-weeded check, weed removed large amount of nutrients from the soil for accumulating their biomass, which leads to the less nutrient uptake of cowpea (Sinchana et al., 2020). In this study, manual weeding three times (W3) had the highest uptake of N, P and K in quinoa. However, there were no significant difference in nutrient uptakes between W2 and W3. Maimunah et al. (2021) reported that increasing frequency of weeding from 0 to 8 times increased N uptake in rice, but no significant difference among frequency of weeding at 4, 6 or 8 times. In addition, weed absorbed more N than crop therefore, decreasing weed density and biomass is necessary to supply more N to the crop (Maimunah et al., 2021). Interestingly, the relationship between nutrient (N, P, and K) uptake of quinoa and weed biomass was negative in both sites (Figure 1), indicating that the frequency of weeding contribute positively to the increase in nutrient uptake efficiency in crop due to minimal crop-weed competition for soil nutrient (Maimunah et al., 2021).

The nutrient uptake of crop itself was also affected by PD due to a possible intra crop competition in addition to crop-weed competition. Nandhakumar et al. (2020) reported that increasing PD increased the N, P and K uptake in rice. However, according to Zhang et al. (2021), nutrient uptake may increase with optimal PD but may reduce gradually with further increase in PD. In this study, the increase in PD significantly increased the uptake of nutrients (N, P, and K) in quinoa with highest nutrient uptake at the highest PD in both sites, which were directly related to their shoot dry matter and nutrient content.

Yield and yield components of quinoa

Previous studies showed that the weeding suppressed weed growth and reduced its nutrient uptake which consequently improved soil chemical properties and microbial population (Manaswini et al., 2020) and increased nutrient uptake by the crop (Sinchana et al., 2020; Maimunah et al., 2021), and ultimately increased their yield (Sinchana et al., 2020; Debela et al., 2023; Hanif et al., 2024). In this study HW generally prevented weed growth and thus provide the opportunity for quinoa to absorb more nutrient to help increase its seed yield compared to un-weeded in both sites (Tables 4). The manual weeding done at least once significantly increased yield components and seed yield of quinoa, although no significant differences in yield components, and seed yield between W2 and W3. This suggests that manual weeding twice at 20 and 40 DAS may be the optimum weed management for quinoa. Nurse et al. (2016) reported that the critical weed-free period for quinoa is less than 30 days after emergence but may slightly vary with different genotypes and origin of each weed species. Cruces et al. (2024) suggested that manual weeding should be done at the early vegetative growth stage and repeated during the flowering stage. Furthermore, the result of systematic review for weed management in quinoa showed that frequencies of manual weeding for quinoa may vary with growing conditions and soil characteristics (Taaime et al., 2023).

The increase in PD has been reported to reduce the number of panicles per plant, number of seeds per panicle, 1000 grain weight and individual plant yield, but generally increased seed yield of quinoa due to the increased in number of plants per unit area (Eisa et al., 2018; Rabbani et al., 2022). However, previous studies showed conflicting reports. Some have reported no difference in quinoa seed yield with increasing densities from 10 to 16 plants m^{-2} (Spehar and Rocha, 2009), while other reported a decrease in seed yield with an increase in density from 10 to 33 plants m^{-2} (Jbawi et al., 2022). In this study, the number of panicles per plant, the number of seeds per panicle, 1000 grain weight and individual plant yield decreased with increase in PD while actual yield increased initially from 8 plants m^{-2} to 10 plants m^{-2}, then reduced gradually as PD was increased to more than 10 plants m^{-2}. The optimum PD can reduce intra crop competition as well as crop–weed competition (Lu et al. 2024), leading to an increased photosynthetic efficiency in crop (Zhang et al., 2021), improved nutrient uptake of plant (Zhang et al., 2021; Lu et al., 2024), and increased in dry matter production (Hanif et al. 2024) and crop yield (Zhang et al., 2021; Lu et al., 2024). However, the optimal PD that ensure high quinoa seed yield and quality can be affected by multiple factors, like climatic conditions, soil characteristics, genotypes, and cultural management practices (Minh et al., 2020; Jbawi et al., 2022; Laouedj et al., 2023; Taaime et al., 2023). Previous studies reported that the optimal PD of quinoa is 8 plants m^{-2} on red basalt soil of Vietnam (Minh et al., 2020), 10–13 plants m^{-2} in Syria (Jbawi et al., 2022), and 17 plants m^{-2} on Aridisol of Pakistan (Hanif et al., 2024). In this study, the PD of 8–10 plants m^{-2} was optimal to suppress weed growth and improve the seed yield and quality in fluvisol regions. The present study also showed negative correlation between the seed yield of quinoa and weed biomass (Figure 2) indicating that effective weed control can improve yield in crops (Sowin'ski et al., 2023).

In both sites, actual yield in W0 was significantly increased with highest planting density at 20 plants m^{-2} (1.19 and 1.28 tons ha^{-1} in Ha Noi and Hung Yen, respectively) while, manual weeding twice (W2) or thrice (W3), significantly increased actual yield at 8 plants m^{-2} and 10 plants m^{-2} (2.08–2.21 tons ha^{-1} in Ha Noi and 2.13–2.28 tons ha^{-1} in Hung Yen). This result indicated that in un-weeded condition, quinoa could be grown at a PD of 20 plants m^{-2} to suppress weed growth and increase seed yield of quinoa while in HW done at least twice, PD of 8–10 plant m^{-2} is economically viable and eco-friendly weed management strategy, allowing quinoa to maximize utilization of available resources, to improve nutrient uptake and ultimately increase its seed yield and quality.

Weed control in quinoa production is the one of most difficult operations, because there are currently no recommended herbicides registered and recommended for use, and hence, weeding is done manually (Damiani et al., 2019; Taaime et al., 2023; Hanif et al., 2024). In addition, quinoa is also marketed as a nutritious food, and hence, the use of herbicides is discouraged because it could negatively impact its quality. Furthermore, in developing countries such as Vietnam, where quinoa has just been introduced and thus mechanization remains limited but agricultural labor is abundant and cheap, manual weeding is still widely practiced, especially in organic farming. Optimizing the frequency of manual weeding and planting density can help reduce labor and costs in quinoa cultivation. Therefore, HW done twice combined with PD at 8–10 plants m^2 can be a realistic solution at the current situation in developing countries. However, in larger quinoa production areas with high labor cost, one-time manual weeding at higher plant densities can be cost-effective, as the faster canopy closure prevents significant weed regrowth without compromising yield. Additionally, it is also anticipated that in larger quinoa production areas, a mechanical method of weeding will be developed and will replace the manual weeding. This will expectedly decrease the cost of production and increase income in quinoa production systems.

This study also showed that seed yield of quinoa was generally higher in Hung Yen than in Ha Noi. This may be attributed to the differences in weed composition and soil characteristic between sites. Generally, the soil chemical properties were higher in Hung Yen than in Ha Noi. Although the soil in both sites was classified as fluvisol, but it was more of silty loam in Ha Noi and loam in Hung Yen. Quinoa is generally adapted to different soil types, but it grew well under loam condition with high organic matter (Taaime et al., 2023).

Seed quality of quinoa

Quinoa seeds have a high nutritional value but varies with variety (Tran et al., 2024) and other external factors, such as weed management (Jacobsen et al., 2010) and PD (Sief et al., 2015; Eisa et al., 2018; Minh et al., 2020). The seed quality of quinoa was high when weeds are suppressed, but reduced significantly when weeds are not controlled (Jacobsen et al., 2010). In this study HW have greater seed quality of quinoa in terms of increased content of protein, starch, sugar and lipid than those in un-weeded plots in both sites (Table 5). This is because under HW, the increase in seed quality was related to reduced weed density and weed biomass, reduced the crop-weed competition for light, water, nutrient and improved nutrient uptake in quinoa. The optimal period of controlling weed plays an important role in increasing quality and yield of crops (Hussain et al., 2015). In this study, although HW three times had the highest protein, starch, sugar and lipid content in seeds, the results with HW twice indicated that the most efficient frequency of manual weeding for sustaining quinoa seed quality can be done twice at 20 and 40 DAS. Previous studies reported that the content of protein and ash were significant higher at lower PDs but had similar fat and starch contents (Eisa et al., 2018; Minh et al., 2020). However, Nguyen et al. (2016) reported that protein and lipid concentrations as well as ash, fiber and sugar concentrations were similar among PDs. In this study, the seed quality of quinoa in terms of protein, starch, lipid and sugar concentrations were also significantly higher at lower PDs but only the content of protein (in both sites) and sugar concentrations (in Ha Noi) were significantly different among PDs. The higher seed quality of quinoa under lower PD may be due the less intra crop competition for limited available resources.

CONCLUSIONS

This study showed that manual weeding is efficient in suppressing weed growth, improving the nutrient uptake, and increasing the yield and seed quality of quinoa compared to un-weeded check. The highest actual seed yield was recorded in manual weeding done three times in both sites. However, the manual weeding done twice to ensure higher yield in quinoa was a feasible weed control strategy because of increasing labour scarcity in agriculture. Planting density significantly affected weed density and weed biomass, nutrient uptake of quinoa, yield and yield components of quinoa, and protein content, but did not significantly affect the starch, lipid and sugar contents. The optimal PD for the highest seed yield and quality of quinoa is at 8–10 plant m^{-2}. Hence, the manual weeding done at 20 and 40 DAS combined with PD of quinoa at 8–10 plant m^{-2} was the most efficient weed control strategy to improve quinoa production in fluvisol regions of Vietnam. Although these practices may incur higher labor costs and time investments, it can lead to significant benefits in terms of effective weed control, increased crop yield and quality in a sustainable way.

REFERENCES

1. Abbas, T., Zahir, Z. A., Naveed, M., & Kremer, R. J. (2018). Limitations of existing weed control practices necessitate development of alternative techniques based on biological approaches. *Advances in Agronomy, 147,* 239–280. doi:10.1016/bs.agron.2017.10.005
2. Afzal, I., Haq, M. Z. U., Ahmed, S., Hirich, A., & Bazile, D. (2023). Challenges and perspectives for integrating quinoa into the agri-food system. *Plants*, *12*(19), 3361. https://doi.org/10.3390/plants12193361
3. Bazile, D. (2023). Global trends in the worldwide expansion of QuinoaCultivation. *Biology and Life Sciences Forum, 13*. https://doi.org/10.3390/blsf2023025013
4. Bertero, H., Vega, A. D L., Correa, G., Jacobsen, S., & Mujica, A. (2004). Genotype and genotype-by-environment interaction effects for grain yield and grain size of quinoa (*Chenopodium quinoa* Willd.) as revealed by pattern analysis of international multi-environment trials. *Field Crops Research, 89*(2–3), 299–318. https://doi.org/10.1016/j.fcr.2004.02.006
5. Debela, C., Tola, M., Abera, G., & Mogasa, E. (2023). Effect of hand weeding frequency and pre-emergence herbicide on weed control in Soybean [(*Glycine max* L.) Merrill] at Bako, Western Ethiopia. *Agricultural Research & Technology: Open Access Journal, 27*(3). https://doi.org/10.19080/ARTOAJ.2023.27.556380
6. Cruces, L., de la Peña, E., & De Clercq, P. (2024). Advances in the Integrated Pest Management of Quinoa (*Chenopodium quinoa* Willd.): A global perspective. *Insects*, *15*(7), 540. https://doi.org/10.3390/insects15070540
7. Duong, V. C., Suk, J. K., Hoang, V., Ho, L.T., Do, T.K.A., Tran, V. P., Nguyen, X. H., Ha, T.T. B., Vu, D.H., Nguyen, V.T. & Nguyen, V.L. (2022). Common weeds in Vietnam. *Agricultural Publishing House* (in Vietnamese).
8. Eisa, S.S., El-Samd, E.H. A., Hussin, S.A., Ali, E.A., Ebrahim, M., González, J.A., Ordano, M., Erazzú, L.E., El-Bordeny, N.E., & Abdel- Ati, A.A. (2018). Quinoa in Egypt – Plant density effects on seed yield and nutritional quality in Marginal regions. *Middle East Journal of Applied Sciences, 8*(2), 515–522
9. FAOSTAT (2024). Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat/en/#data/QCL
10. Hanif, M.K., Afzal, I., Munir, M. K., Khaliq, A., & Asghar, H.N. (2024). Enhancing productivity and profitability of quinoa through optimization of plant spacing and weeding regimes. *Field Crops Research*, *315*. https://doi.org/10.1016/j.fcr.2024.109453
11. Hussain, S., Khaliq, A., Matloob, A., Fahad, S., & Tanveer, A. (2015). Interference and economic threshold level of little seed canary grass in wheat under different sowing times. *Environmental Science and Pollution Research*, *22*(1), 441–449. https://doi.org/10.1007/s11356-014-3304-y
12. Jabran, K., Chauhan, B.S. (2018): Chapter 1 - Overview and Significance of Non-Chemical Weed Control, in: Jabran, K., Chauhan, B. S. (eds.): Non-Chemical Weed Control. Academic Press, 1–8.
13. Jacobsen, S.E., Christiansen, J.L., & Rasmussen, J. (2010). Weed harrowing and inter-row hoeing in organic grown quinoa (*Chenopodium quinoa* Willd.). *Outlook on Agriculture*, *39*(3), 223–227. https://doi.org/10.5367/oa.2010.0001
14. Jbawi, A.E., Othman, M., Hunnish, A.T., & Abbas, F. (2022). The effect of plant density on growth and seed yield of quinoa (*Chenopodium quinoa* Willd.) in the middle region of Syria. *International Journal of Phytology Research, 2*(1), 19–24. https://doi.org/10.13140/RG.2.2.36733.84967
15. Kebede, M., Sharma, J. J., Tana, T., & Nigatu, L. (2015). Effect of plant spacing and weeding frequency on weed infestation, yield components, and yield of Common Bean (*Phaseolus vulgaris* L.) in Eastern Ethiopia. *East African Journal of Sciences, 9*(1), 1–14.
16. Langeroodi, A.r.S., Mancinelli, R., & Radicetti, E. (2020). How do intensification practices affect weed management and yield in Quinoa (*Chenopodium quinoa* Willd) Crop? *Sustainability*, *12*(15), 6103. https://doi.org/10.3390/su12156103
17. Laouedj, H., Kherraz, K., Touati, S., Messoudi, M., Ghemam Amara, D., & Kadour, A. (2023). Effect of planting density on *Chenopodium quinoa* Willd growth and yield in desert areas. *NeuroQuantology, 21*(1), 1002–1011. https://doi.org/10.48047/nq.2023.21.01.NQ20077
18. Lu, Y., Ma, R., Gao, W., You, Y., Jiang, C., Zhang, Z., Kamran, M., & Yang, X. (2024). Optimizing the nitrogen application rate and planting density to improve dry matter yield, water productivity and N-use efficiency of forage maize in a rainfed region. *Agricultural Water Management,* 305. https://doi.org/10.1016/j.agwat.2024.109125
19. Maimunah, M.A., Kautsar, V., Bimantara, P.O.,

Kimani, S.M., Torita, R., Tawaraya, K., Murayama, H., Utami, S.N.H., Purwanto, B.H., & Cheng, W. (2021). Weeding frequencies decreased rice–weed competition and increased rice N uptake in organic paddy field. *Agronomy*, 11. https://doi.org/10.3390/agronomy11101904

20. Manaswini, M., Laxminarayana, K., & Nedunchezhiyan, M. (2021). Influence of weed management practices on soil microbial activities and corm yield of elephant foot yam (*Amorphophallus paeoniifolius*) in alfisols of Coastal Odisha. *Journal of the Indian Society of Coastal Agricultural Research, 39*(1), 66–77. https://cabidigitallibrary.org

21. Minh, N.V., Hoang, D.T., Van Loc, N., & Long, N.V. (2020). Effects of plant density on growth, yield and seed quality of quinoa genotypes under rainfed conditions on red basalt soil regions. *Australian Journal of Crop Science, 14*(12), 1977–1982. https://doi.org/10.21475/ajcs.20.14.12.2849

22. Minh, N.V, Hoang D.T, Loc N.V & Long N.V. (2021a). Effects of plant density on growth, yield and seed quality of quinoa genotypes under rainfed conditions on red basalt soil regions. *Australian Journal of Crop Science, 14*(12), 1977-1982. https://doi.org/10.21475/ajcs.20.14.12.2849.

23. Minh, N.V, Hoang D.T, Anh D.T.P & Long N.V. (2021b). Effect of nitrogen and potassium on growth, yield, and seed quality of quinoa in ferralsols and acrisols under rainfed conditions. *Journal of Ecological Engineering, 23*(4), 164–172. https://doi.org/10.12911/22998993/14651

24. Nandhakumar, M. R., Velayudham, K., and Thavaprakaash, N. (2020). Nutrient uptake and soil health as influenced by plant density and age of seedlings of rice (*Oryza sativa* L.) under Modified SRI Method of Planting. *International Journal of Current Microbiology and Applied Sciences, 9*(8), 2809–2822.

25. Nguyen, I.T., Tran, T.T., Nguyen, T.C., Ton, T.S. (2016). Effect of nitrogen rate and plant density on yield of quinoa (*Chenopodium quinoa* Willd). *Soil Science*. 49, 32–37.

26. Nurse, R.E., Obeid, K., & Page, E.R. (2016). Optimal planting date, row width, and critical weed-free period for grain amaranth and quinoa grown in Ontario, Canada. *Canadian Journal of Plant Science, 96*(3), 360–366. https://doi.org/10.1139/cjps-2015-0160

27. Rabbani, B., Khoramivafa, M., Saeidi, M., Zarei, L., & Bagheri, M. (2023). The effect of sowing date and planting density on grain yield and some nutritional quality characteristics of three seed-quinoa genotypes. *Journal of Plant Physiology and Breeding, 2023*(2), 197–215.

28. Sief, A.S., El-Deepah, H.R.A., Kamel, A.S.M., & Ibrahim, J.F. (2015). Effect of various inter and intra spaces on the yield and quality of quinoa (*Chenopodium quinoa* Willd.). *Journal of Plant Production (Mansoura University), 6*(3), 371–383.

29. Sinchana, J.K., Raj, S.K., & Girijadevi, L. (2020). Nutrient uptake by crop and weed as influenced by the weed management practices in bush type vegetable cowpea, Vigna unguiculata sub sp. unguiculata (L.) Verdcourt. *Journal of Crop and Weed, 16*(2), 210–218. https://doi.org/10.22271/09746315.2020.v16.i2.1339

30. Spehar, C., & Rocha, J. (2009). Effect of sowing density on plant growth and development of quinoa, genotype 4.5, in the Brazilian Savannah Highlands. *Bioscience Journal*, *25*, 53–58.

31. Taaime, N., Rafik, S., El Mejahed, K., Oukarroum, A., Choukr-Allah, R., Bouabid, R., & El Gharous, M. (2023). Worldwide development of agronomic management practices for quinoa cultivation: a systematic review. *Frontiers in Agronomy*, *5*. https://www.frontiersin.org/journals/agronomy/articles/10.3389/fagro.2023.1215441

32. Tran, T.T., Thieu, T.P.T., & Nguyen, T.L. (2020). Effect of plant density and hand weeding on weed control and yield of the vegetable corn. *Vietnam Journal of Agricultural Sciences, 3*(4), 784–797. https://doi.org/10.31817/vjas.2020.3.4.02

33. Tran, T.T, Nguyen, T.L, Vu, H.T.T., & Nguyen, L.V. (2024). Variation in agronomic and grain nutritional traits of quinoa (*Chenopodium quinoa* Willd.) cultivars. *Journal of Bangladesh Agricultural University, 22*(1), 60–71. https://doi.org/10.5455/jbau.179790

34. Vu, D.H., & Ha, T.T.B. (2015). Effect of maize-soybean intercropping and hand weeding on weed control. *Journal of Sciences and Development, 13*(3), 354–363.

35. Wang, N., Wang, F., Shock, C.C., Meng, C., & Qiao, L. (2020). Effects of Management Practices on Quinoa Growth, Seed Yield, and Quality. *Agronomy*, *10*(3), 445. https://doi.org/10.3390/agronomy10030445

36. Zhang, Y., Xu, Z., Li, J., & Wang, R. (2021). Optimum planting density improves resource use efficiency and yield stability of rainfed maize in semiarid climate. *Frontiers in Plant Science, 12*. https://doi.org/10.3389/fpls.2021.752606