PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 12(1): 1-11
https://doi.org/10.14719/pst.4750

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RESEARCH ARTICLE

Comparative analysis of weed management techniques in taro (*Colocasia esculenta* (L.) Schott)

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OPEN ACCESS

ARTICLE HISTORY

Received: 21 August 2024
Accepted: 28 September 2024

Available online
Version 1.0 : 23 December 2024
Version 2.0 : 01 January 2025

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
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Paul S, Rahman M H, Tamanna M, Halder D, Kobir M S, Munshi M H, Hajong P, Anwar M B. Comparative analysis of weed management techniques in taro (*Colocasia esculenta* (L.) Schott). Plant Science Today. 2025; 12(1): 1-11. https://doi.org/10.14719/pst.4750

Abstract

Weed management poses a significant challenge in taro cultivation since it's a long-duration crop grown during the monsoon season. The warm, humid conditions of its extended growing period promote rapid weed germination and growth, complicating weed management efforts. To address this issue, a study was conducted at the Bangladesh Agricultural Research Institute, Jashore, in 2021 and 2022 to evaluate sustainable weed management strategies for taro. The experiment, designed as a randomized complete block (RCB) with three replications, tested seven weed control methods: T_1= straw mulching (SM), T_2= pre-emergence herbicide + SM, T_3= poly mulching (PM), T_4= pre-emergence herbicide + PM, T_5= intercropping + two hand-weeding, T_6= pre-emergence herbicide, and T_7= four hand-weeding, alongside T_8= weed-free and T_9= weedy control treatments. Results indicated that all mulching treatments achieved 70% to 80% weed control efficiency, significantly reducing weed growth up to 120 days after emergence (DAE). The intercropping + hand-weeding treatment provided 75% to 80% weed control up to 90 DAE. Among the mulches, straw mulching resulted in the tallest plant and widest plant base girths, leading to the highest yield and benefit-cost ratio, followed by other mulch and intercropping + hand-weeding treatments. Pre-emergence herbicide treatments were ineffective due to their short duration of action. Additionally, combining mulching (SM & PM) with pre-emergence herbicide offered no advantage over mulching alone. These findings highlight straw mulch as the most effective weed management strategy for taro, eliminating the need for herbicides. Where mulch is unavailable, intercropping combined with hand weeding can be a viable alternative for effective weed control.

Keywords

straw mulch; poly mulch; herbicide; taro; weed management; intercropping

Introduction

Weeds are considered significant biotic constraints that adversely affect crop growth and yield. The weed infestation can lead to yield losses in tuber and root crops ranging from 40% to 100%, depending on factors such as crop type, weed species, and weed density (1). This is extremely problematic for root crops grown during monsoon season, which is characterized by high temperatures and humidity. These conditions enhance weed germination and its' vigorous growth (2, 3), leading to substantial yield loss of tuber and root crops.

Among the tuber and root crops, taro (*Colocasia esculenta* (L.) Schott) ranks 4th among global food crops and is widely cultivated in the South Pacific, Asia, and Africa (4). Commonly known as a "poor man's crop," taro is a staple food in numerous developing countries across Asia and Africa (5, 6). This significant herbaceous perennial root crop belonging to the Araceae family has gained attention from commercial farmers due to its adaptability to diverse environmental conditions, especially in the face of climate change (4). In Bangladesh, taro has also become an important vegetable during the *kharif* season due to the scarcity of other vegetables during this period. Additionally, taro has garnered attention from consumers due to its significant health advantages. The health benefits include strengthening the immune system, decreasing blood pressure, aiding in weight loss, alleviating fatigue, preventing cell damage, promoting bone health, and supporting thyroid function (4, 7, 8).

Despite these immense benefits, the cultivation of taro faces a significant challenge due to weed infestation (2, 9). In addition, the slow initial growth of this crop impedes the ability to compete with weeds for resources, making effective weed control crucial, particularly within the first 120 days after planting (DAP) (1). This extended critical period necessitates frequent manual weeding, typically 7–9 times, to maintain a weed-free environment (1).

Traditionally, weed management in taro cultivation has relied heavily on manual labor and cultural practices, often consuming up to 30% of total labor input, equivalent to 150–200 person-days per ha depending on efficiency (2, 7). In regions where labor is scarce, chemical weed control methods have been adopted, with pre-emergence herbicides proving effective in other tuber crops (2). While the use of chemical herbicides is studied in crops such as yam, sweet potato, and cocoyam (10, 11), there is limited research focused specifically on taro, often considering it an "orphan crop" (9, 12). Few studies have investigated alternative weed management strategies for tuber crops, such as mulching (13, 14) and intercropping (1). Additionally, the impact of different mulching materials on crop yield, agro-ecosystems, and their economic viability also needs further investigation (15). Moreover, developing a comprehensive weed management system that reduces reliance on synthetic herbicides is crucial for sustainable agriculture (2, 16).

Despite these needs, there is still a lack of comprehensive and comparative studies on various weed management strategies, including cultural, biological, organic, and synthetic methods, specifically tailored to taro cultivation. This gap contributes to ongoing challenges in production and productivity (2, 9). To address this research gap, the present study aims to evaluate the effectiveness of individual or combined weed management technique(s) to support sustainable taro agriculture.

Materials and Methods

Experimental site, land preparation, and planting

This experiment was executed under irrigated conditions at the Regional Agricultural Research Station (RARS) of the Bangladesh Agricultural Research Institute (BARI) in Jashore, Bangladesh (latitude 23°18', longitude 89°18', elevation 19 m) during the *Kharif* season (March to October) of 2021 and 2022. The objective was to identify effective and sustainable weed management techniques for taro cultivation. The soil was tested in the Regional Laboratory, Soil Resource Development Institute, Jashore, Bangladesh. The experimental plots consisted of sandy loam soil classified under AEZ 11, exhibiting pH levels ranging from 7.67 to 8.38. The soil was found to have salinity levels of 0.5–1.07 dSm^{-1}, organic matter content of 1.52%, nitrogen content of 0.088%, phosphorus content of 11.82 µg/g soil, sulphur content of 13.99 µg/g soil, boron content of 0.32 µg/g soil, magnesium content of 1 mEq/100 g soil, and potassium content of 0.24 mEq/100 g soil. To meet the nutrient requirements of taro, 10 t ha^{-1} of vermicompost was applied to the field before final land preparation.

Additionally, 80 kg ha^{-1} of N, 60 kg ha^{-1} of P_2O_5, and 30 kg ha^{-1} of K_2O, along with 7 kg ha^{-1} of S, were added. Half of the N and all of the P_2O_5, K_2O, and S were applied during final land preparation, while the remaining half of N was split equally at 25 days after emergence (DAE) and 50 DAE during both years. Taro corms of 45 kg were collected from Tuber Crop Research Centre, RARS, Jashore. The unit plot size was 4.8 m × 4.0 m, having 80 plants/plots with row to row spacing of 60 cm and plant to plant spacing of 40 cm for both years. Irrigation was initiated immediately after planting to ensure proper germination and subsequent irrigations were scheduled every 25 days after planting. Irrigations were adjusted based on rainfall, with irrigations being skipped if there was adequate rainfall. A disease named Colletotrichum leaf spot was diagnosed in this crop during the first year. This disease was managed by spraying tilt (0.5 ml L^{-1}), a fungicide of the propiconazole group two times. The date of crop and weed emergence and taro cultivation timeline has been shown in Table 1.

Treatments and experimental design

The experiment utilized a randomized complete block (RCB) design with three replications to assess nine treatments. Treatments were as follows: T_1= Straw Mulching (SM) (6 cm thick organic mulch: wheat straw), T_2= Pre-emergence herbicide (Pendimethalin @ 1.5 L ha^{-1})+SM (Straw Mulching), T_3= Poly Mulch (PM), T_4= Pre-emergence

Table 1. Timeline of taro cultivation and weed emergence during 2021 and 2022.

Crop year	Sowing date	1st taro emergence	Weed emergence	50% taro emergence	Harvesting date
2021	08th April 2021	29th April 2021	18th April 2021	7th May 2021	1st October 2021
2022	17th April 2022	3rd May 2022	22nd April 2022	8th May 2022	11th October 2022

herbicide + PM, T_5= Intercropping (living mulch) + Hand Weeding (HW) at 51 DAE and 71 DAE, T_6= Pre-emergence herbicide (Pendimethalin @ 1.5 L ha^{-1}), T_7 = Hand Weeding (HW) (4 times) at 31 DAE, 51 DAE, 71 DAE & 91 DAE, T_8 = Weed Free, and T_9= Control (no weeding). In the mulch treated (SM & PM) and control plots, earthing up was done, followed by mulching on the same day of planting. In other treatments, earthing up was done 40 DAE during both years. The taro variety BARI Mukhikachu-1 (Bilasi) was selected as the test crop for the experiment.

Data collection

To determine weed density, a quadrat method was employed, where a quadrat frame measuring 1 m^2 was randomly placed three times at each of the following time points: 30, 60, 90, and 120 days after emergence (DAE) in both years. Weeds within the quadrat were identified and counted during each observation period. The dry weight of weeds (gm^{-2}) was assessed at 30, 60, 90, and 120 days after emergence (DAE). Weeds were collected, washed, dried in an oven with hot air of 70°C temperature, and then weighed, following the previously described method (17). The plant height (cm) and plant base diameter (cm) were measured by selecting five random plants, excluding border plants, using a meter ruler and digital slide callipers, respectively.

The occurrence of various weed species was assessed, and the density of each species was computed following the previously described method (18)

$$\text{Weed density (no m}^{-2}) = \frac{\text{Total number of weed}}{\text{Total survey area}} \quad \text{..........(Eqn. 1)}$$

Weed control efficiency (WCE%) was calculated by comparing the reduction in weed dry weight in treated plots to the weed dry weight in the control plots (no-weeding). It was expressed as a percentage.

$$\text{WCE (\%)} = \frac{WC - WT}{WC} \times 100 \quad \text{..........(Eqn. 2)}$$

Where, WC= Weed dry weight in control plot (no-weeding). WT= Weed dry weight in the treated plot.

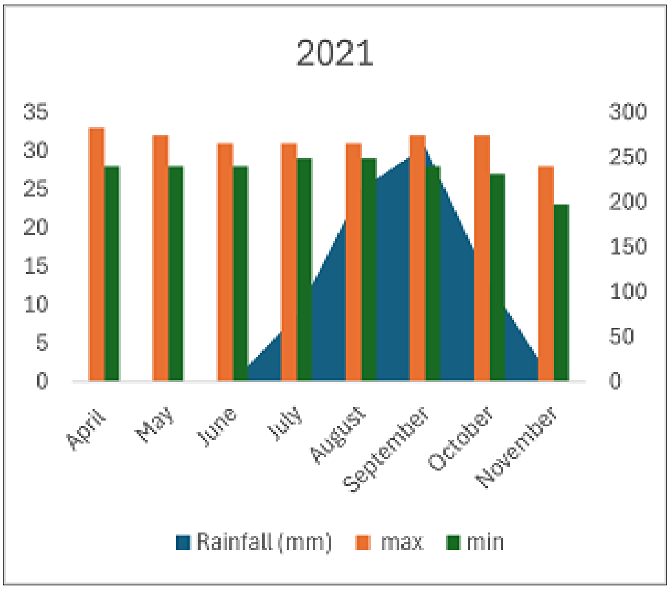
The experimental field was dominated by both broad and narrow leaf weeds comprising *Cyperus rotundus, Cynodon dactylon, Amaranthus viridis, Enhydra fluctuans, Eleusine indica, Brassica kaber, Physalis heterophylla,* and *Celosia argentia*. Throughout the growing period, weed density fluctuated across different management treatments.

Rainfall and temperature

Daily maximum and minimum temperature (°C) and monthly total rainfall (mm) data were collected from the mini weather station, RARS, Jashore, during both the years 2021 and 2022 during the cropping season (Fig. 1).

Statistical analysis

The experiment was replicated three times, and the data were analysed using analysis of variance (ANOVA) in the R software. Thus, the weed density (no. m^{-2}) was a fraction for the treatments. Analysis was performed separately for the parameters observed in 2021 and 2022. All treatments were treated as experimental factors during the analysis.



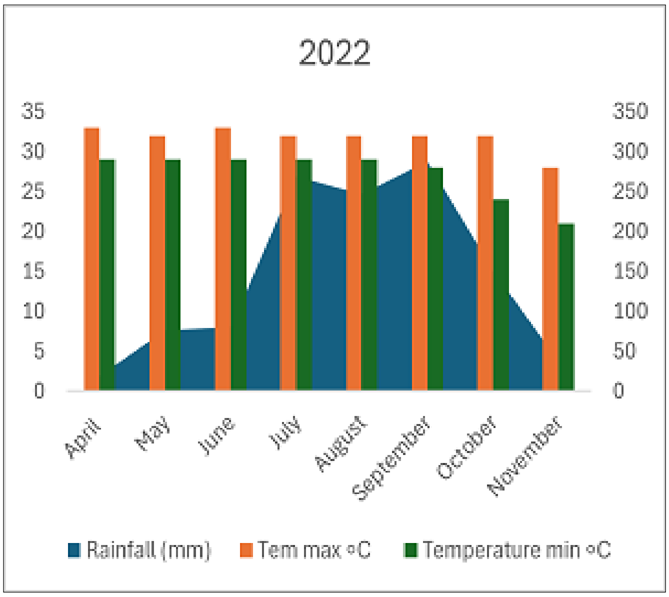


Fig. 1. Rainfall and temperature during 2021 and 2022.

Results

Weed density (no. m^{-2})

Weed density showed significant variations for all treatments, and weed density varied for the same treatments across both 2021 and 2022 (Fig. 1 and Table 2). At 30, 60, 90, and 120 days after emergence (DAE) of taro, the lowest weed density was observed in the weed-free (T_8) plot (19.74–33 no. m^{-2}), which was statistically parallel to all mulched plots (T_1–T_4) up to 60 DAE for both years. During 90 and 120 DAE, all mulched (T_1–T_4) plots showed the second lowest weed density (120.67–206.95 no. m^{-2}) for both years. T_5 (intercropping+two HW) and T_7 (HW) exhibited weed densities of 64–634 no. m^{-2} between 30 to 60 DAE and 223–531.23 no. m^{-2} between 90 to 120 DAE during both years.

Table 2. The impact of weed management on weed (broad and narrow leaf weeds) density at 30, 60, 90, 120 DAE during 2021 and 2022.

Treatment	Weed density during 2021				Weed density during 2022			
	30 DAE	60 DAE	90 DAE	120 DAE	30 DAE	60 DAE	90 DAE	120 DAE
T_1	70.57 bc	100 d	174.17cd	206.95cd	80 de	107.72 c	128.21 d	136.39 d
T_2	93.21 bc	140 cd	184cd	177cd	80.17 de	166.08 c	116.14de	172.67 d
T_3	53.38 bc	91 d	129.53de	126.04d	42.18 e	92.07 cd	122 de	135.35 d
T_4	53 bc	121.23 cd	185.15cd	132d	34.27 e	98 cd	120.67de	138.62 d
T_5	145.19 b	64 d	263.24 c	531.23ab	195.63 c	112.37 c	360 bc	525.12 b
T_6	304 a	437.27 b	546.61 b	461b	141.30cd	805.88 a	446 ab	460 b
T_7	404.27 a	234 c	289 c	223c	634 b	273.77 b	334.67 c	257 c
T_8	21.46 c	25.21 d	30 e	23.67e	19.74 e	27.72 d	33 e	21.29 e
T_9	392.64 a	622.61 a	858 a	553.53a	728 a	800.85 a	520.00 a	609 a
LSD $_{(0.05)}$	112.52	117.98	115.76	81.56	62.51	78.5	89.32	71.70
CV%	38.02	33.41	22.62	17.42	16.62	16.53	21.28	15.16

T1 = straw mulching (SM) (6 cm thick organic mulch: wheat straw), **T2** = pre-emergence herbicide (pendimethalin @ 1.5 L ha-1)+SM (wheat straw), **T3** = poly mulch (PM), **T4** = pre-emergence herbicide+PM, **T5** = intercropping (living mulch)+hand weeding (HW) at 71 DAE and 91 DAE, **T6** = pre-emergence herbicide (pendimethalin @ 1.5 L ha-1), **T7** = hand weeding (4 times) at 31 DAE, 51 DAE, 71 DAE & 91 DAE, **T8** = weed free and **T9** = control (no weeding). **LSD** = least significant difference at 5% level and **CV%** = coefficient of variation.

In contrast, the control plot (T_9) showed the highest weed densities, ranging from 392.64 to 858 no. m^{-2} in 2021 and from 520 to 728 no. m^{-2} in 2022 over the growing periods, which was statistically analogous to T_6 (pre-emergence herbicide) treatment for both years.

Weed control efficiency (%)

The efficiency of weed control (WCE%) was markedly influenced by various treatments applied (Table 3). In 2021, the weed-free (T_8) treatment achieved the highest efficacy, with a WCE ranging from 96.77% to 99.08% between 30 to 120 DAE; this level was statistically equivalent to all mulched treatments (T_1–T_4) (with or without herbicide) up to 90 DAE. At 120 DAE, all mulched treatments (T_1–T_4) showed the second-highest efficiency in controlling weeds, with WCE values of 65.56%–79.45%. The WCE of the T_5 (intercropping+two HW) plot ranged from 77.43% to 91.93% up to 90 DAE; however, its efficiency sharply declined to 34.57% at 120 DAE. The hand weeding (T_7) treatment efficiency was 78.45%–86.05% from 60 to 120 DAE. The WCE of pre-emergence herbicide (T_6) was 82.51% at 30 DAE, which dropped to 28.94% at 60 DAE, marking the lowest efficiency over the cropping season.

Similarly, in 2022, the weed-free (T_8) plot demonstrated the highest WCE, ranging from 97.93%–99.51% throughout the period. At 30 DAE, all treatments were statistically alike weed-free plots except the hand weeding (T_7) treatment. The hand weeding (T_7) controlled weeds actively from 60 DAE (93.31%) to 120 DAE (80.04%). During 60 and 90 DAE, all mulched plots (T_1–T_4) (with or without herbicide) were significantly comparable to the weed-free (T_8) treatment. However, by 120 DAE, the WCE of the mulched plots decreased, resulting in the second-highest efficiency at 82.79%. The T_5 (intercropping+two HW) treatment provided moderate weed control up to 120 DAE, with

Table 3. Effect of weed control efficiency (%) during 2021 and 2022 at 30, 60, 90 and 120 days after emergence (DAE).

Treatments	Weed control efficiency (%) during 2021				Weed control efficiency (%) during 2022			
	30 DAE	60 DAE	90 DAE	120 DAE	30 DAE	60 DAE	90 DAE	120 DAE
T_1	84.14bc	88.56a-c	87.77ab	73.38 b	91.45a-c	91.40a-c	85.71 ab	82.79 b
T_2	91.69ab	78.53 cd	84.22ab	65.56 b	88.88 bc	79.39 c	84.21 ab	81.28 b
T_3	92.46ab	86.42a-c	73.67 b	75.04 b	94.69a-c	90.79a-c	81.34 ab	81.10 b
T_4	92.89ab	74.63 d	71.52 b	79.45 b	95.46 ab	91.22a-c	83.14 ab	81.37 b
T_5	82.40 c	91.93 ab	77. 43 b	34.57 c	93.53a-c	83.2 bc	72.69 bc	71.71 c
T_6	82.51 c	28.94 e	29.67 c	48.22 c	86.51 c	51.18 d	34.41 d	34.04 d
T_7	20.83 d	86.05 bc	74.71 b	78.45 b	21.35 d	93.31 ab	59.51 c	80.04 b
T_8	96.77 a	97.61 a	98.82 a	99.08 a	97.93 a	98.63 a	98.29 a	99.51 a
T_9	0 e	0 f	0 d	0 d	0 e	0 e	0e	0 e
LSD $_{(0.05)}$	7.97	11.28	18.84	15.75	8.67	13.4	18.21	6.27
CV%	6.44	9.27	16.39	14.79	6.73	10.26	15.8	5.33

T1 = straw mulching (SM) (6 cm thick organic mulch: wheat straw), **T2** = pre-emergence herbicide (pendimethalin @ 1.5 L ha-1)+SM (wheat straw), **T3** = poly mulch (PM), **T4** = pre-emergence herbicide+PM, **T5** = intercropping (living mulch)+hand weeding (HW) at 71 DAE and 91 DAE, **T6** = pre-emergence herbicide (pendimethalin @ 1.5 L ha-1), **T7** = hand weeding (4 times) at 31 DAE, 51 DAE, 71 DAE & 91 DAE, **T8** = weed free and **T9** = control (no weeding). **LSD** = least significant difference at 5% level and **CV%** = coefficient of variation.

WCE values ranging from 71.71%–93.53%. In contrast, the pre-emergence herbicide (T_6) plots showed the poorest WCE after 30 DAE to the study period.

Growth parameters

All treatments considerably influenced plant height (cm) and plant pseudo-stem base girth (cm) at 60, 90, and 120 days after emergence (DAE) for both years (Fig. 2 and 3).

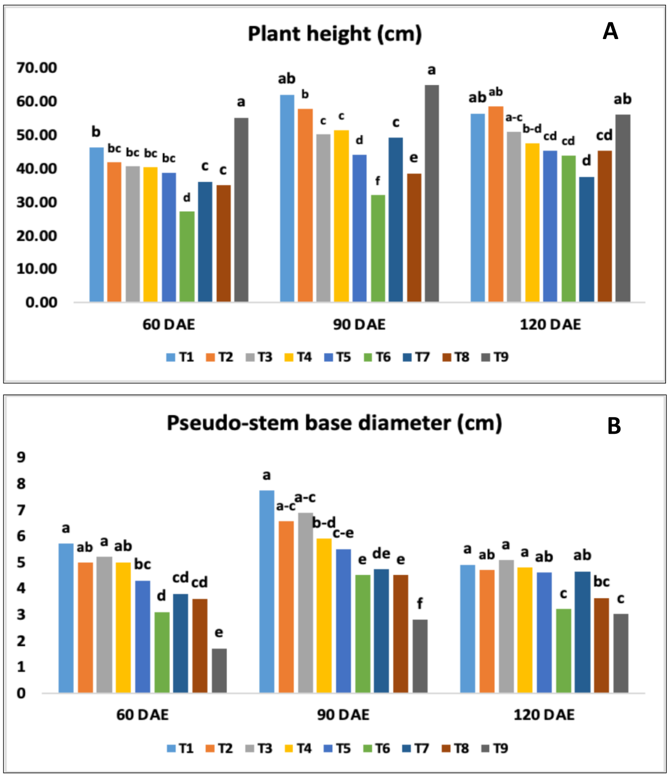


Fig. 2. Plant height (cm) (**A**) and plant pseudo-stem base diameter (cm) (**B**) during 2021.

During 2021 (Fig. 2), at 60 DAE, the tallest plants were observed in the control (T_9) plot (55.17 cm), followed by the straw-mulched plot without herbicide (T_1) (46.21 cm), which was not notably different from the other mulched treatments and the shortest plants were present in the pre -emergence herbicide (T_6) plot (27.17 cm). Again, the widest plant base diameter was observed in the straw mulch treatment (T_1) (5.74 cm), likewise in other mulched treatments (T_2–T_4), while the narrowest was in the control weedy (T_9) plot (1.7 cm) and the pre-emergence herbicide (T_6) plot (3.1 cm). At 90 DAE, the tallest plants were again in the control (T_9) plot (64.94 cm), statistically indistinguishable from the straw mulch plot (T_1) without herbicide, followed by all mulched treatments (T_2–T_4). The shortest plants were in the pre-emergence herbicide plot (32.04 cm), followed by the weed-free plot and intercropping + hand-weeded (T_7) plot. In terms of base diameter, the widest was perceived in the straw mulch (T_1) plot (7.74 cm), like other mulch treatments (T_2–T_4), while the control (T_9) plot showed the narrowest base diameter (2.8 cm). By 120 DAE, the tallest plants were found in the straw mulched plot with pre-emergence herbicide (T_2) (58.6 cm), empirically similar to the control plot and all other mulched plots. Base diameter differences at 120 DAE were not significant, except for the weedy (T_9) plot (3.1 cm), weed-free treatment (T_8) (3.64 cm), and herbicide plot (T_6) (3.24 cm).

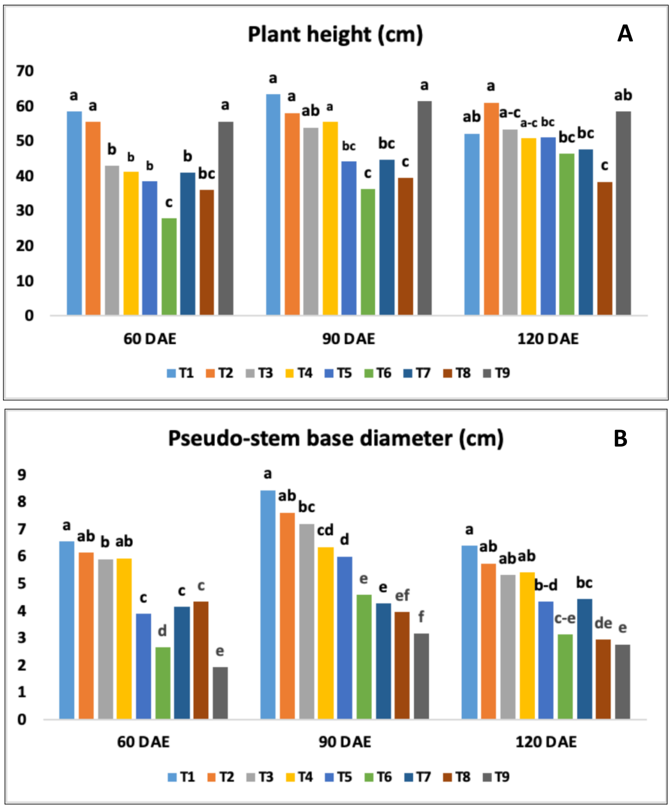


Fig. 3. Plant height (cm) (**A**) and plant pseudo-stem base diameter (cm) (**B**) during 2022.

In 2022 (Fig. 3), at 60 DAE, the tallest plants were in the straw mulched (T_1) treatment (58.27 cm), numerically equivalent to the weedy control (T_9) and the straw mulched plot with herbicide (T_2). At 90 DAE, the tallest plants were again in the straw mulched plot (T_1) (63.2 cm), statistically comparable to all mulched plots (T_2–T_4) and weedy control treatment (T_9) (61.3 cm). By 120 DAE, the tallest plants were perceived in the straw mulch + herbicide (T_2) plot (60.93 cm), which was statistically similar to all other mulched plots (T_1, T_3, T_4), the control (T_9) plot, pre -emergence (T_6), and hand weeded (T_7) plots. The shortest plants at various stages were consistently observed in the pre-emergence herbicide (T_6) plot, with heights ranging from 27.73 cm to 38.27 cm. The widest base diameter was consistently found in the straw mulch plot (T_1) (6.38 to 8.42 mm), while the narrowest diameter was in the weedy (T_9) treatment (1.19 mm to 3.15 mm) over the study period.

Yield (t ha^{-1})

The corm yield of *C. esculenta* showed notable variation across different treatments during both years (Table 4). During 2021, the highest yield (18.07 t ha^{-1}) was in the straw mulched (T_1) treatment, followed by other mulched treatments (T_2–T_4), which were numerically indistinguishable from the intercropping + two hand weeding (T_5) treatment (16.47 t ha^{-1}). Thus, the highest benefit cost ratio (BCR) (3.43) was calculated in the straw mulched plot (T_1), statistically equivalent to the T_2 (pre-emergence herbicide + SM) treatment (3.27) followed by the intercropping + two hand weeding (T_5) (2.52) treatment. The lowest yield was obtained from the T_9 (weedy control) plot (2.20 t ha^{-1}), followed by the T_6 (pre-emergence herbicide) plot (4.26 t ha^{-1}), the T_8 (weed-free) plot (7.48 t ha^{-1}), and the T_7 (hand-weeded) plot (14.34 t ha^{-1}).

Table 4. Corm yield influenced by different weed management treatments during 2021 and 2022.

Treatments	Total cost (USD) during 2021 and 2022	Economic analysis during 2021			Economic analysis during 2022		
		Yield (t ha^{-1})	Net income (USD)	Benefit cost ratio	Yield (t ha^{-1})	Net income (USD)	Benefit cost ratio
T_1	1630 e	18.07 a	5596.67 a	3.43 a	21.78 a	7215.33 a	4.42 a
T_2	1630 e	17.40 ab	5330 ab	3.27 a	20.45 a	6416.67 b	3.93 b
T_3	2250 b	16.77 ab	4456.67 c	1.98 c	18.63 b	5067.33 cd	2.25 d
T_4	2250 b	16.40 b	4310 cd	1.92 c	17.52 bc	4358 e	1.93 d
T_5	1870 d	16.47 b	4716.67 bc	2.52 b	17.98 b	5590 c	2.98 c
T_6	1450 f	4.26 e	252.67 e	0.17 d	4.46 e	243.33 g	0.17 f
T_7	2050 c	14.34 c	3686 d	1.8 c	16.4 c	4642 de	2.26 d
T_8	2800 a	7.48 d	192 e	0.07 d	11.63 d	1852 f	0.66 e
T_9	1450 f	2.20 f	-570 f	-0.39 e	4.25 e	250 g	0.17 f
LSD $_{(0.05)}$	7.37*10^{-14}	1.59	635.09	0.36	1.51	679.73	0.37
CV%	2.20*10^{-11}	7.28	11.8	12.75	5.91	9.92	10.17

T1 = straw mulching (SM) (6 cm thick organic mulch: wheat straw), **T2** = pre-emergence herbicide (pendimethalin @ 1.5 L ha^{-1})+SM (wheat straw), **T3** = poly mulch (PM), **T4** = pre-emergence herbicide+PM, **T5** = intercropping (living mulch)+hand weeding (HW) at 71 DAE and 91 DAE, **T6** = pre-emergence herbicide (pendimethalin @ 1.5 L ha-1), **T7** = hand weeding (4 times) at 31 DAE, 51 DAE, 71 DAE & 91 DAE, **T8** = weed free and **T9** = control (no weeding). **LSD** = least significant difference at 5% level and **CV%** = coefficient of variation

In 2022, the highest yield of 21.78 t ha^{-1} was achieved with the T_1 (SM) treatment, which was statistically akin to the T_2 (herbicide+SM) treatment. Thus, the highest BCR of 4.42 was in the straw mulch (T_1) plot. The T_3 (PM) treatment produced the second-highest yield at 18.63 t ha^{-1}, statistically resemblance to T_5 (intercropping + two HW) treatment (7.98 t ha^{-1}) and T_4 (herbicide + PM) treatment (17.52 t ha^{-1}) followed by the T_7 (hand-weeding) treatment alone, which yielded 16.4 t ha^{-1}. However, the second-highest BCR 3.93 was found in the pre-emergence herbicide + SM (T_2) treatment, followed by the intercropping + two-hand weeding treatment (T_5) (2.98). The BCR of the T_3 (PM), T_7 (hand-weeded) plot, and T_4 (herbicide + PM) was 2.25, 2.26, and 1.93, respectively. Furthermore, the lowest yield of 4.25 t ha^{-1} and the lowest BCR of 0.17 were observed in the control plot (T_9), which was statistically similar to the pre-emergence herbicide-treated plot (T_6) (4.46 t ha^{-1}). The weed-free plot (T_8) yielded 11.63 t ha^{-1}, and the BCR was 0.66.

Relationship between weed and crop yield

Yield showed a direct relationship with weed parameters and plant growth during both crop growth years of 2021 and 2022 (Fig. 4A & B). For both years, yield was strongly and negatively ($-0.85 \leq r \leq -0.6$) correlated with weed density (no. m^{-2}) and strongly and positively ($0.6 \leq r \leq 0.75$) correlated with WCE (%) from 60 to 90 DAE. In this study, plant height had a poor relation and no relation to crop yield during 2022 and 2021, respectively. However, plant pseudo-stem diameter (mm) at 60 and 90 DAE had a robust and significant positive ($0.75 \leq r \leq 0.88$) relationship with yield over the years.

During 2022, corm yield could be interpreted according to the equation: Y = 19.79 + (-0.02) X at 60 DAE, where Y denoted the corm yield and X denoted the weed density at 60 DAE (Fig. 5B). Here, corm yield decreased by 2 t ha^{-1} when weed density reached 100 no. m^{-2}, which resulted in an 11.24% loss compared to a weed-free con-

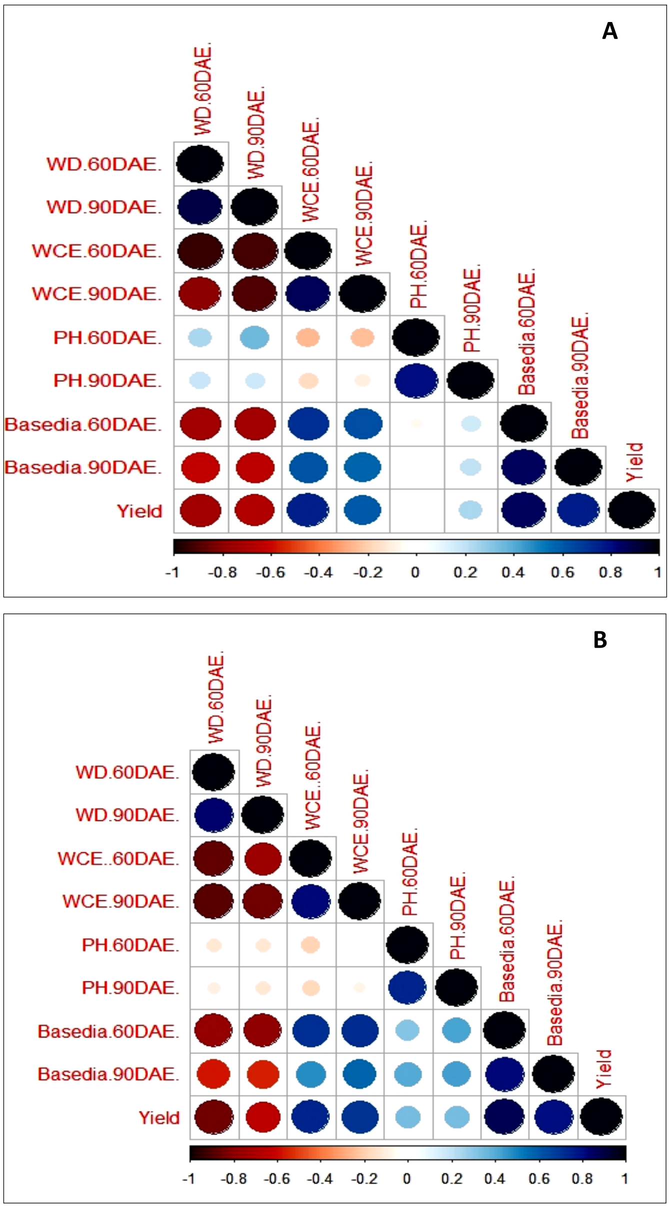


Fig. 4. Correlation among weed parameters, plant growth parameters and yield during 2021 (**A**) and 2022 (**B**).

dition. Additionally, as weed density increased to 400 or 700 no. m^{-2}, corm yields decreased by 8.00 and 14 t ha^{-1}, respectively, representing reductions of 44.97% and 78.70% compared to ideal weed control. At 90 days after emergence (DAE), when weed density was 100 no. m^{-2}, yield loss was recorded at 10.8%. This suggests that for every one-unit increase in weed density, yield decreased by 0.1%. Furthermore, in 2021 (Fig. 5A), at both 60 and 90 DAE, an increase in weed density up to 100 no. m^{-2} resulted in an approximately 13.0% yield loss.

Without any weed control, the lowest crop yield could be 2.5 to 5.4 t ha^{-1} during both years (Fig. 5C & D), and with the 1% increase of WCE, yield could be increased by 0.11–0.14 t ha^{-1} in 2021 (Fig. 5C) and 0.14–0.15 t ha^{-1} in 2022 (Fig. 5D).

Discussion

Weed management in *C. esculenta* is crucial due to its slow growth and long cultivation period, which can lead to weed dominance if left untreated. Thus, this study explores various weed management strategies aimed at improving corm yield and promoting environmental conservation.

Weeds density (no. m^{-2})

Weed density fluctuated over the years for the same treatment influenced by the weather conditions of each year. These variations across different management treatments occurred throughout the growing period due to competition between crops and weeds, as well as interspecific and intraspecific weed competition.

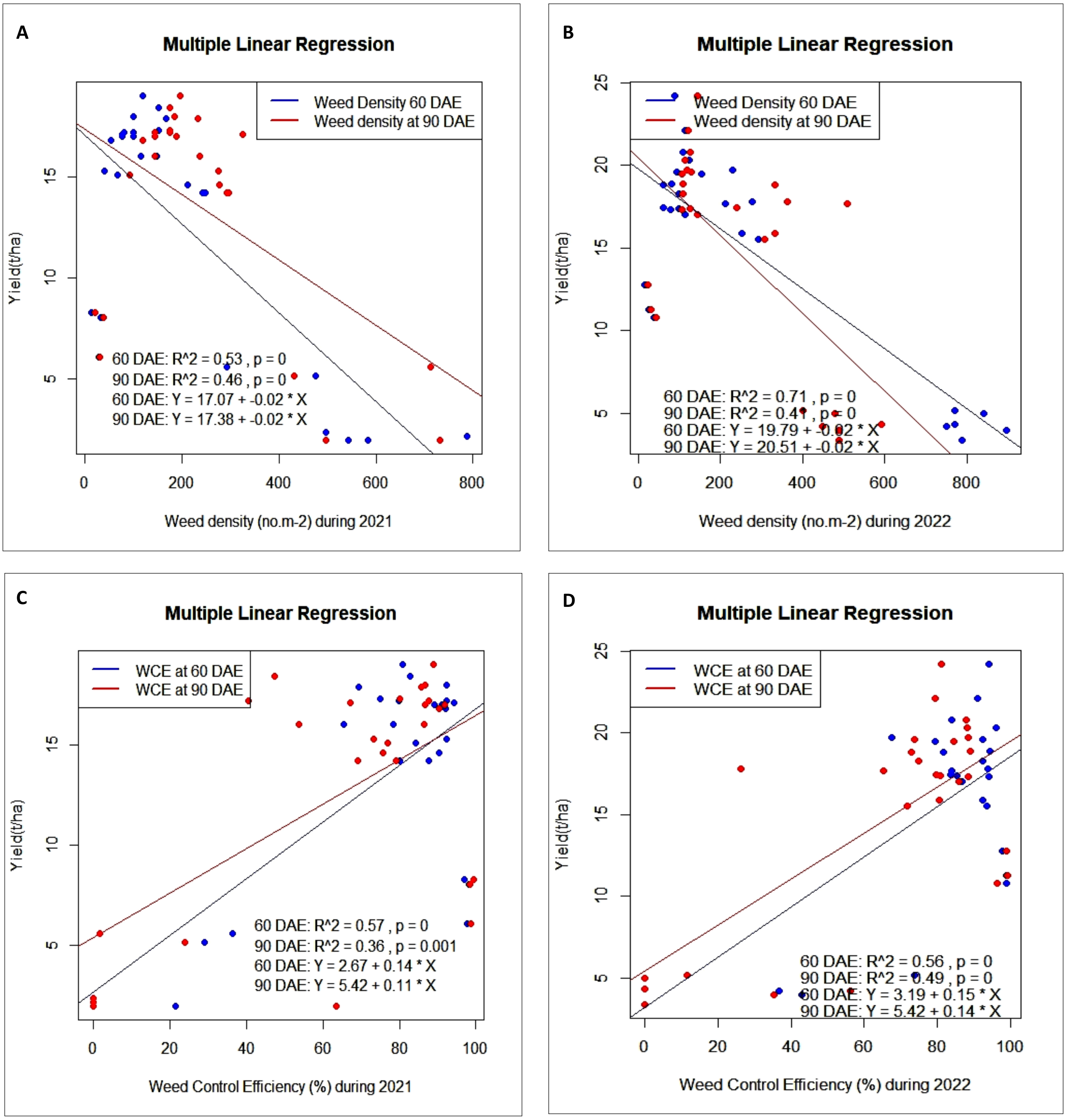


Fig. 5. Weed density (**A** & **B**) and weed control efficiency (**C** & **D**) at 60 DAE and 90 DAE during 2021 and 2022.

The weed density was the lowest in the weed-free plots, which could be the reason for extensive and frequent hand-weeding, and this was mathematically equivalent to all types of mulched plots, which indicated that mulch materials prevented the germination of weeds, restricting the natural resource like sunlight (11, 19, 20). Straw was more efficient in weed management as it was applied thickly (6 cm), which supports the result of Nwosisi et al. (11) indicating that organic mulches can offer effective weed control when applied at sufficient depth. Pre-emergence herbicide application exhibited short-term weed suppression, lasting up to 30 days after emergence, followed by a resurgence of weed growth and the highest weed count in 60 DAE, and this result was supported by Mitra et al. (18), who highlighted that only pre-emergence herbicide is not sufficient for weed management even in rice. Our result is also in consonance with Demo and Bogale (21) who stated that straw and polythene-mulch controlled weed intensity more efficiently than chemicals. Again, combining intercropping with two-hand weeding and only 4 times HW showed moderate effectiveness in weed management by restricting resources for weeds (1) and eradicating weeds periodically, although it was not entirely satisfactory, especially during the monsoon period when weed density fluctuates rapidly, posing continuous challenges for slow-growing crops like *C. esculenta*. Intriguingly, there was no significant difference observed between mulched plots and those treated with a combination of herbicides and mulch, as physical inhibition was stronger than chemical inhibition. So, weeds can be eradicated by mulch in taro fields without harmful herbicides, turning our cultivation into sustainable agriculture.

Weed control efficiency (%)

Weed control efficiency (WCE%) of weed-free treatment was almost 100% over the period. WCE of mulch materials was more than 90% up to 60 DAE as the dry biomass of total narrow and broad leaf weed was low compared to weedy control treatment in the early stage, and WCE at 90 –120 DAE decreased to almost 75% as dry biomass of weed increased with time duration. The causes of weed resurgence in straw-mulched plots might be due to the decay of straw mulch with time (14) and giving the space and light to the weed seeds for germination, and for poly-mulch, weeds were found to emerge by tearing the mulch. This result aligns with Nwosisi et al. (11) who reported an 80% reduction of weeds by straw mulch. Weed control efficiency changes over the year due to weather conditions as it impacts weed growth and development directly (22).

In T_5 and T_7 treatments, WCE (%) fluctuated due to the imposition of treatments that controlled weed for a short period, and hot moist conditions accelerated the weed growth again before the sampling date. In intercropping and hand weeding combinations, weed was controlled by more than 70% for both years, which was supported by Weerarathne et al. (1). Using chemicals was effective up to 30 DAE and could not control weed effectively over the critical time for the crop-weed competition, which might be due to the short lifespan of this chemical, which is consistent with Nath et al. (23) who stated that a pre-emergence herbicide with hand weeding at 25 days after planting achieved the highest weed control in maize + black gram intercropping.

Again, in the linear regression, it was true that at 60 DAE, WCE (%) influenced the crop yield by 53%–57% over the years. It might be due to the WCE (%) of weed-free plots where extensive weeding depleted moisture and nutrients (24) and this treatment couldn't improve crop growth and yield, thus negatively influencing the total weed control efficiency. At 90 DAE, weed control efficiency had a weaker influence on yield (36%–49%), possibly because the active growth stage of taro primarily occurs within the 90 days after emergence (25, 26).

Plant height (cm), plant pseudo-stem base diameter (cm)

Plant height and plant base diameter fluctuated considerably across the treatments. In this study, plant growth (plant height and base diameter) peaked at 90 DAE for both years and then started to decline, which is almost comparable to Gunrah (26) who observed the highest plant growth of taro during 100 DAE or 1–4 months after planting. Sharma et al. (15) also noted the highest plant height and stem diameter in tomatoes when organic mulch was used. In the control plot, the tallest plants were found, likely due to the shade effect, which promoted vertical growth. This observation is supported by Li H et al. (27) who found that winter wheat developed longer internodes and peduncles under shaded conditions to capture more light, which was also corroborated by Weselek et al. (28) and McMater GS et al. (29).

Conversely, the base diameter of the plant was the lowest in the control plot, as they didn't get enough nutrients due to weed engagement. This result was validated by Mu et al. (30), who mentioned that shading decreased grain yield by reducing yield contributing characters. In the straw-mulched plot, both the plant height and base girth were consistently higher over the period in both years, likely due to the addition of soil nutrients and improvements in soil physical properties and soaking of water from irrigation or rainfall, unlike plastic mulch (30), thereby promoting better plant growth by providing optimum natural resources. In only poly-mulched and herbicide-treated mulched plots, growth was lower than the only straw mulched treatment, which might be due to the adverse effect of synthetic mulch on soil moisture (30) and the effect of chemical herbicide on soil microbes. In weed-free plots, though there was no competition for weeds, crop growth was not satisfactory, which may be because extensive weeding decreased the soil moisture, disturbed root growth, and affected nutrient absorption. In pre-emergence herbicide application, crop height and base diameter were the lowest as the chemical affected the plant also.

Yield (t ha^{-1})

Corm yield showed significant variation across different weed management treatments. Notably, the highest yield observed in the wheat straw mulch treatment is consistent with the result of Zhu et al. (14) as straw mulching effectively mitigated crop-weed competition and promoted crop growth by regulating soil conditions and adding soil nutrients like nitrogen (31, 32). This finding is consistent with the study by Du et al. (33), which highlighted the soil-enhancing effects of straw mulching, including increased soil organic matter content, improved soil moisture regulation, and prevention of water loss through evaporation, run-off, and drought. This can be attributed to the ability of organic mulches to enhance soil percolation and water retention as opposed to inorganic mulches (34, 35, 15). Ahmad et al. (36) also reported an increase in wheat grain yield and quality under straw mulching. Additionally, the lower cost of straw mulch compared to synthetic mulch reduced production costs and subsequently increased the benefit-cost ratio (BCR), which is also supported by Sharma et al. (15), who reported higher net revenue in organic mulch.

In contrast, the combination of intercropping and hand weeding resulted in increased taro equivalent yield due to enhanced component crop yield and reduced labor costs associated with fewer hand weeding sessions, resulting in the second highest BCR. This weed management strategy could be applied where mulch is not available.

The lower crop yield observed in the poly mulch treatment may be attributed to poor thermal insulation compared to straw mulch, affecting soil moisture levels by increasing temperature in hot summer (37–39), consistent with other research indicating that inorganic mulches harm agro-ecosystem, restricting soil percolation and water retention compared to organic mulches (35, 23, 16). Hand weeding treatment showed lower yields than mulched plots but higher yields than weedy control plots, indicating an effective reduction of crop-weed competition by approximately 70%, as highlighted by Weerarathne et al. (1). However, hand weeding incurred higher labor costs, increasing the total production cost and thus reducing the BCR.

Interestingly, pre-emergence herbicide application did not increase crop yield in mulched plots and only provided effective weed control for the initial 30 days after emergence. Conversely, in weed-free plots, the yield was lower, possibly due to fluctuations in soil moisture and temperature compared to mulched soil (40) and disruption of root growth caused by extensive weeding. This contrasts with the findings of Adenwaala et al. (41), who mentioned that weekly weeding in jute resulted in the highest yield over the growth period. The lower BCR observed in weed-free plots was due to higher total production costs associated with higher labor requirements for hand weeding. Therefore, among the weed management techniques studied, straw mulching emerged as an economically and environmentally sustainable method for taro production.

Conclusion

Our study indicates that mulching is an effective strategy for weed suppression without reliance on herbicides. Among the mulching techniques examined, straw mulch emerged as the most effective and green method, fostering optimal taro growth, yield, and economic benefits. In scenarios where mulch is unavailable, adopting intercropping + two sessions of hand weeding offers a practical alternative. Future research should focus on elucidating the specific impacts of different mulching treatments on soil moisture and temperature dynamics for taro cultivation.

Acknowledgements

The authors would like to express their sincere gratitude to Dr. Kawsar Uddin Ahammad, Chief Scientific Officer, Regional Agricultural Research Station (RARS), BARI, Jashore, for his invaluable support throughout this research. Heartfelt thanks are extended to Md. Abul Bashar, Field Assistant, RARS, BARI, Jashore, for his dedication in managing irrigation, fertilization, and labor during the study. The authors are also thankful to the Tuber Crop Research Center, RARS, BARI, Jashore, for providing the planting material (corm). Additionally, they appreciate the contributions of the Soil Resource Development Institute, Jashore, for conducting the soil analysis. Their collective efforts have been instrumental in the successful completion of this research.

Authors' contributions

SP: Experimented, collected data, performed statistical analysis, and drafted the whole manuscript. MHR: Contributed to the planning and design of the study. MT: Assisted with data collection in the field. MSK: Provided support with statistical analysis. DH: Formatted the reference section and conducted a critical review of the article. MHM: Reviewed the manuscript and offered critical feedback. BMA: Provide advice on plant protection and reviewed the article. PH: Assisted in analysing the economic aspects of the weed management techniques. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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