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RESEARCH ARTICLE

Synergistic integration of crop residue mulch and cultural practices with herbicides for managing weed complex in turmeric in North-Western India

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ABSTRACT

Turmeric being a wide spaced and long duration crop, weeds pose a serious problem due to its delayed emergence and slow initial growth which provide ideal environment for weeds to grow. This warrants for synergistic integration of residue mulch, cultural practices, and herbicides for effective weed management. Two field experiments were conducted during 2012-13 - 2013-14 and 2014-15 - 2015-16 at CCS Haryana Agricultural University, Regional Research Station, Karnal to evaluate different approaches involving integration of crop residue mulch and cultural practices with herbicides for effective and economical weed management in turmeric. The uncontrolled weeds caused 42-66% turmeric yield loss. Based on four years studies, it may be concluded that pre-emergence (PE) application of metribuzin 700 g/ha or pendimethalin 1000 g/ha or atrazine 750 g/ha integrated with rice straw mulching (10 t/ha) after herbicide application at 3 days after sowing (DAS) and hand weeding at 50 or 75 DAS provided effective control (86-100%) of complex weed flora in turmeric with improved rhizome yield (14.29 to18.60 t/ha), which was comparable to weed free, better economic returns without phyto-toxicity on the crop and detectable herbicidal residues in the turmeric rhizomes and soil at harvest. Integration of 2-hoeing with metribuzin 700 g/ha PE or pendimethalin 1000 g/ha PE were the two other viable options of integrated weed management (IWM) strategy. Among post-emergence (PoE) herbicides, fenoxaprop 67 g/ha 45 DAS, was safe to turmeric while metsulfuron 4 g/ha PoE was toxic. Glyphosate 0.3% PoE at 25 DAS could also be integrated with hoeing twice at 45 and 75 DAS for effective weed management in turmeric. Use of rice straw in IWM strategies in turmeric will also help in reducing herbicide dose, crop residue management without burning, conservation of soil moisture and other natural resources which will helps in long term sustainable and economical production system.

Keywords: Herbicides, Herbicide residues, Integrated weed management, Phyto-toxicity, Straw mulching, Turmeric

INTRODUCTION

Turmeric (*Curcuma longa* L.) is an important herbaceous perennial spice crop in the world and particularly in India. India is the largest producer (about 80% share) and consumer of turmeric in the world. The total area under turmeric is 2.38 lakh ha with a total production of 11.33 lakh tons and average yield of 4.76 t/ha (NHB 2019). In Haryana, it is grown only on 829 ha with production of 10,898 tons and average yield of 13.1 t/ha (DOH-GOH 2019). However, a great scope exists for area expansion particularly under agro-forestry system with poplar in northern districts of Haryana. It also has great significance in north-western Indo-Gangetic Plains particularly in areas near to Shivalik foothills. Turmeric is an important component of Indian kitchen which provides colour and flavour to various dishes. It is also widely used in pickles, curries, confectionaries, as a pigmenting agent in textiles and in Ayurveda for anti-inflammatory diseases (Goel *et al.* 2008).

Turmeric is a long duration crop grown during rainy season; hence, a variety of weeds infest the crop and compete for moisture, nutrients and space resulting into sizeable yield reductions (Daulay and Singh 1982; Hossain *et al.* 2008, Kaur *et al.* 2008). Due to wide spaced planting and longer growing period, weeds pose a serious problem in turmeric particularly during initial phase of growth. Delayed emergence, slow initial growth and poor initial canopy development provide ideal environment for weeds to grow and compete with the crop for nutrients, moisture and space causing considerable yield reduction of about 30-75 percent (Krishnamurthi and Ayyaswamy 2000). Uncontrolled weeds have been reported to remove 61, 60 and 74% of total N, P and K utilized by both crop and weeds, respectively (Kaur *et al.* 2008). The yield losses in turmeric caused by weeds are reported to range from

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30 to 80% (Krishnamurthi and Ayyaswamy 2000, Hossain *et al.* 2008, Kaur *et al.* 2008, Ratnam *et al.* 2012). Weed free conditions for a long period is desired for better production of rhizomes. Weeds are difficult to control with any single herbicide as diverse weed flora infests the turmeric crop, and use of more than one herbicide particularly at later stages of crop may not be advisable being a spice crop. Many herbicidal options may be explored as pre-emergence (PE) or as post-emergence (PoE) for turmeric (Ratnam *et al.* 2012, Sathiyavani and Prabhakaran 2015), but herbicides alone may not be a viable option for long-term weed management in turmeric.

The turmeric crop is a shade loving plant and requires high moisture in soil for better growth of plants and development of rhizomes. The agronomic practices and mulching could play an important role in reducing weed interference for better yields (Hossain 2005). Crop residue mulching may help as a viable option for maintaining optimum soil moisture for better growth and development in turmeric with added advantage of weed suppression. Hence, the strategies for synergistic integration of crop residue mulch and cultural practices with herbicides are needed to be chalked out for better and economical weed management in turmeric without herbicidal residues in crop produce. A limited information is available on integrated weed management (IWM) by synergistic use of crop residue mulch and cultural practices with herbicides in turmeric crop. Hence, field experiments were conducted to assess the suitability of crop residue mulch and agronomic practices integrated with herbicides for sustainable, viable and economical weed management in turmeric of the region.

MATERIALS AND METHODS

Experiment-1: Field experiment-1 was conducted at CCS Haryana Agricultural University, Regional Research Station, Karnal to evaluate different combination of herbicides along with the cultural practices for control of weeds in turmeric during 2012-13 and 2013-14. The treatments included: pre-emergence application (PE) of metribuzin 700 g/ha and pendimethalin 1000 g/ha at 0-3 days after seeding (DAS), each followed by (*fb*) hoeing twice at 40 and 70 DAS or *fb* fenoxaprop+ metsulfuron 67+4 g/ha at 2-4 leaf stage (LS) or *fb* rice straw mulch 10 t/ha at 3 DAS+ hand weeding (HW) at 50 DAS, and atrazine 750 g/ha PE *fb* fenoxaprop+ metsulfuron 67+4 g/ha at 2-4 leaf stage of weeds (2-4 LS) or *fb* straw mulch 10 t/ha at 3 DAS *fb* HW 50 DAS, along with weed free and weedy checks. The treatments were laid out in randomized block design with three replicates. The plot size was 5.0 m x 2.8 m during 2012-13 and 5.0 m x 4.2 m during 2013-14. Turmeric variety CSTH-9 was planted at a row spacing of 70 cm on 10th July, 2012 and 26th June, 2013. Crop was raised according to package of practices of the State University. The observations on weed density and biomass were recorded at 120 DAS. For weed density, numbers of individual weed species were counted from two randomly placed quadrats (0.5 m x 0.5 m) in each of the plots and converted to per m^2. These weeds were grouped as grassy, broad-leaved weeds and sedges and weed dry weight (biomass) was taken after sun drying and oven drying of samples at 70^{0}C for 48 hours. Weed control efficiency (WCE) was computed based on weeds biomass by using the following formula used by different workers (Hasanuzzaman *et al.* 2009, Singh *et al.* 2013),

$$\text{WCE (\%)} = \frac{\text{(Weed biomass in unweeded plot – weed biomass in treated plot)}}{\text{Weed biomass in unweeded plot}} \times 100$$

Crop growth parameters viz., number of plants/ha, plant height and number of tillers/ plants were recorded at 180 DAS, and crop yield was recorded at harvest. Plant stand was counted on plot basis and converted to per ha. Plant height and number of tillers of five plants were taken from each plot and averaged for recording average plant height and number of tillers per plant, respectively. For crop yield, rhizomes were dug out from the soil and weighed from net plot area (after discarding one row on each side and 1 m on each end) and converted to per hectare. Crop was harvested on 30th April, 2013 and 2014.

Experiment-2: Crop phyto-toxicity was observed in some of the treatments during the experiment-1 and based on it, field experiment-2 was conducted with suitable changes in the treatment combinations during 2014-15 to 2015-16. The treatments included: metribuzin 700 g/ha PE at 0-3 DAS *fb* hoeing twice at 45 and 75 DAS, metribuzin 700 g/ha PE at 0-3 DAS *fb* fenoxaprop 67 g/ha PoE at 45 DAS or metribuzin 700 g/ha PE at 0-3 DAS *fb* rice straw mulching 10 t/ha at 3 DAS *fb* hoeing at 45 DAS, pendimethalin 1000 g/ha PE at 0-3 DAS *fb* hoeing twice at 45 and 75 DAS, pendimethalin 1000 g/ha PE at 0-3 DAS *fb* fenoxaprop 67 g/ha PoE at 45 DAS, pendimethalin 1000 g/ha PE at 0-3 DAS *fb* straw mulching 10 t/ha at 3 DAS *fb* HW at 45 DAS, atrazine 750 g/ha PE at 0-3 DAS *fb* hoeing twice at 45 and 75 DAS, atrazine 1000 g/ha PE at 0-3 DAS *fb* fenoxaprop 67 g/ha PoE at 45 DAS, atrazine 750 g/ha PE at 0-3 DAS *fb* rice straw mulching 10 t/ha at 3 DAS *fb* HW at 45 DAS, oxyfluorfen 300 g/ha PE at 0-3 DAS *fb* hoeing twice at 45 and 75 DAS, oxadiargyl 250 g/ha PE at 0-3 DAS *fb* hoeing twice at 45 and 75 DAS, glyphosate 0.2% (5.0 ml product/L) PoE at 25 DAS *fb* hoeing twice at 45 and 75 DAS, glyphosate 0.3% (7.5 ml product/L) PoE at 25 DAS *fb* hoeing twice at 45 and 75 DAS, along with HW thrice at 25, 45 and 75 DAS, weed free and weedy checks. Glyphosate was applied as PoE spray, as turmeric has tolerance to its lower doses. The experiment was laid out in randomized block design with three replicates. The plot size was 5.0 x 4.2 m, and the same turmeric variety was planted at a row spacing of 70 cm on 25th June, 2014 and 4th July, 2015. Crop was raised according to package of practices of the State University. Herbicides in both the experiments were applied with knapsack sprayer fitted with flat-fan nozzle using spray volume of 500 L/ha.

The observations on weed density and biomass were recorded at 105 DAS in 2014-15 and 75 DAS in 2015-16. As infestation and growth of weeds was more and at an early stage during second year, hence observations were recorded at 75 DAS instead of 105 DAS to avoid intermingling of weeds at advanced stage which makes the weed count difficult. Crop yield was recorded at harvest, and crop was harvested on 19th April, 2015 and 24th March, 2016. The observations on weeds and crop were recorded and weed control efficiency was computed as per methodology explained earlier. Economic parameters like variable cost, net returns over variable cost and benefit-cost ratio were also computed for understanding the economic viability of the treatments.

Residue studies

For residue studies, soils samples and rhizomes of turmeric were collected at harvest from herbicide applied plots during 2014-15 and 2015-16. Residues of herbicides were analyzed using GCMS/MS in Agrochemicals Residues Testing Laboratory, CCS Haryana Agricultural University, Hisar.

Residue analysis: Extraction and clean-up of glyphosate from soil and turmeric rhizome was done by using the method of Hu *et al.* (2008) through derivatization of glyphosate using triflouroacetic anhydride (TFAA) and triflouroethane (TFE). For extraction and clean-up of pendimethalin, metribuzin, atrazine, oxadiargyl and oxyfluorfen, the methodology of (Duhan *et al.* 2018) was used.

GCMS/MS analysis*:* Analysis of different herbicides was carried out using GCMS tandem mass spectrometry (Agilent 7890 A series with 7000 GCMS/MS detector). The details of methodology are elaborated by Kumari *et al.* (2021).

Statistical analysis: Before statistical analysis, the data on weed density were subjected to square root ($\sqrt{x+1}$) transformation to improve the homogeneity of the variance. The data were subjected to the Fisher's method of analysis of variance (ANOVA) (Fisher 1958) and significant treatment effect was judged with the help of 'F' test at the 5% level of significance by adopting the procedure described by Panse and Sukhatme (1985).

RESULTS AND DISCUSSION

Effect on weeds

The weed flora of the field consisted of grasses: *Dactyloctenium aegyptium, Brachiaria reptans, Eragrostis tenella* which were recorded during all the years of the study. In addition to these, other grasses recorded include: *Poa annua* and *Commelina benghalensis* during 2012-13, *Cynodon dactylon* and *Leptochloa chinensis* during 2013-14; and *Digitaria sanguinalis* during 2015-16. Some variation in grassy weed flora occurred during different years due to variation in time of weather, sowing time and growing conditions. Among broad-leaved weeds: *Euphorbia hirta, Phyllanthus niruri* occurred during 2012-2014. *Melilotus indica, Coronopus didymus, Anagallis arvensis* occurred during 2012-13. *Ammannia baccifera* occurred during 2013-14; *Melilotus indica, Coronopus didymus* and *Anagallis arvensis* occurred during 2014-15; *Trianthema monogyna* during 2015-16. Among sedges: *Cyperus rotundus* occurred during all the years. It indicated that along with *kharif* weeds, few *rabi* season broad-leaved weeds also infested the crop due to its long duration.

The treatments with rice straw mulch were found most effective against all type of weeds (**Table 1, 2, 5, 6**). Metribuzin 700 g/ha PE, pendimethalin 1000 g/ha PE or atrazine 750 g/ha PE *fb* straw mulch 10 t/ha at 3 DAS + HW at 50 DAS resulted into lowest density of grassy weeds, broad-leaved weeds and sedges during all the years of the study. Integration of hoeing twice with metribuzin 700 g/ha PE or pendimethalin 1000 g/ha PE was found to be the next best combination in reducing the weed density particularly the grassy weeds and sedges; however, it was inferior to the treatments with rice straw mulch. The tank-mix (TM) application of fenoxaprop 67 g/ha + metsulfuron 4 g/ha at 2-4 LS in sequence each with metribuzin 700 g/ha PE, pendimethalin 1000 g/ha PE or atrazine 750 g/ha PE also significantly reduced the grassy and broad-leaved weeds density and biomass (**Table 1**).

During 2014-15 and 2015-16, sequential application of fenoxaprop 67 g/ha PE with pendimethalin PE or metribuzin PE or atrazine PE was found to be the second-best treatment combination in reducing the density and biomass of grassy weeds indicating effectiveness of fenoxaprop as PoE herbicide against grassy weeds in turmeric (**Table 5, 6**). Those treatments were statistically similar to 2-hoeing treatment combinations each with pendimethalin, metribuzin, atrazine, oxyfluorfen or oxadiargyl (PE) and glyphosate (PoE), and the 3-HW treatment. The treatments having integration of PE herbicides with straw mulching + HW or PE/ PoE herbicides with 2-hoeing were the next best treatment combinations in reducing density and biomass of grassy weeds, and were similar to HW thrice with few exceptions. Among PE herbicides, pendimethalin was found better in reducing density and biomass of grassy weeds followed by metribuzin and atrazine during all the years (**Table 1, 2, 5, 6**).

Metribuzin PE or pendimethalin PE or atrazine PE *fb* straw mulch *fb* HW provided the lowest density and biomass of broad-leaved weeds and sedges during all the years, which was similar to weed free check and superior to all other weed management treatments (**Table 1, 2, 5, 6**). The PE herbicide combinations with 2-hoeing were the next best treatment combination in reducing BLW population and biomass and were similar to HW thrice. Among PE herbicidal treatment combinations, treatments with fenoxaprop (PoE) resulted in maximum density of BLW. Integration of hoeing twice with oxyfluorfen 300 g/ha PE in 2014-15 or glyphosate 0.3% (PoE) in 2015-16 was also found effective in reducing BLW population similar to HW thrice. Glyphosate 0.3% also provided control of BLW and sedges.

Integration of hoeing twice with PE herbicides including oxyfluorfen PE were found to be the next best treatment combinations in reducing sedges population and biomass in 2014-15, and were similar to HW thrice but such effects were not repeated in 2015-16 (**Table 5, 6**). Fenoxaprop was non-effective against sedges during all the years. The treatments with straw mulch could effectively reduce the sedges population among all the weed management treatments over the years (**Table 1, 2, 5, 6)**.

Maximum weed control efficiency (86.1-100.0%) was recorded under metribuzin, pendimethalin or atrazine PE + rice straw mulch 10 t/ ha *fb* one HW during all the years (**Table 2, 6).**

Table 1. Effect of different treatments on density of grassy weeds at 120 DAS in turmeric, 2012-13 and 2013-14

Treatment	Dose (g/ha)	Time (DAS)	Density of weeds (no./m^2)					
			Grassy weeds		Broad-leaved weeds		Sedges	
			2012-13	2013-14	2012-13	2013-14	2012-13	2013-14
Metribuzin *fb* hoeing *fb* hoeing	700/-/-	0-3/40/70	6.48(41.3)	1.00(0.0)	8.68(74.7)	5.45(28.7)	5.62(30.7)	4.79(23.3)
Metribuzin *fb* fenoxaprop+ metsulfuron	700/67+4	0-3/2-4 LS	4.58(20.0)	2.43(5.3)	8.25(67.3)	4.37(18.7)	7.54(56.0)	6.98(48.0)
Metribuzin *fb* straw mulching + HW	700/10T/-	0-3/50	2.56(6.0)	1.00(0.0)	4.58(20.7)	1.00(0.0)	2.52(6.0)	1.00(0.0)
Pendimethalin *fb hoeing fb* hoeing	1000/-/-	0-3/40/70	6.34(39.3)	1.00(0.0)	7.73(59.3)	5.96(34.7)	6.02(35.3)	5.45(29.3)
Pendimethalin *fb* fenoxaprop+ metsulfuron	1000/67+4	0-3/2-4 LS	4.79(22.0)	2.34(4.7)	8.72(75.3)	4.86(22.7)	7.68(58.7)	7.19(52.0)
Pendimethalin *fb* straw mulching + HW	1000/10T/-	0-3/50	3.83(14.0)	1.00(0.0)	5.25(27.3)	1.00(0.0)	1.67(2.7)	1.00(0.0)
Atrazine *fb* fenoxaprop+ metsulfuron	750/67+4	0-3/2-4 LS	5.17(26.0)	3.21(9.3)	7.53(56.0)	4.56(20.0)	7.27(52.0)	6.56(42.0)
Atrazine *fb* straw mulching + HW	750/10T/-	0-3/50	2.83(7.3)	1.00(0.0)	4.32(18.0)	1.00(0.0)	2.85(7.3)	1.00(0.0)
Weed free			1.00(0.0)	1.00(0.0)	1.00(0.0)	1.00(0.0)	1.00(0.0)	1.00(0.0)
Weedy check			8.54(72.0)	9.43(88.7)	1.00(0.0)	5.80(32.7)	1.00(0.0)	5.48(29.3)
LSD (p=0.05)			0.92	0.80	1.30	0.72	1.19	1.38

*Original figures in parentheses were subjected to square root transformation $(\sqrt{x+1})$ before statistical analysis; Abbreviations: HW=hand weeding, *fb*= followed by, DAS=days after sowing, LS=leaf stage, T=tons/ha

Table 2. Effect of different weed control treatments on weed biomass at 120 DAS in turmeric, 2012-13 and 2013-14

Treatment	Dose (g/ha)	Time (DAS)	Weed biomass (g/m^2)								Weed control efficiency (%)	
			Grass weeds		BLW		Sedges		Total weeds			
			2012-13	2013-14	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14
Metribuzin *fb* hoeing *fb* hoeing	700/-/-	0-3/40/70	23.9	0.0	13.2	3.9	3.3	2.9	40.4	6.8	79.2	92.5
Metribuzin *fb* fenoxaprop+ metsulfuron	700/67+4	0-3/2-4LS	43.8	8.6	30.9	2.1	6.8	10.4	81.5	21.1	58.1	76.6
Metribuzin *fb* straw mulching + HW	700/10T/-	0-3/50	7.2	0.0	4.2	0.0	1.4	0.0	12.8	0.0	93.4	100
Pendimethalin *fb* hoeing *fb* hoeing	1000/-/-	0-3/40/70	24.3	0.0	13.9	4.3	3.7	2.7	41.9	7.0	78.5	92.2
Pendimethalin *fb* fenoxaprop+ metsulfuron	1000/67+4	0-3/2-4LS	43.8	11.3	37.3	2.1	7.0	9.5	88.1	22.9	54.7	74.6
Pendimethalin *fb* straw mulching + HW	1000/10T/-	0-3/50	10.9	0.0	5.0	0.0	0.5	0.0	16.4	0.0	91.6	100
Atrazine *fb* fenoxaprop+ metsulfuron	750/67+4	0-3/2-4LS	48.1	14.6	38.3	2.3	7.0	8.6	93.4	25.5	52.0	71.7
Atrazine *fb* straw mulching + HW	750/10T/-	0-3/50	10.3	0.0	4.1	0.0	1.7	0.0	16.1	0.0	91.7	100
Weed free			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100	100
Weedy check			194.5	81.8	0.0	4.6	0.0	3.8	194.5	90.2	0.0	0.0
LSD (p=0.05)			10.4	11.8	8.6	1.2	1.8	2.2	16.3	12.5		

Abbreviations: HW=hand weeding, BLW=broad-leaved weeds, *fb*= followed by, DAS=days after sowing, LS=leaf stage, T=tons/ha

Channappagoudar *et al.* (2013) also reported better weed control efficiency with pendimethalin 1.5 kg/ha in turmeric. Integration of hoeing twice with PE herbicides was found to be the next best combination which resulted in 68.3 to 92.5% WCE. Integration of hoeing twice with oxyfluorfen PE or oxadiargyl PE (67.4-69.9%) or glyphosate 0.3% PoE (65.2-87.0%) during 2014-15 and 2015-16 also resulted in satisfactory WCE. The fenoxaprop treatments provided WCE (80.7-84.7%) almost similar to HW thrice (82.4%) during 2015-16 but similar or lower WCE (62.7-68.6%) than 3-HW (72.9%) during 2014-15.

Suppressing effect of straw mulch on weeds is due to physical obstruction to germinating weed seedlings and barrier to light penetration towards soil surface, resulting in fewer emergence of weeds. Gill *et al.* (2000) found that the herbicidal treatments alone did not provide season-long weed control in turmeric, but the integration of metribuzin PE, atrazine PE or diuron PE with one hand weeding at 55 DAS achieved effective control of weeds. Manhas *et al.* (2011) has also reported that increase in the paddy straw mulch levels from no mulch to 6.25 t/ha and then to 9.38 t/ha significantly decreased weeds in turmeric. Kaur *et al.* (2008) reported that pendimethalin PE, metribuzin PE or atrazine PE integrated with straw mulch 9 t/ha gave satisfactory weed management in turmeric in Punjab. Similarly, integration of hoeing, hand weeding or straw mulch 10 t/ha with metribuzin PE, pendimethalin PE or atrazine PE were found effective in controlling weeds in turmeric by Barla *et al.* (2015). Ratnam *et al.* (2012) reported the weed control efficacy of integration of oxyfluorfen 0.25 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha PoE and hand weeding twice at 60 and 90 DAS.

Effect on crop

During 2012-13 and 2013-14, metribuzin 700 g/ha PE, pendimethalin 1000 g/ha PE or atrazine 750 g/ha PE with straw mulch 10 t/ha at 3 DAS and one HW, resulted in maximum number of surviving plants at 180 DAS, which were similar to metribuzin or pendimethalin with 2-hoeing and weed free check (**Table 3**). These treatments resulted in higher plant stand than weedy check, but the differences were not always significant. Lowest number of surviving

Table 3. Effect of different weed control treatments on yield attributes (at 180 DAS) and yield of turmeric, 2012-13 and 2013-14

Treatment	Dose (g/ha)	Time (DAS)	No. of plants ('000/ha)		Plant height (cm)		No. of tillers/ plant		Yield (t/ha)	
			2012-13	2013-14	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14
Metribuzin *fb* hoeing *fb* hoeing	700/-/-	0-3/40/70	43.1	41.7	98.0	103.1	5.53	4.07	10.01	10.30
Metribuzin *fb* fenoxaprop+ metsulfuron	700/67+4	0-3/2-4 LS	24.7	35.1	22.4	55.1	1.87	3.67	2.40	5.96
Metribuzin *fb* straw mulching + HW	700/10T/-	0-3/50	42.1	45.9	97.5	124.8	6.33	5.33	14.29	15.24
Pendimethalin *fb hoeing fb* Hoeing	1000/-/-	0-3/40/70	42.8	40.8	97.2	102.1	5.27	4.07	11.81	12.44
Pendimethalin *fb* fenoxaprop+ metsulfuron	1000/67+4	0-3/2-4 LS	25.2	33.8	20.9	49.0	1.47	3.40	1.60	6.49
Pendimethalin *fb* straw mulching + HW	1000/10T/-	0-3/50	46.2	44.1	98.2	111.3	6.47	4.80	15.05	17.16
Atrazine *fb* fenoxaprop+ metsulfuron	750/67+4	0-3/2-4 LS	21.2	34.7	22.9	53.7	1.73	3.60	1.88	5.83
Atrazine *fb* straw mulching + HW	750/10T/-	0-3/50	45.7	44.3	96.8	118.9	6.20	5.07	14.99	16.97
Weed free			45.2	41.6	94.3	106.9	5.60	4.53	13.51	13.55
Weedy check			36.4	39.3	87.9	105.7	3.80	3.80	4.58	7.50
LSD (p=0.05)			6.9	4.2	5.3	14.6	0.96	0.75	1.57	0.76

Abbreviations: HW=hand weeding, *fb*= followed by, DAS= days after sowing, LS=leaf stage, T=tons/ha

Table 4. Phyto-toxicity of different herbicidal treatments on turmeric crop at different intervals, 2012-13 and 2013-14

Treatment	Dose (g/ha)	Time (DAS)	Phyto-toxicity (%)							
			2012-13				2013-14			
			30 DAS	60 DAS	90 DAS	12 DAS	30 DAS	60 DAS	90 DAS	12 DAS
Metribuzin *fb* hoeing *fb* hoeing	700/-/-	0-3/40/70	10.0	4.0	0.0	0.0	0.0	0.0	3.3	3.3
Metribuzin *fb* fenoxaprop+ metsulfuron	700/67+4	0-3/2-4 LS	10.0	28.3	78.3	90.0	0.0	48.3	50.0	35.0
Metribuzin *fb* straw mulching + HW	700/10T/-	0-3/50	10.0	1.3	0.0	0.0	0.0	0.0	0	0.0
Pendimethalin *fb* hoeing *fb* Hoeing	1000/-/-	0-3/40/70	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
Pendimethalin *fb* fenoxaprop+ metsulfuron	1000/67+4	0-3/2-4 LS	0.0	33.3	86.7	90.0	0.0	61.7	55.0	43.3
Pendimethalin *fb* straw mulching + HW	1000/10T/-	0-3/50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Atrazine *fb* fenoxaprop+ metsulfuron	750/67+4	0-3/2-4 LS	2.0	31.7	83.3	90.0	0.0	40.0	50.3	53.3
Atrazine *fb* straw mulching + HW	750/10T/-	0-3/50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Weed free			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Weedy check			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Abbreviations: HW=hand weeding, *fb* =followed by, DAS=days after sowing, LS=leaf stage, T=tons/ha plants was recorded under the fenoxaprop + metsulfuron (TM) treatment, due to the phyto-toxicity of the herbicide combination on turmeric. Plant height under all the weed management treatments, except fenoxaprop + metsulfuron, were similar to each other and weed free check during 2012-13. During 2013-14, plant height was maximum under PE herbicides + straw mulch + HW treatments, which was followed by PE herbicides + 2-hoeing treatments. Plant height under herbicide + straw mulch + HW treatments and weed free check was higher than weedy check during both the years; however, during 2013-14, plant height under weed free and weedy checks was similar. Falling of dried weeds after maturity in weedy check resulted in high soil moisture conditions due to its mulching effect, which might have mitigated the negative effect of weeds on plant height.

Among weed management treatments, metribuzin or pendimethalin PE or atrazine PE + straw mulch + HW resulted in maximum number of tillers, which was followed by metribuzin PE or pendimethalin PE + hoeing twice during 2012-13 and 2013-14 (**Table 3**). All weed management treatments, other than treatments having fenoxaprop + metsulfuron, resulted in tillering statistically similar

Table 5. Effect of different weed control treatments on density of weeds at 105/ 75 DAS* in turmeric, 2014-15 and 2015-16

Treatment	Dose (g/ha)	Time (DAS)	Weed density (no./m^2) Grass weeds 2014-15	Grass weeds 2015-16	Broad-leaved weeds 2014-15	Broad-leaved weeds 2015-16	Sedges 2014-15	Sedges 2015-16
Metribuzin *fb* hoeing *fb* hoeing	700/-/-	0-3/45/75	4.85(24.0)	3.31(10.0)	6.61(44.0)	5.54(30.0)	5.18(26.0)	15.96(254.0)
Metribuzin *fb* fenoxaprop	700/67/-	0-3/45	3.82(14.7)	2.37(4.7)	7.40(58.7)	7.49(55.3)	6.83(46.0)	15.28(233.3)
Metribuzin *fb* straw mulching *fb* HW	700/10T/-	0-3/3/75	1.00(0.0)	3.69(12.7)	1.00(0.0)	2.79(7.3)	1.00(0.0)	5.31(29.3)
Pendimethalin *fb* hoeing *fb* hoeing	1000/-/-	0-3/45/75	3.95(16.7)	1.66(2.0)	6.49(42.0)	5.62(30.7)	5.12(25.3)	14.64(214.0)
Pendimethalin *fb* fenoxaprop	1000/67	0-3/45	4.43(18.7)	1.00(0.0)	7.90(62.0)	7.50(56.0)	6.71(45.3)	15.80(250.0)
Pendimethalin *fb* straw mulching *fb* HW	1000/10T/-	0-3/3/75	1.00(0.0)	2.37(4.7)	1.00(0.0)	2.63(6.0)	1.00(0.0)	5.97(35.3)
Atrazine *fb* hoeing *fb* hoeing	750/-/-	0-3/45/75	4.57(20.0)	3.69(12.7)	5.69(32.0)	5.36(28.0)	5.17(26.0)	11.43(130.0)
Atrazine *fb* fenoxaprop	750/67	0-3/45	5.12(25.3)	3.21(9.3)	7.36(53.3)	6.91(47.3)	6.79(45.3)	11.85(140.7)
Atrazine *fb* straw mulching *fb* HW	750/10T/-	0-3/3/75	1.00(0.0)	4.43(18.7)	1.00(0.0)	2.95(8.0)	1.00(0.0)	5.47(29.3)
Oxyfluorfen *fb* hoeing *fb* hoeing	300/-/-	0-3/45/75	4.39(18.7)	3.59(12.0)	6.98(48.0)	8.08(64.7)	5.83(33.3)	15.60(243.3)
Oxadiargyl *fb* hoeing *fb* hoeing	250/-/-	0-3/45/75	4.49(19.3)	3.32(10.0)	8.18(66.0)	9.39(87.3)	6.66(43.3)	14.71(216.7)
Glyphosate *fb* hoeing *fb* hoeing	0.2%/-/-	25/45/75	3.88(14.7)	3.49(11.3)	8.79(76.7)	9.71(93.3)	3.60(12.0)	8.47(71.3)
Glyphosate *fb* hoeing *fb* hoeing	0.3%/-/-	25/45/75	2.97(8.0)	1.90(2.7)	9.33(86.0)	6.98(48.0)	2.85(7.3)	7.21(52.0)
Hand weeding thrice	-/-/-	25/45/75	3.90(14.7)	3.40(10.7)	6.99(48.7)	6.34(39.3)	4.91(23.3)	9.49(89.3)
Weed free			1.00(0.0)	1.00(0.0)	1.00(0.0)	1.00(0.0)	1.00(0.0)	1.00(0.0)
Weedy check			6.71(44.7)	7.63(57.3)	9.45(88.7)	11.15(123.3)	6.80(45.3)	17.38(301.3)
LSD (p=0.05)			1.19	0.47	1.62	1.03	0.96	1.52

Abbreviations: HW=hand weeding, *fb*= followed by, DAS=days after sowing, T=tons/ha; *At 105 DAS in 2014-15 and 75 DAS in 2015-16; **Original figures in parentheses were subjected to square root transformation ($\sqrt{x+1}$) before statistical analysis

Table 6. Effect of different weed control treatments on weed biomass and weed control efficiency (WCE) at 105/75 DAS* in turmeric, 2014-15 and 2015-16

Treatment	Dose (g/ha)	Time (DAS)	Weed biomass (g/m^2) Grassy weeds 2014-15	Grassy weeds 2015-16	Broad-leaved weeds 2014-15	Broad-leaved weeds 2015-16	Sedges 2014-15	Sedges 2015-16	Total weeds 2014-15	Total weeds 2015-16	WCE (%) 2014-15	WCE (%) 2015-16
Metribuzin *fb* hoeing *fb* hoeing	700/-/-	0-3/45/75	33.1	14.3	6.3	6.3	6.4	30.3	45.8	50.9	68.3	85.1
Metribuzin *fb* fenoxaprop	700/67/-	0-3/45	28.9	1.9	8.3	13.9	8.1	44.6	45.3	60.4	68.6	82.4
Metribuzin *fb* straw mulching *fb* HW	700/10T/-	0-3/3/75	0.0	36.4	0.0	4.4	0.0	0.3	0.0	41.1	100.0	88.0
Pendimethalin *fb* hoeing *fb* hoeing	1000/-/-	0-3/45/75	21.5	12.7	5.7	9.8	5.5	38.1	32.7	60.6	77.3	82.3
Pendimethalin *fb* fenoxaprop	1000/67	0-3/45	34.1	0.0	10.0	16.5	8.1	49.5	52.2	66.0	63.8	80.7
Pendimethalin *fb* Straw mulching *fb* HW	1000/10T/-	0-3/3/75	0.0	23.5	0.0	4.0	0.0	2.4	0.0	29.9	100.0	91.3
Atrazine *fb* hoeing *fb* hoeing	750/-/-	0-3/45/75	29.8	20.3	5.2	7.9	4.6	21.0	39.6	49.2	72.6	85.6
Atrazine *fb* fenoxaprop	750/67	0-3/45	36.8	8.2	8.2	11.6	8.8	32.7	53.8	52.5	62.7	84.7
Atrazine *fb* straw mulching *fb* HW	750/10T/-	0-3/3/75	0.0	42.1	0.0	4.8	0.0	0.8	0.0	47.7	100.0	86.1
Oxyfluorfen *fb* hoeing *fb* hoeing	300/-/-	0-3/45/75	30.9	46.8	5.9	20.7	6.7	44.1	43.5	111.6	69.9	67.4
Oxadiargyl *fb* hoeing *fb* hoeing	250/-/-	0-3/45/75	28.7	39.6	7.0	28.9	10.1	36.9	45.8	105.4	68.3	69.2
Glyphosate *fb* hoeing *fb* hoeing	0.2%/-/-	25/45/75	32.5	13.8	12.2	35.0	5.5	15.2	50.2	64.0	65.2	81.3
Glyphosate *fb* hoeing *fb* hoeing	0.3%/-/-	25/45/75	19.6	5.9	12.2	25.6	3.5	12.9	35.3	44.4	75.5	87.0
Hand weeding thrice	-/-/-	25/45/75	27.4	22.5	6.1	18.9	5.6	19.0	39.1	60.4	72.9	82.4
Weed free			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0
Weedy check			120.5	194.8	12.7	60.5	11.1	87.3	144.3	342.6	0.0	0.0
LSD (p=0.05)			20.1	9.5	2.6	9.8	2.0	17.6	20.8	22.7		

Abbreviations: HW: hand weeding, *fb:* followed by, DAS: days after sowing, T: tons/ha; *At 105 DAS in 2014-15 and 75 DAS in 2015-16 to weed free with few exceptions. Lowest number of tillers was recorded under fenoxaprop + metsulfuron treatments which was even lower than the weedy checks (3.80/plant), owing to its phyto-toxicity on turmeric.

PE herbicides + mulching + HW produced highest rhizome yield of turmeric which was similar or even higher than weed free check during all the years (**Table 3, 7**) confirming observations of Manhas *et al.* (2011). The second-best treatment combination was realized to be metribuzin PE or pendimethalin PE *fb* hoeing twice during 2012-13 and 2013-14 (**Table 3**). Integration of hoeing twice with PE of metribuzin, pendimethalin, atrazine, oxyfluorfen or glyphosate 0.3% PoE produced rhizome yields similar to HW thrice in 2014-15 and 2015-16 except metribuzin + hoeing twice being better than HW thrice and similar to weed free check during 2014-15 (**Table 7**). The treatments of PE herbicides + fenoxaprop PoE also produced rhizome yield similar to weed free check/ HW thrice in 2014-15, but these were inferior to weed free check/ HW thrice in 2015-16 except pendimethalin *fb* fenoxaprop being at par with HW thrice. Oxadiargyl PE or glyphosate 0.2% (PoE) + hoeing twice produced lower yield than weed free/HW thrice during both the years. Performance of oxyfluorfen treatment was not consistent, as it produced rhizome yield like HW thrice in 2014-15 but like weedy check in 2015-16. HW thrice produced grain yield like weed free checks during 2014-15, but lower in 2015-16. Lowest rhizome yields were recorded under the treatments having fenoxaprop + metsulfuron (**Table 3**), due to its phyto-toxicity on the crop. There was 42-66% loss in rhizome yield of turmeric under due to weeds during all the years (**Table 3, 7**).

Phyto-toxicity

The treatments with fenoxaprop+ metsulfuron showed phyto-toxicity on the crop at all the stages of observation (90% in 2012-13 and 35-53% in 2013-14 at 120 DAS) (**Table 4**). The differential behavior might be attributed to early planting of crop in second year. There was minor phyto-toxicity at initial stage (10% at 30 DAS) with metribuzin 700 g/ha PE during 2012-13, which recovered with time. Other treatments did not show any phyto-toxic effects on the crop.

There was no phyto-toxicity of any of the herbicidal treatments on turmeric during 2014-2015 and 2015-2016, indicating possibilities of their safe use in turmeric. No phyto-toxicity of fenoxaprop in 2014-15 and 2015-16 but fenoxaprop+ metsulfuron showed phytotoxicity in earlier years (**Table 3**) indicating that fenoxaprop was safe to the turmeric crop but not the metsulfuron.

Economics

The integration of PE herbicides with mulching + HW resulted in highest net returns and benefit-cost ratio among all the treatments during both the years (**Table 7**) as reported by Kaur *et al.* (2008). PE herbicides + fenoxaprop PoE treatments were the next best treatments in respect of net returns and B-C ratio during 2014-15. While during 2015-16, hoeing twice integrated with metribuzin/ atrazine were

Table 7. Effect of different weed control treatments on productivity and economics of turmeric, 2014-15 and 2015-16

Treatment	Dose (g/ha)	Time (DAS)	Yield (t/ha)		Variable cost (₹/ha)		Net returns (₹/ha)		B:C ratio	
			2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16
Metribuzin *fb* hoeing *fb* hoeing	700/-/-	0-3/45/75	14.25	15.51	65,887	66,358	76,605	88,709	2.16	2.34
Metribuzin *fb* fenoxaprop	700/67/-	0-3/45	16.01	12.69	54,758	55,228	105,309	71,628	2.92	2.30
Metribuzin *fb* straw mulching *fb* HW	700/10T/-	0-3/3/75	18.30	17.50	61,185	61,655	121,803	113,306	2.99	2.84
Pendimethalin *fb* hoeing *fb* hoeing	1000/-/-	0-3/45/75	14.42	13.95	65,704	66,175	78,454	73,358	2.19	2.11
Pendimethalin *fb* fenoxaprop	1000/67	0-3/45	15.86	13.08	54,575	55,045	104,011	75,785	2.91	2.38
Pendimethalin *fb* straw mulching *fb* HW	1000/10T/-	0-3/3/75	18.60	16.93	61,002	61,472	124,994	107,874	3.05	2.75
Atrazine *fb* hoeing *fb* hoeing	750/-/-	0-3/45/75	14.05	14.63	65,051	65,522	75,414	80,732	2.16	2.23
Atrazine *fb* fenoxaprop	750/67	0-3/45	15.44	12.10	53,922	54,392	100,473	66,561	2.86	2.22
Atrazine *fb* straw mulching *fb* HW	750/10T/-	0-3/3/75	17.94	16.62	60,349	60,819	119,001	105,390	2.97	2.73
Oxyfluorfen *fb* hoeing *fb* hoeing	300/-/-	0-3/45/75	14.14	7.68	65,156	65,626	76,201	11,205	2.17	1.17
Oxadiargyl *fb* hoeing *fb* hoeing	250/-/-	0-3/45/75	12.62	10.48	65,417	65,887	60,798	38,955	1.93	1.59
Glyphosate *fb* hoeing *fb* hoeing	0.2%/-/-	25/45/75	13.22	11.78	65,417	65,887	66,788	51,892	2.02	1.79
Glyphosate *fb* hoeing *fb* hoeing	0.3%/-/-	25/45/75	16.09	13.31	66,070	66,540	94,807	66,540	2.43	2.00
Hand weeding thrice	-/-/-	25/45/75	15.53	13.24	69,754	70,224	85,512	62,202	2.23	1.89
Weed free			15.17	15.18	69,754	70,224	81,900	81,539	2.17	2.16
Weedy check			6.73	8.79	50,944	51,414	16,367	36,463	1.32	1.71
LSD (p=0.05)			1.51	0.46						

Abbreviations: HW: hand weeding, *fb:* followed by, DAS: days after sowing, T: tons/ha superior to metribuzin/ atrazine + fenoxaprop treatments as reported by Barla *et al*. (2015). Glyphosate 0.3% + hoeing twice was also found promising in respect of net returns and B-C ratio.

Residue studies

None of the soil and turmeric rhizome samples collected at harvest were found to contain residues of any of the applied herbicides above detection limit of 0.01 µg/ml (in case of glyphosate and oxadiargyl) and 0.001 µg/ml (in case of pendimethalin, atrazine, metribuzin and oxyfluorfen). This indicated about the safe application of these herbicides for weed management in turmeric.

The present four years study revealed that the weeds pose a profoundly serious problem in turmeric causing yield losses to the extent of 42-66%. Pre-emergence application of metribuzin 700 g/ha, pendimethalin 1000 g/ha or atrazine 750 g/ha integrated with 10 t/ha rice straw mulching after three days of herbicide application and one hand weeding at 50/75 DAS proved effective to control complex weed flora in turmeric with improved rhizome yields and better economic returns. The integration of hand hoeing twice at 45 and 75 DAS with metribuzin 700 g/ha PE, pendimethalin 1000 g/ha PE or atrazine 750 g/ha PE were also found to be the next best IWM options, if straw for mulching is available. Use of rice straw in IWM strategies in turmeric will also help sustain and economize such production systems by curtailing undesired herbicide load, better crop residue management (avoiding burning) and conserving soil moisture and other natural resources. There were no detectable residues of any of the tested herbicides in the soil and turmeric rhizomes at harvest, indicating their safety for weed management in turmeric.

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