



RESEARCH ARTICLE

Effect of crop establishment and weed management on weed suppression and productivity of Basmati rice

Shipra Yadav^{1,2}, S B Singh², Robin Kumar², Saurav Chaurasiya², Anand Singh², Prakash Yadav², Dharmendra Kumar^{3*}, Dev Narayan Yadav⁴ & Sharddha Yadav²

¹Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut 250 110, Uttar Pradesh, India

²Acharya Narendra Deva University of Agriculture and Technology Kumarganj, Ayodhya 224 229, Uttar Pradesh, India

³School of Advanced Agriculture Sciences and Technology (SAAST), Chhatrapati Shahu Ji Maharaj University, Kanpur 208 024, Uttar Pradesh, India

⁴International Rice Research Institute-South Asia Regional Centre, Varanasi 221 106, Uttar Pradesh, India

*Correspondence email - dharmendrakumar@csjmu.ac.in

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Abstract

A field experiment was conducted during the kharif seasons of 2019 and 2020 at the Crop Research Centre, Sardar Vallabhbhai Patel University of Agriculture and Technology (SVPUAT), Meerut, Uttar Pradesh, to evaluate the effect of crop establishment and weed management on weed suppression and productivity of Basmati rice (*Oryza sativa* L.). The experiment was laid out in a split-plot design with three establishment methods-conventional puddled transplanting (CPT), unpuddled flat planting (UPF) and furrow-irrigated raised beds (FIRB) and five weed management treatments including herbicidal combinations, hand weeding and a weedy check. The results revealed that CPT recorded the highest growth parameters and grain yield, followed by FIRB, whereas UPF recorded the lowest performance. Although FIRB produced slightly lower yield than CPT, it compensated through improved soil health and higher economic returns. For weed control, two rounds of hand weeding did the best job at keeping weeds down, but using pretilachlor followed by bispyribac sodium or combining mix with bispyribac sodium worked almost as well and brought in even more profit. So, pairing FIRB with pretilachlor and bispyribac sodium represents a viable, sustainable and profitable strategy for Basmati rice cultivation.

Keywords: Basmati rice; crop establishment; profitability; weed dynamics; weed management; yield

Introduction

Basmati rice (*Oryza sativa* L.) has a distinct role in Indian agriculture due to its aroma, grain quality and export potential. India is the world's biggest exporter of Basmati rice and the crop generates significant farm revenue, particularly in the Indo-Gangetic Plains. Despite its economic importance, Basmati rice cultivation confronts several obstacles, one of the most important being weed infestation. Weeds compete with rice for nutrients, water, light and space and yield losses in rice due to weeds can range from 30 % to as high as 60 % if no control measures are adopted (1,2).

Crop establishment methods play a crucial role in determining crop-weed competition. Conventional puddled transplanting (CPT) has long been the dominant method of rice cultivation; however, it is often criticised for its high water and labour requirements and its adverse effects on soil structure. Consequently, alternative methods such as direct seeding, unpuddled flat planting (UPF) and furrow-irrigated raised beds (FIRB) have been promoted to enhance water-use efficiency and improve sustainability (3, 4). Each of these methods creates a different soil and crop environment, which directly affects weed flora composition and weed dynamics (5). Effective weed management is essential for ensuring the success of these establishment methods. Manual weeding although effective, is labour-intensive and often not feasible under current labour shortages.

Herbicide based weed management has become common but exclusive reliance on herbicides can lead to shifts in weed flora and resistance development (6). Integrated strategies combined use of pre-emergence and post-emergence herbicides with cultural methods offering a more sustainable solution (7, 8).

Despite advances in weed management research, few studies have investigated how different establishment strategies interact with weed control practices in Basmati rice. Understanding these connections is critical for developing lucrative and sustainable production systems. Thus, the present study was undertaken "to evaluate the effect of crop establishment methods and weed management practices on weed dynamics, crop growth, yield and profitability of Basmati rice" in western Uttar Pradesh.

Materials and Methods

The field experiment was carried out at Sardar Vallabhbhai Patel University of Agriculture and Technology's Crop Research Centre in Meerut, Uttar Pradesh, during the kharif seasons of 2019 and 2020. The region is in western Uttar Pradesh and has a semi-arid, subtropical climate characterised by hot, dry summers, cold winters and an average annual rainfall of 845 mm, almost 80–90 % of which falls during the south-west monsoon months of June to September.

The soil at the experimental site was sandy loam in texture, somewhat alkaline in reactivity, low in organic carbon and accessible nitrogen and medium in phosphorus and potassium. The experiment was laid out in a split-plot design with 4 replications, comprising three crop establishment methods in main plots such as CPT, UPF and FIRB and five weed management practices in sub-plots, namely: pretilachlor at 0.75 kg ha⁻¹ PE followed by bispyribac sodium at 20 g a.i. ha⁻¹ PoE at 20 days after transplanting (DAT), Almix at 4 g a.i. ha⁻¹ + bispyribac sodium at 20 g a.i. The gross plot size was 6.0 m × 3.6 m (21.6 m²), whereas the net plot size was 5.0 m × 2.8 m (14.0 m²). Observations and yield data were collected after eliminating border rows to reduce edge effects. An irrigation channel of 1.5 m width was maintained between plots. Crop establishment methods were assigned to main plots and weed management treatments to sub-plots following a randomised procedure within each replication. The crop was transplanted using a seed rate of 30 kg ha⁻¹. Spacing under flat conditions was maintained at 20 cm × 10 cm, while in the FIRB system, a spacing of 15 cm × 10 cm was followed. The Basmati rice variety Pusa Basmati-1 was used as the test crop grown under recommended cultural practices with timely irrigation and fertiliser application based on soil test values. Observations were recorded on weed flora, weed density and dry weight at different crop stages, as well as crop yield attributes and grain yield. Data from both years were pooled and analysed following the split-plot design procedure (9). The standard error of mean (SEM±) was calculated and treatment comparisons were made using the critical difference (CD) at a 5% level of probability.

Results and Discussion

Effect of crop establishment methods and weed management options on weed

Weed density

Total weed density was significantly influenced by crop establishment methods and weed management practices at all growth stages during both years (Fig. 1). The CPT recorded lower weed density (6.14–6.74 No. m⁻² at 30 DAT and 7.81–8.28 No. m⁻² at harvest) than UPF (8.80–9.22 No. m⁻² at 30 DAT). Among weed control treatments, two hand weeding had the lowest weed density (4.43–5.15 No. m⁻² at 30 DAT) followed by pretilachlor pre-emergence followed by bispyribac sodium post-emergence (5.30–5.85 No. m⁻²), while the weedy check recorded the highest values (14.42–14.75 No. m⁻² at 30 DAT) indicating severe competition (10, 11).

The density of specific weeds *Echinochloa crus-galli* (L.) P.Beauv., *Cyperus rotundus* L., *Eclipta alba* (L.) Hassk., *Eleusine indica* (L.) Gaertn., *Phyllanthus niruri* L. and other flora showed similar trends. The CPT continuously had lower densities compared to UPF, while two hand weeding and successional herbicide application minimised infestation across all species. Maximum densities occurred in the weedy check. Reduced weed density under puddled transplanting and integrated weed management may be attributed to suppression of weed germination restricted tuber sprouting under anaerobic conditions and effective control of successive weed flushes (10, 12–16).

Weed dry matter

Total weed dry weight was significantly affected by crop establishment methods and weed management practices at all stages during both years (Fig. 2). The CPT had the lowest weed biomass across stages

(3.25–3.73 g m⁻² at 30 DAT and 5.83–6.14 g m⁻² at harvest), while UPF had the highest values (4.36–4.70 g m⁻² at 30 DAT and 7.81–8.01 g m⁻² at harvest), with FIRBs in the middle. Among weed control strategies, two-handed weeding resulted in the lowest weed dry weight (2.20–2.78 g m⁻² at 30 DAT and 4.78–5.12 g m⁻² at harvest), followed by Pretilachlor followed by Bispyribac sodium, while the weedy check consistently had the highest biomass throughout the season.

Dry weight of individual weed species also varied significantly with treatments. *Echinochloa crus-galli* and *C. rotundus* recorded the lowest biomass under CPT and highest under UPF with two hand weeding or successional herbicide application being most effective (5, 17). *Eclipta alba* showed comparatively higher biomass under FIRBs, whereas *E. indica* and *P. niruri* were most abundant under UPF and were effectively suppressed by hand weeding or Pretilachlor followed by Bispyribac sodium (10, 18, 19). Other weed species followed a similar trend with lowest biomass under CPT and highest under UPF and effective control through integrated weed management practices (20, 21).

Weed control efficiency

Weed control efficiency (WCE) was significantly influenced by crop establishment methods and weed management practices in both years (Fig. 3). Conventional puddled transplanting recorded the highest WCE among crop establishment methods (61.34–57.74 % at 60 DAT and 59.42–57.8 % at 90 DAT), while UPF showed the lowest efficiency (51.99–48.4 % at 60 DAT and 49.22–48.15 % at 90 DAT). Furrow irrigated raised beds were intermediate. Among weed management strategies, two hand weeding exhibited the maximum WCE (83.83–78.75 % at 60 DAT and 80.22–78.33 % at 90 DAT) closely followed by Pretilachlor followed by Bispyribac sodium, whereas bispyribac sodium alone recorded the least efficiency. Enhanced WCE under puddled transplanting and integrated chemical/manual control is likely due to reduced weed emergence and better suppression of successive flushes, supporting previous observations (20, 22).

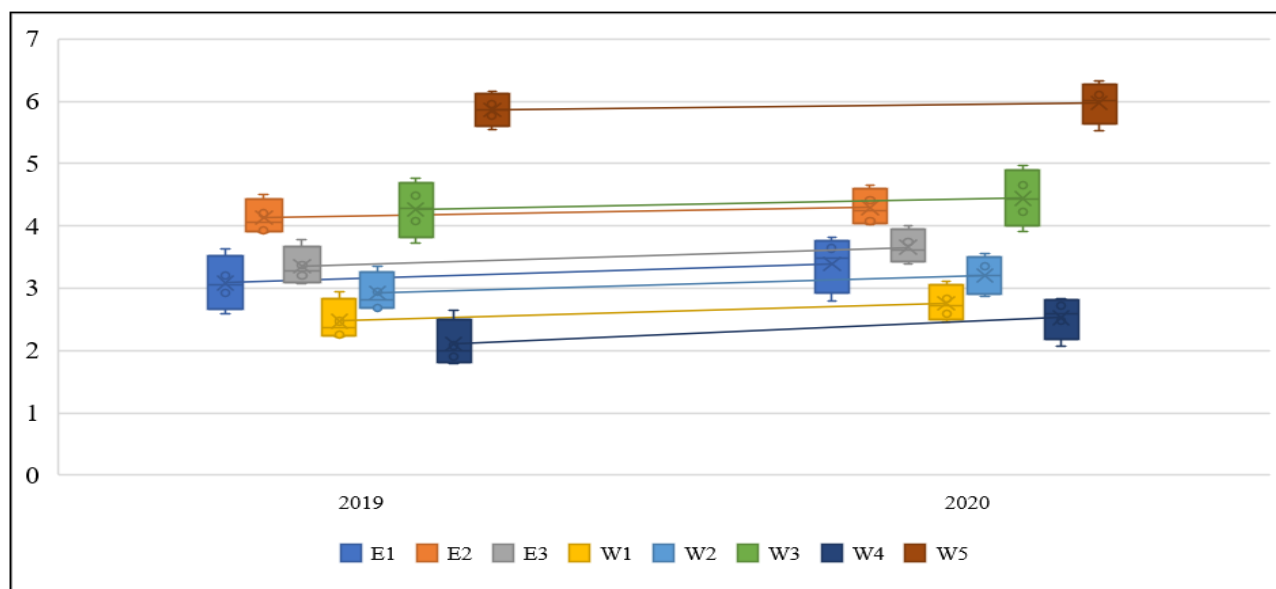
Effect of crop establishment methods and weed management options on growth parameters of Basmati rice

Plant height

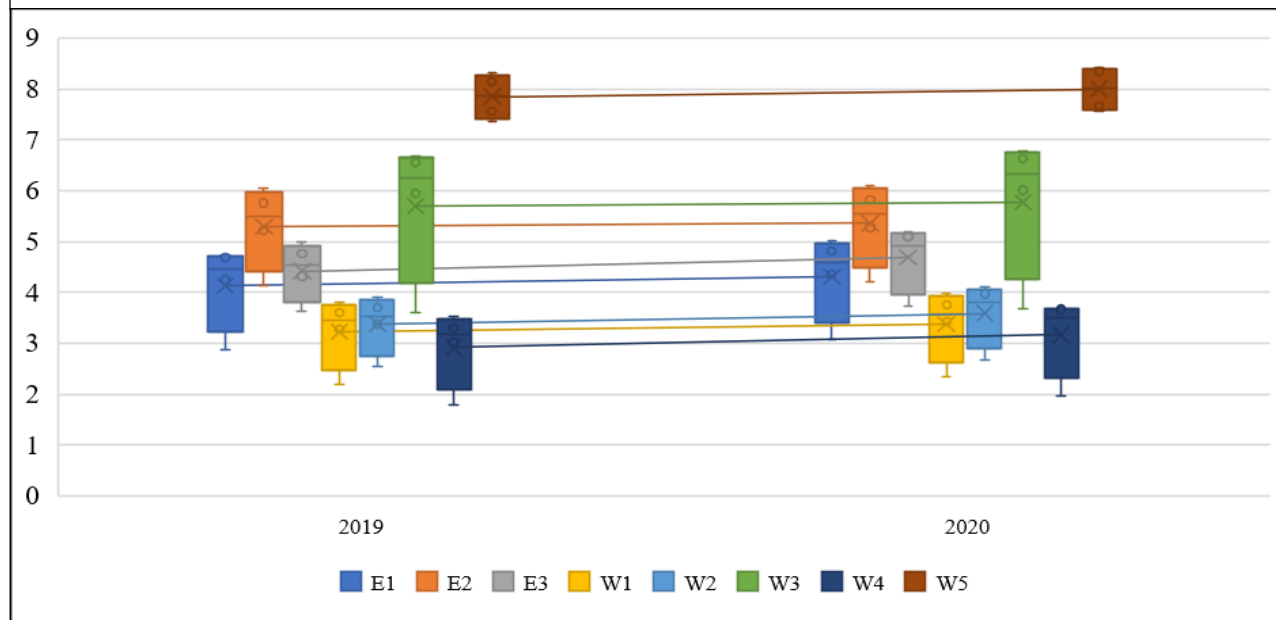
In 2019 and 2020, crop establishment strategies and weed control had a substantial impact on rice plant height across all growth stages (30, 60, 90DAT and harvest) (Fig. 4). The CPT produced the tallest plants at all stages (44.3–46.3 cm at 30DAT to 96.3–99.2 cm at harvest), followed by FIRBs (42.4–44.4 cm to 92.8–93.8 cm) and UPF (40.2–40.8 cm to 88.1–90 cm). Weed management had a significant impact on plant height at all stages. The sequential application of Pretilachlor followed by bispyribac sodium (W1) resulted in the tallest plants (45.5–46.5 cm to 98.8–100.6 cm), while the weedy check (W5) produced the shortest plants (39.1–40.8 cm to 75.2–76.8 cm). These findings show that combining effective crop establishment (CPT) with timely and suitable weed control (W1) consistently improves vegetative growth at all phases of rice development (23).

Number of tillers

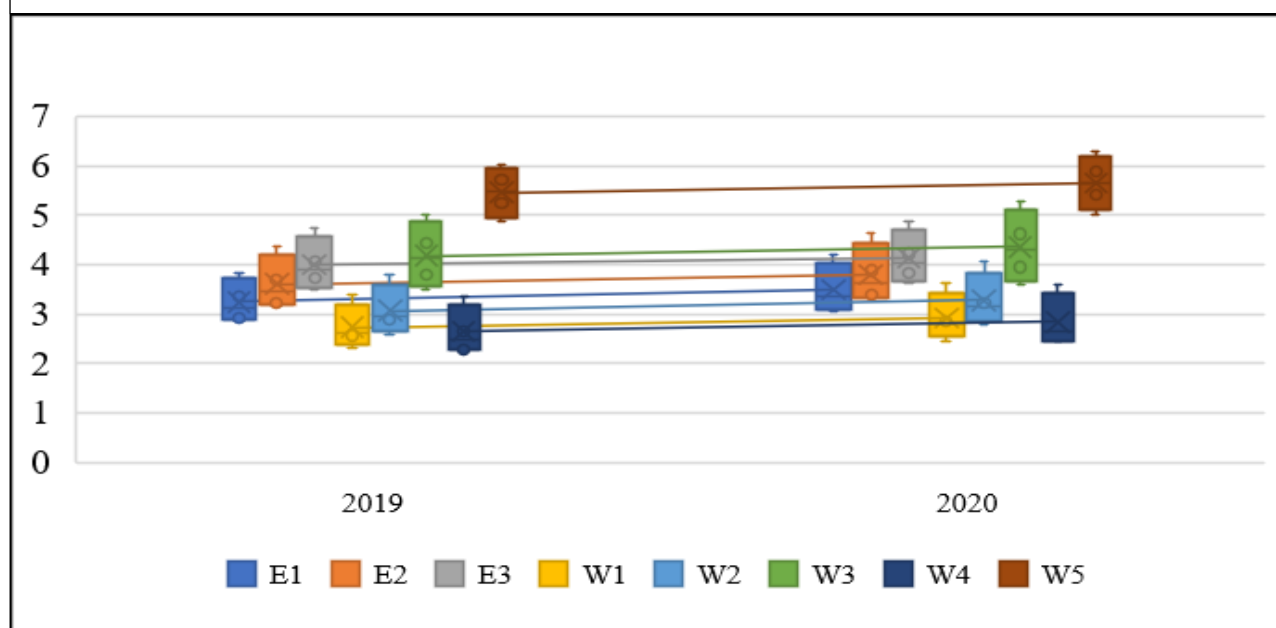
In 2019 and 2020, crop establishment strategies and weed control had a considerable impact on the quantity of tillers in rice across all growth stages (30, 60, 90DAT and harvest) (Fig. 5). The FIRBs consistently generated the most tillers at all stages (132.9–134.7 at 30DAT to 225–227.6 at harvest), followed by standard puddled transplanting (125.4–127.4 to 218.4–220.8) and UPF (121.5–122.5 to 204.8–208.1). This is most likely owing to enhanced soil aeration and



(a)



(b)



(c)

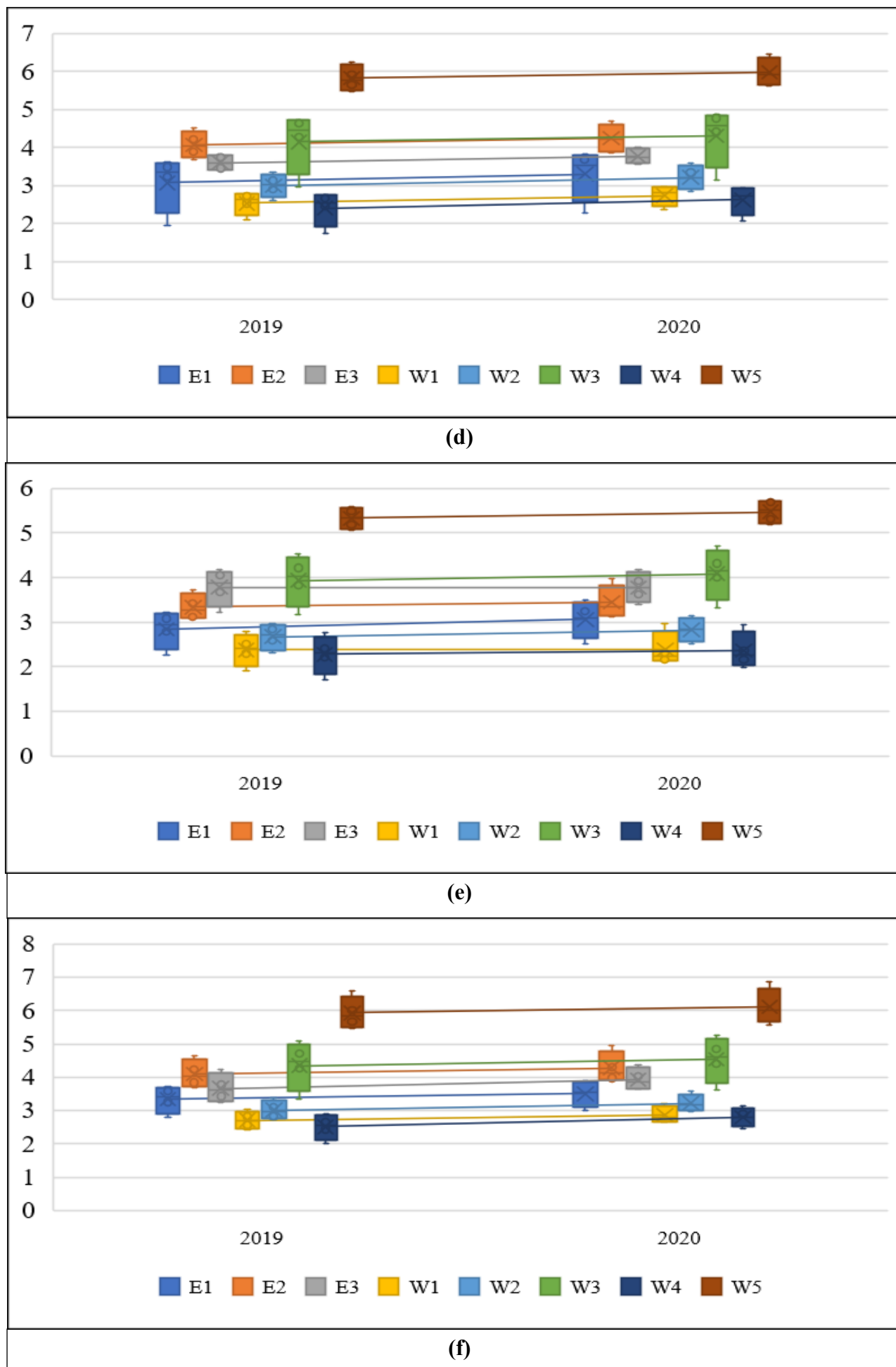
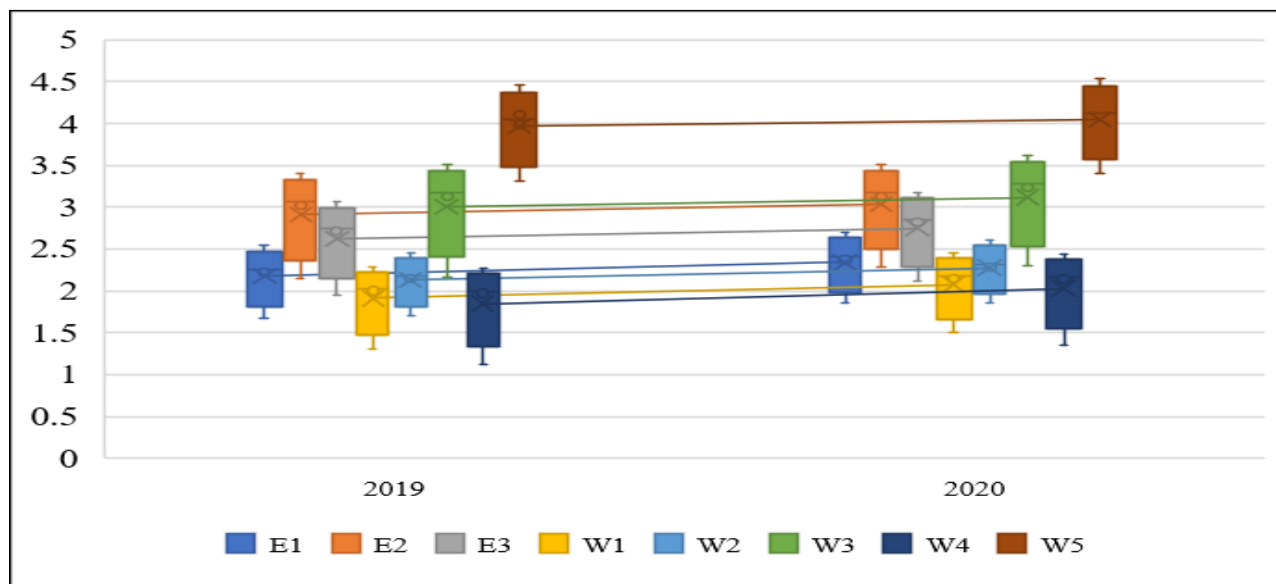
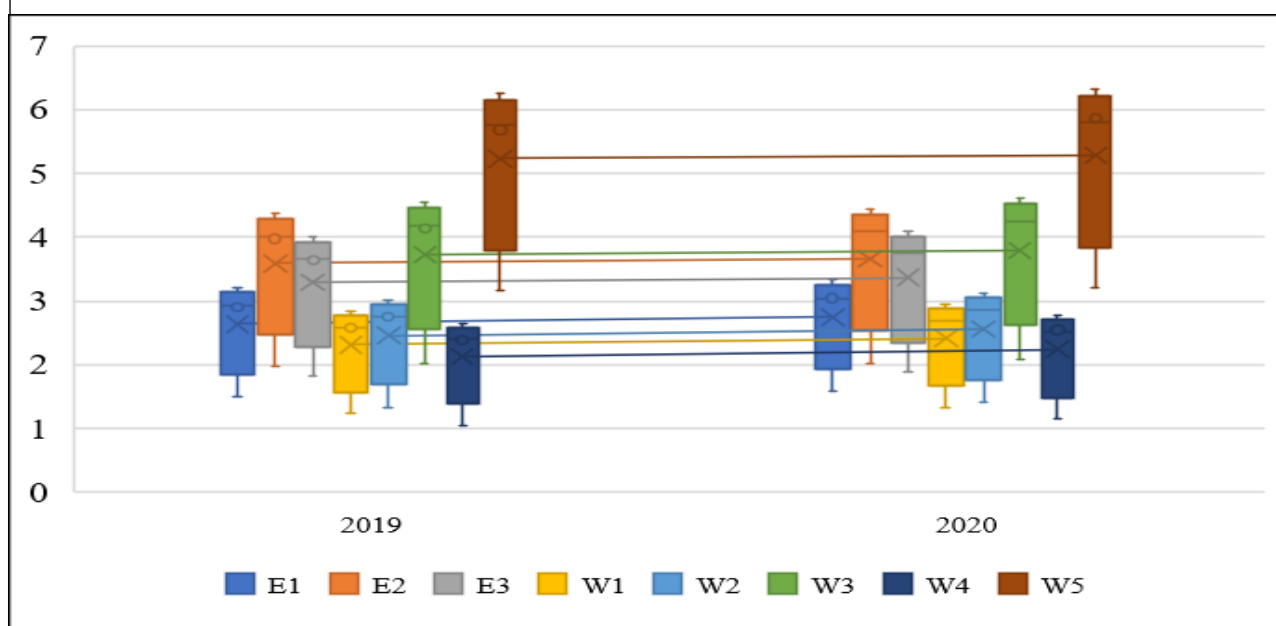


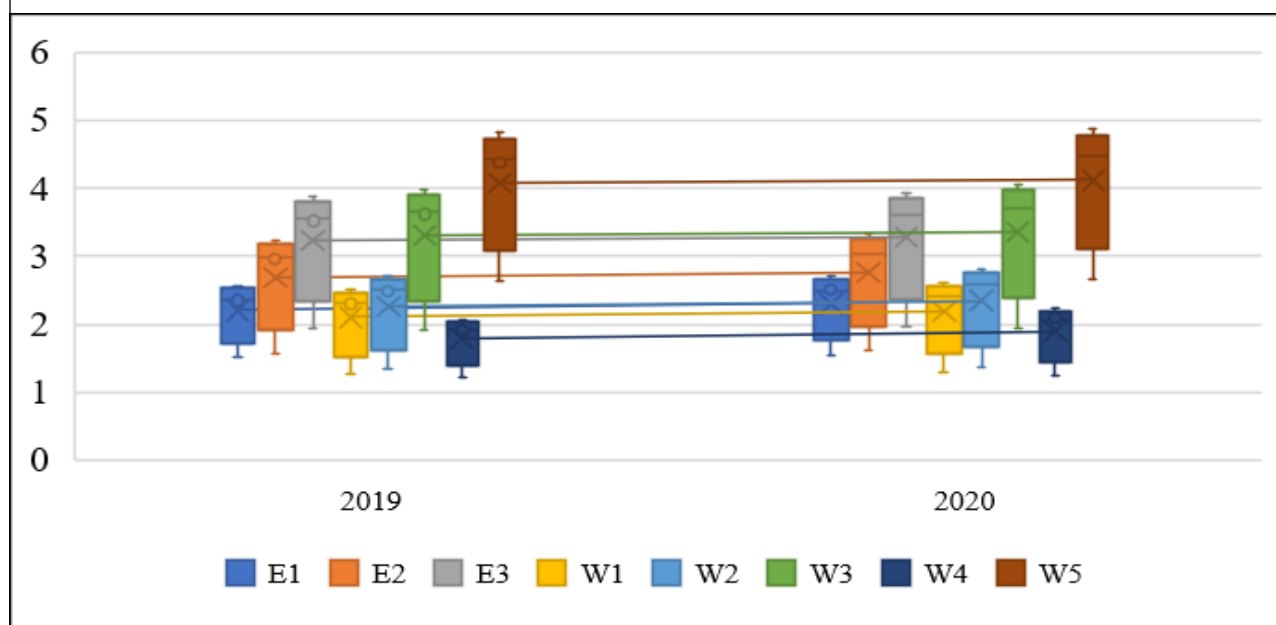
Fig. 1. Effect of crop establishment methods and weed management practices on weed density in Basmati rice: (a) *Echinochloa crus-galli* (m⁻²); (b) *Cyperus rotundus* (m⁻²); (c) *Eclipta alba* (m⁻²); (d) *Eleusine indica* (m⁻²); (e) *Phyllanthus niruri* (m⁻²); (f) *Cyperus rotundus* (m⁻²).



(a)



(b)



(c)

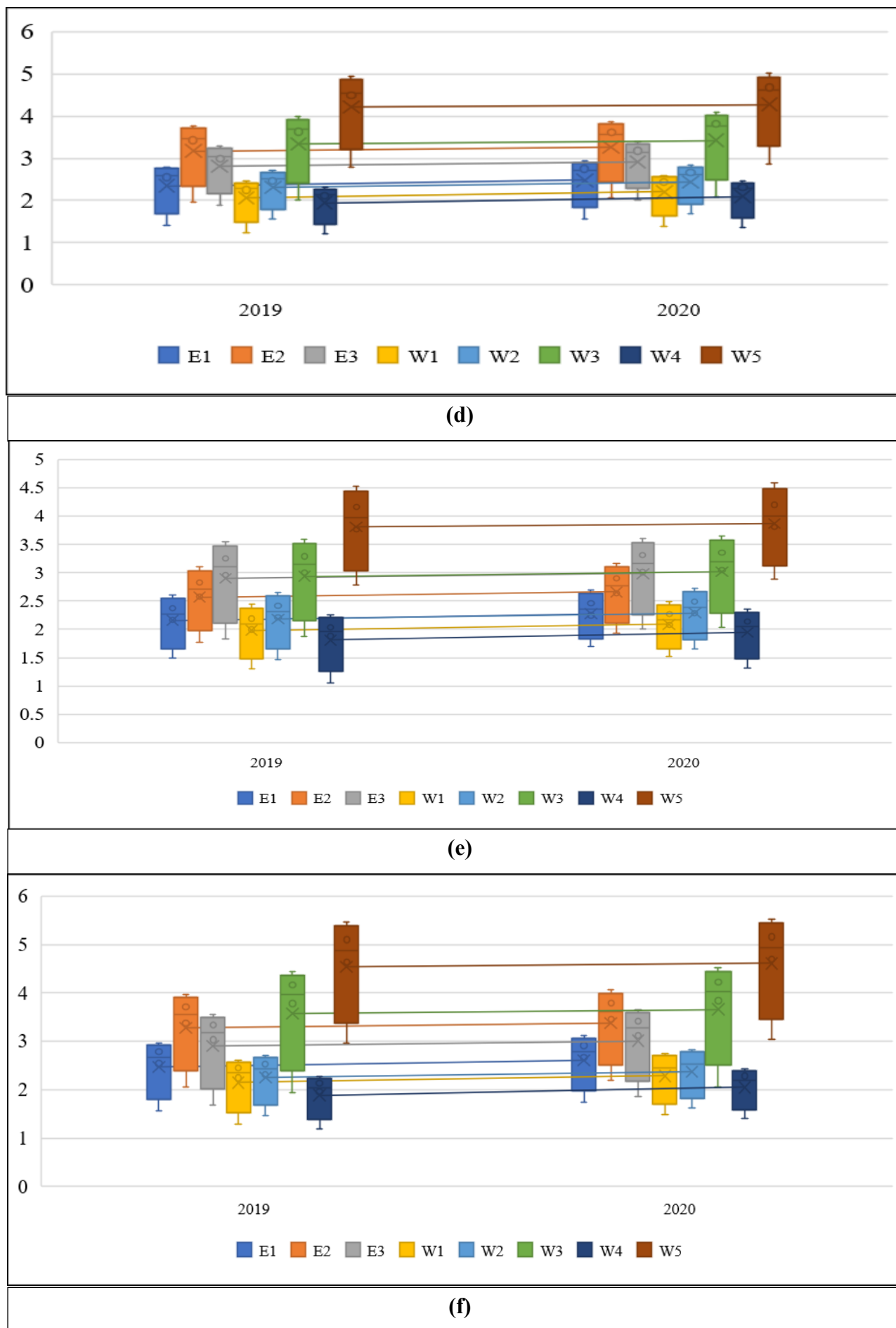


Fig. 2. Effect of crop establishment methods and weed management practices on weed dry weight in Basmati rice: (a) total weed dry weight of *Echinochloa crus-galli* (g m^{-2}); (b) total weed dry weight of *Cyperus rotundus* (g m^{-2}); (c) total weed dry weight of *Eclipta alba* (g m^{-2}); (d) total weed dry weight of *Eleusine indica* (g m^{-2}); (e) total weed dry weight of *Phyllanthus niruri* (g m^{-2}); (f) total weed dry weight of *Cyperus rotundus* (g m^{-2}).

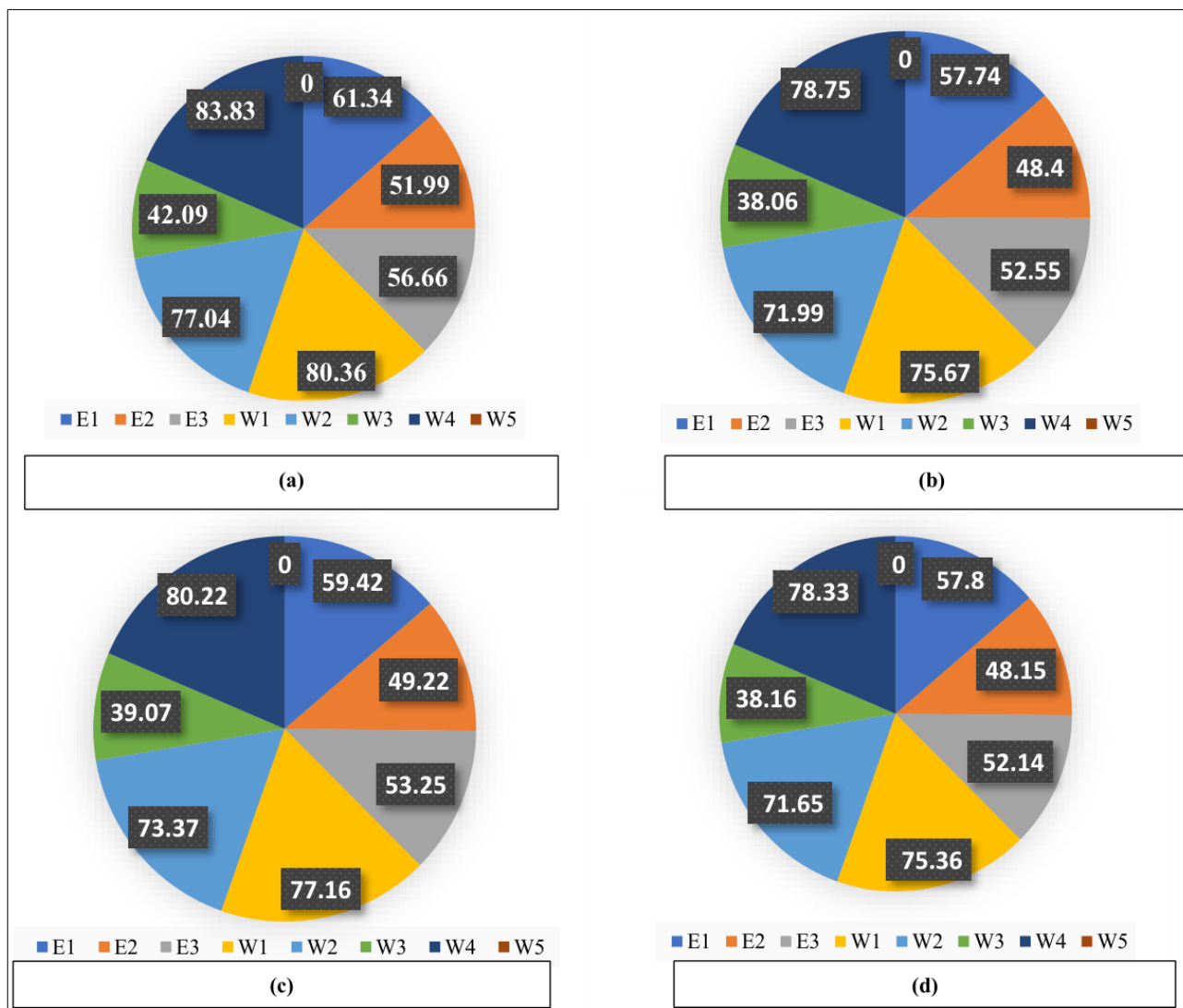


Fig. 3. Effect of crop establishment methods and weed management practices on weed control efficiency (WCE) in Basmati rice: (a) WCE (%) at 60 DAT (2019); (b) WCE (%) at 60 DAT (2020); (c) WCE (%) at 90 DAT (2019); (d) WCE (%) at 90 DAT (2020).

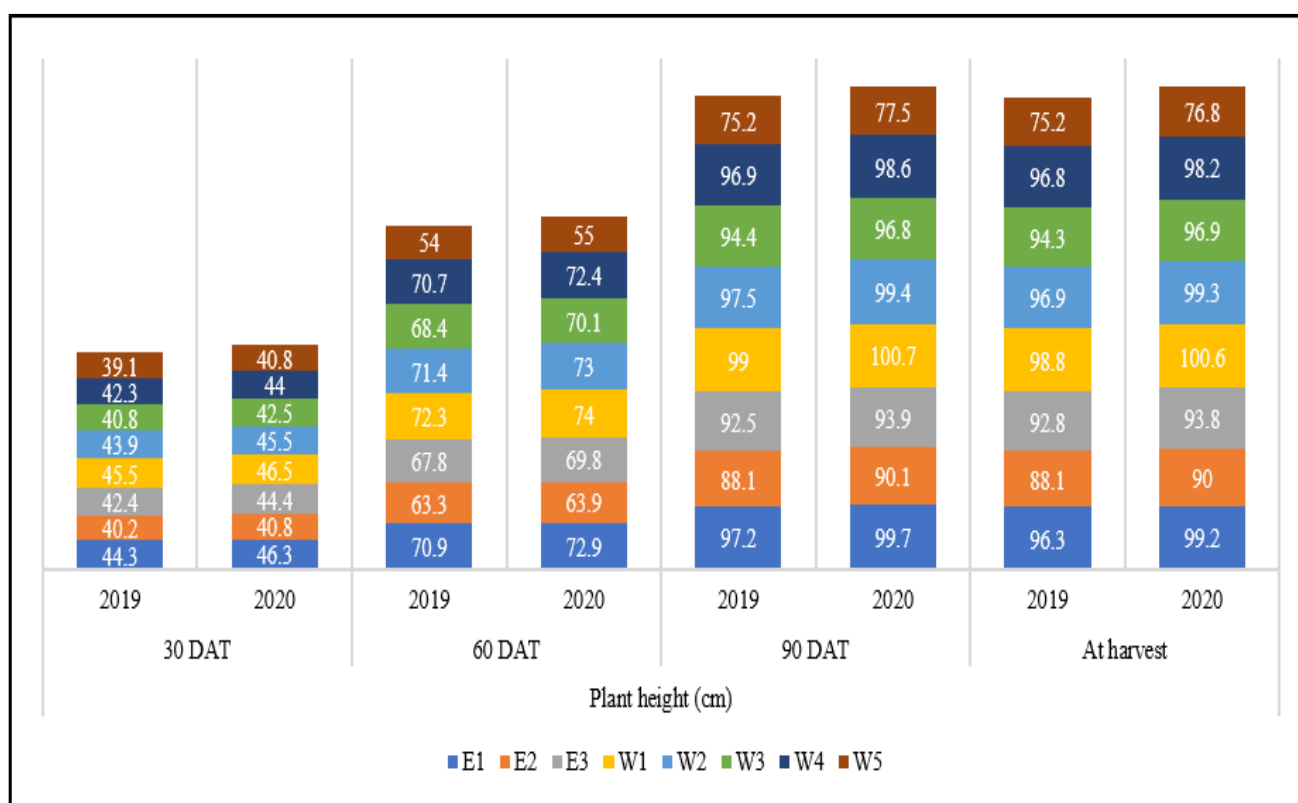


Fig. 4. Effect of crop establishment methods and weed management options on plant height (cm).

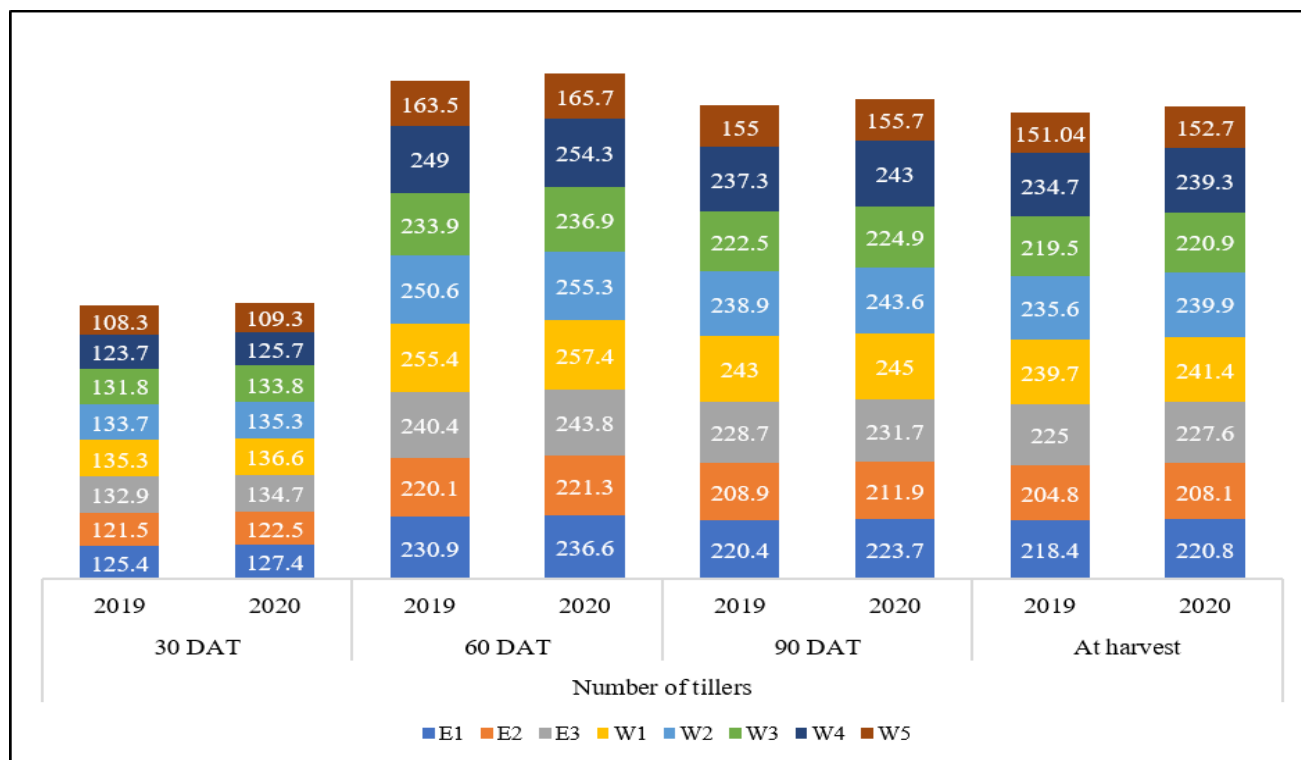


Fig. 5. Effect of crop establishment methods and weed management options on number of tillers/plant.

nutrient availability in FIRBs, which encourage tiller initiation and survival. Weed management had a significant impact on tillering. The successional application of Pretilachlor followed by Bispyribac sodium (W1) resulted in the highest number of tillers at all stages (135.3–136.6 at 30DAT to 239.7–241.4 at harvest). The weedy check (W5) had the lowest tiller numbers (108.3–109.3 to 151–152.7) due to weed competition. These data suggest that combining FIRBs or CPT with good weed management (W1) consistently improves tiller production and may lead to increased yield (23).

Dry matter accumulation

In 2019 and 2020, crop establishment strategies and weed control had a substantial impact on dry matter accumulation (DMA) in rice across all growth stages (30, 60, 90 DAT and harvest) (Fig. 6). Among

crop establishment methods, CPT accumulated the highest dry matter at all stages (150.6–155.8 g plant⁻¹ at 30DAT to 1091.4–1109.4 g plant⁻¹ at harvest), followed by furrow irrigated raised beds (FIRBs, 142.3–145.7 g plant⁻¹ to 1049.6–1051.6 g plant⁻¹) and UPF (133.8–137.2 g plant⁻¹ to 921.6–957.6 g plant⁻¹). The CPT's greater performance is most likely attributed to improved early development and nutrient uptake in a more favourable root environment. Weed management had a significant impact on DMA at all stages. The successional application of Pretilachlor followed by Bispyribac sodium (W1) resulted in the highest biomass (151.5–155.0 g plant⁻¹ at 30DAT to 1119.5–1122.2 g plant⁻¹ at harvest), while the weedy check (W5) had the lowest accumulation (120.9–125.0 g plant⁻¹ to 826.9–852.9 g plant⁻¹) due to intense resource competition. These findings are consistent with prior

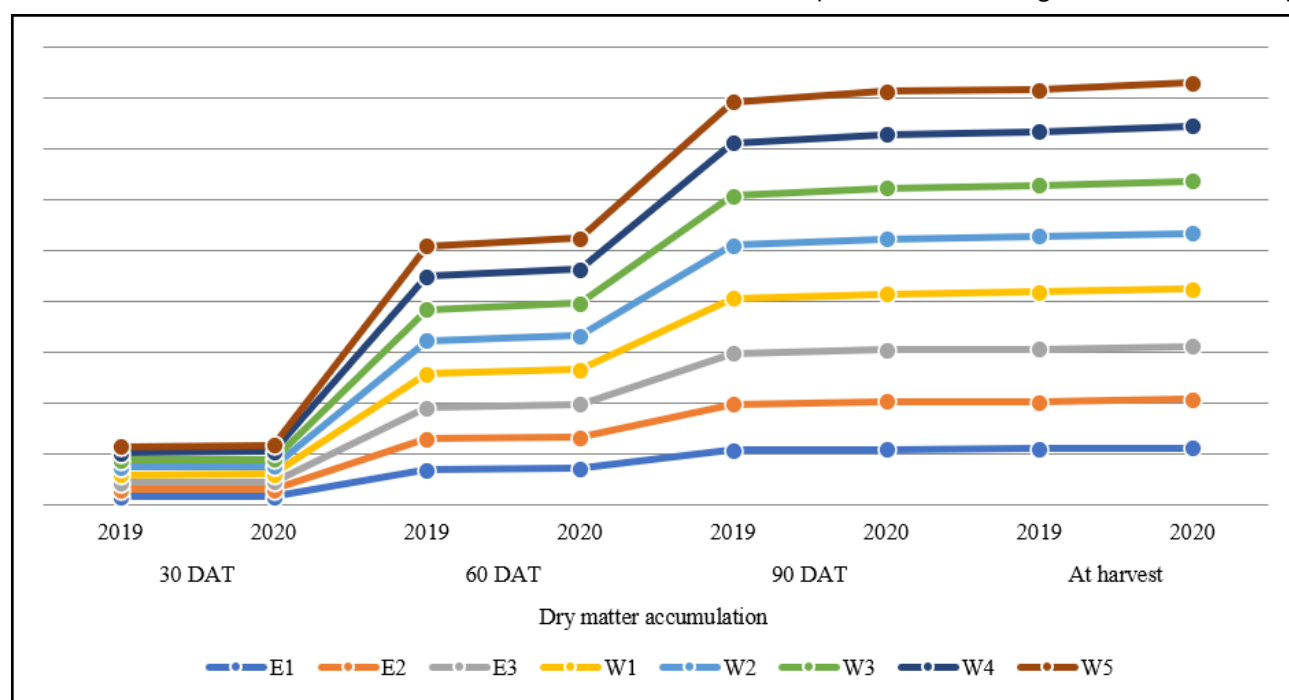


Fig. 6. Effect of crop establishment methods and weed management options on dry matter accumulation (g).

research, which has shown that establishing procedures and weed management have a considerable impact on rice growth and productivity (24).

Leaf area index

Leaf area index (LAI) of rice was significantly influenced by both crop establishment methods and weed management at all measured stages 30, 60 and 90DAT in 2019 and 2020 (Fig. 7). Among CPT continuously produced the highest LAI at all stages (2.47–2.51 at 30DAT to 4.8–5.0 at 90DAT) followed by FIRBs (2.37–2.4 to 4.77–4.92) and UPF (2.3–2.35 to 4.46–4.59). This is likely due to better early canopy development and efficient nutrient uptake under CPT. Weed management also significantly affected LAI successional application of Pretilachlor followed by Bispyribac sodium (W1) produced the highest LAI at all stages (2.48–2.52 to 5.25–5.41), whereas the weedy check (W5) continuously had the lowest values (2.14–2.18 to 3.33–3.45) due to competition from weeds for light and nutrients. These results indicate that combined of effective crop establishment

(CPT) with timely and appropriate weed control (W1) enhances canopy development and photosynthetic capacity supporting better growth and yield (24).

Crop growth rate

Crop establishment methods and weed control approaches have a substantial impact on rice crop growth rate (CGR) in 2019 and 2020 (30–60 DAT and 60–90 DAT, respectively) (Fig. 8). The CPT and FIRBs had higher CGR (17.82–18.25 and 12.58–12.72 $\text{g m}^{-2} \text{day}^{-1}$ for CPT and 16.01–16.89 and 12.46–12.59 $\text{g m}^{-2} \text{day}^{-1}$ for FIRBs) compared to UPF 15.73–15.86 and 10.43–10.90 $\text{g m}^{-2} \text{day}^{-1}$ indicating stronger assimilate production and vegetative vigour. Weed management had a significant impact on CGR. Pretilachlor followed by Bispyribac sodium (W1) resulted in the highest growth rates (17.09–17.66 and 13.89–13.98 $\text{g m}^{-2} \text{day}^{-1}$), while weedy check (W5) had the lowest rates (7.4–7.65 $\text{g m}^{-2} \text{day}^{-1}$), likely due to competition for light and nutrients. These findings are consistent with previous research, which has shown that agronomic and weed control

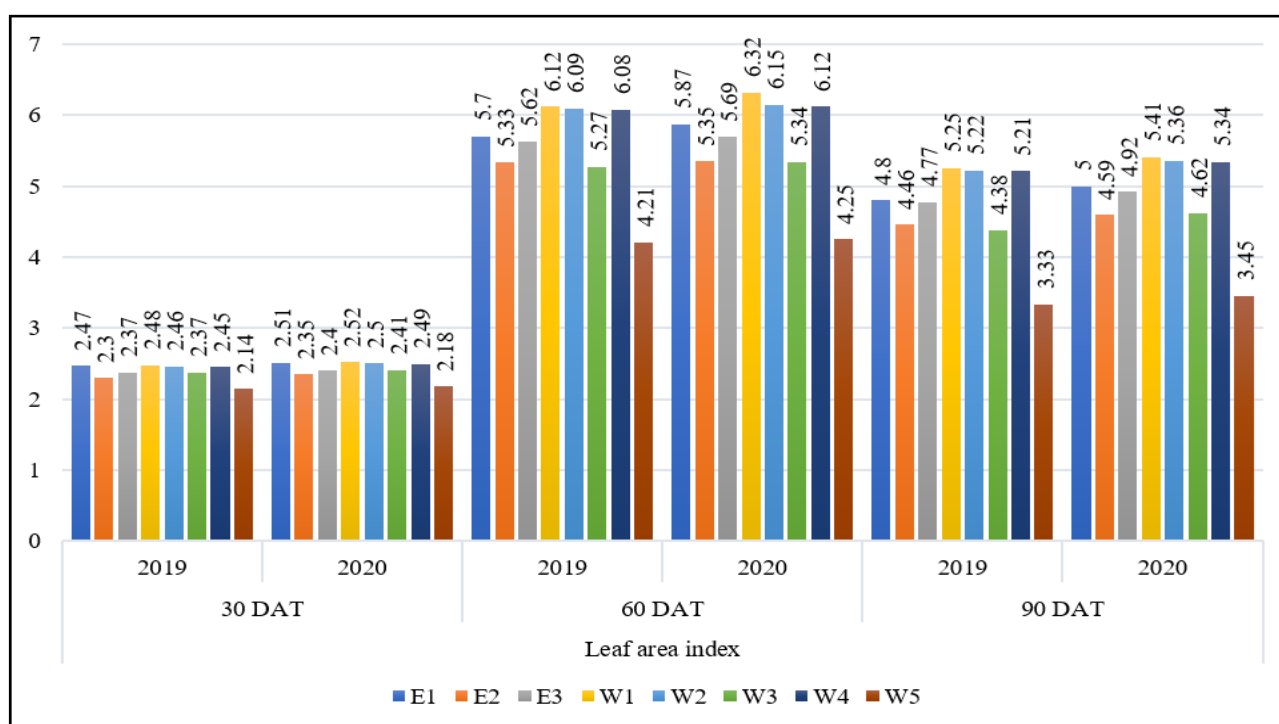


Fig. 7. Effect of crop establishment methods and weed management options on leaf area index.

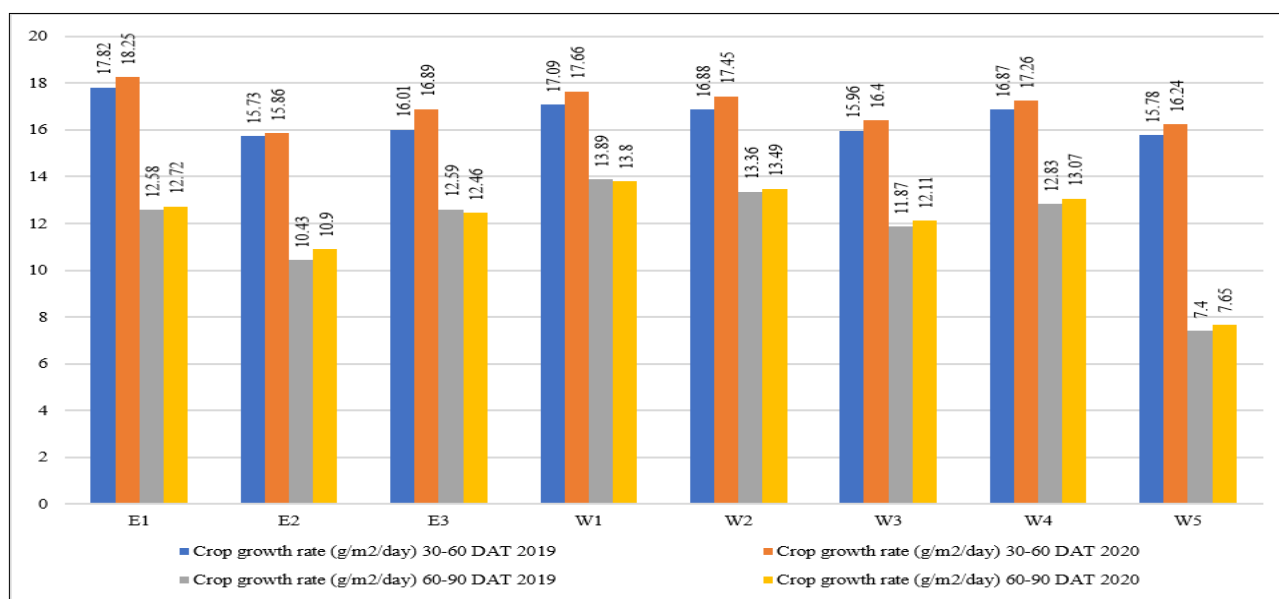


Fig. 8. Effect of crop establishment methods and weed management options on crop growth rate (CGR).

strategies have a considerable impact on rice growth dynamics and CGR (25).

Effective tillers

Effective tiller (m^{-2}) of rice was significantly affected by both crop establishment methods and weed management in 2019 and 2020 (Fig. 9). Among the CPT produced the highest number of effective tillers (182.4 – $182.6m^{-2}$) followed by FIRBs (171.2 – $173.4m^{-2}$) and UPF (163.1 – $170.3m^{-2}$) indicating that proper puddling and transplanting favour tiller survival and panicle formation. Weed management also significantly affected on number of effective tillers, successional application of Pretilachlor followed by Bispyribac sodium (W1) recorded the maximum number of effective tillers (187.1 – $190.4m^{-2}$) whereas the weedy check (W5) had the lowest (129.6 – $132.3m^{-2}$) highlighting the negative impact of weed competition on yield

components. These findings are relevant with previous research showing that crop establishment methods and timely weed control significantly enhanced tiller formation and ultimately grain yield in rice (26).

Panicle length

Panicle length of rice was significantly influenced by crop establishment methods and weed management in 2019 and 2020 (Fig. 10). Among establishment methods like CPT produced the longest panicles (24 – $24.5cm$) followed by FIRBs (22.9 – $23.8cm$) and UPF ($21.8cm$) showing that better early growth and nutrient uptake under CPT favours panicle development. Weed management also had a significant effect; sequential application of Pretilachlor followed by Bispyribac sodium (W1) resulted longest panicles (25 – $25.6cm$) while the weedy check (W5) recorded the shortest panicle length (18 – $18.8cm$) due to competition for resources. These results agree with previous studies that report effective crop

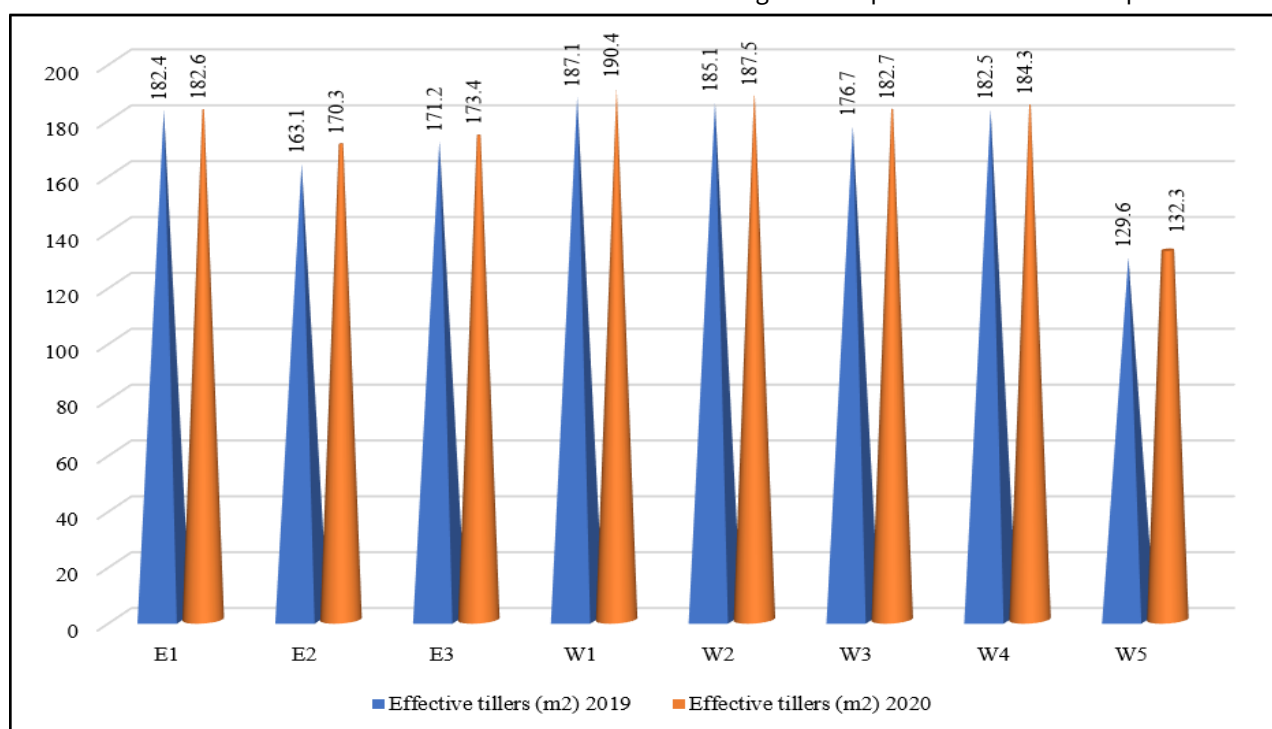


Fig. 9. Effect of crop establishment methods and weed management options on effective tillers (m^{-2}).

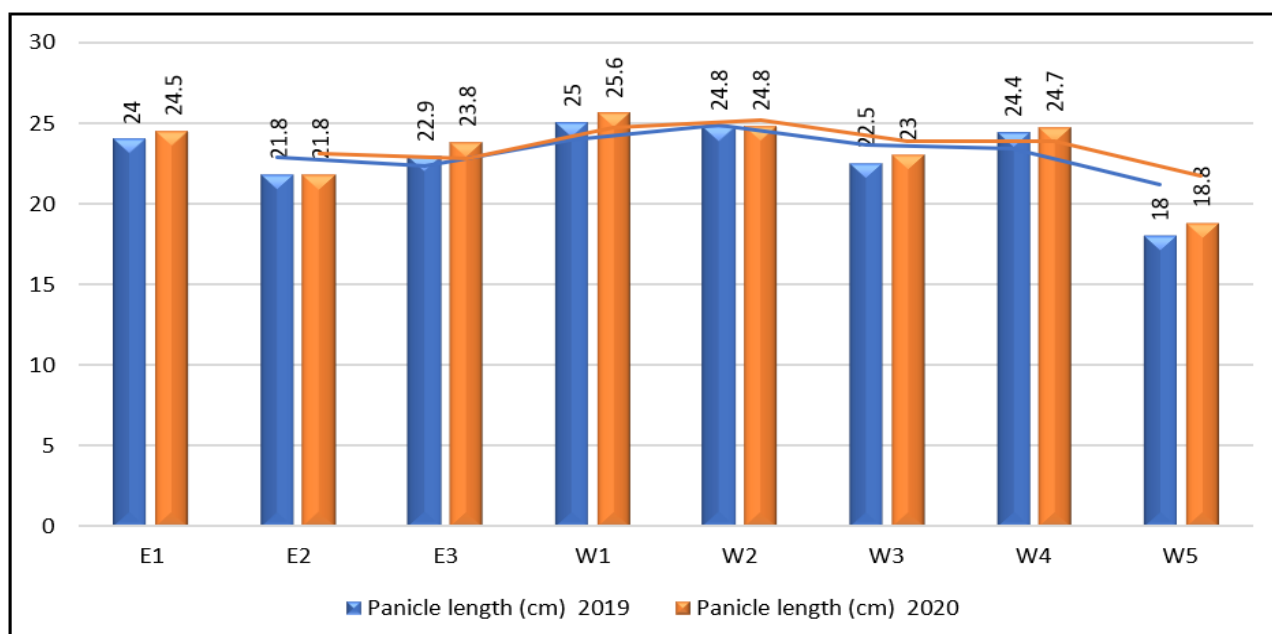


Fig. 10. Effect of crop establishment methods and weed management options on panicle length.

establishment and timely weed control improve panicle characteristic and overall yield potential in rice (27).

Effect of crop establishment methods and weed management options on yield parameters

Crop establishment methods and weed management options significantly influenced yield parameters (Table 1).

Number of grains per panicle

Crop establishment strategies and weed management had a substantial impact on rice grain yield per panicle in 2019 and 2020 (Fig. 11). Conventional puddled transplanting produced the most grains panicle⁻¹ (123.5–127), followed by FIRBs 119.3–120.6 and UPF 112.9–116.6, indicating improved nutrient uptake and panicle development under CPT conditions. Weed management also had a significant impact on the number of grain successions. Pretilachlor was applied first, followed by Bispyribac sodium (W1), which resulted in the most grains per panicle (124.6–127), while the weedy check (W5) had the fewest (111.9–113) due to intense competition for light and nutrients. These findings are consistent with previous research demonstrating that proper crop establishment and good weed control greatly improve grain formation and yield components in rice

(27).

1000-grain weight

The 1000-grain weight of rice was influenced by both crop establishment methods and weed management although differences among establishment methods were not always statistically significant. Furrow irrigated raised beds had the highest 1000-grain weight (20.43–20.62g), followed by CPT (19.85–19.96g) and UPF (18.85–18.98g) (Fig. 12). This suggests that better aeration and root growth under FIRBs may boost grain filling. Weed management had a substantial impact on 1000-grain weight. The application of Pretilachlor followed by Bispyribac sodium (W1) resulted in heavier grains (20.51–20.90g), whereas the weedy check (W5) had the lowest (18.08–18.15g) due to competition for assimilates. These findings are consistent with prior research, which found that adequate crop establishment and effective weed control improve rice grain weight and quality (27).

Effect of crop establishment methods and weed management options on yield of Basmati rice

Grain, straw and biological yields

Crop establishment and weed control approaches had a considerable impact on rice grain, straw and biological yields in both

Table 1. Effect of crop establishment methods and weed management options on yield of Basmati rice

Treatments	Yield (q ha ⁻¹)						Harvest index (%)	
	Grain		Straw		Biological		2019	2020
	2019	2020	2019	2020	2019	2020		
(E) Crop establishment methods								
E ₁ -Conventional puddled transplanting (CPT)	44.91	46.26	76.4	77.74	121.31	124	36.9	37.17
E ₂ - Unpuddled flat (UPF)	37.23	39.93	65.1	70.3	102.33	110.23	36.17	36.06
E ₃ - Furrow irrigated raised beds (FIRBs)	42.97	44.08	73.22	73.82	116.19	117.9	36.76	37.23
SE(m)±	0.89	0.86	1.44	1.38	2.07	2.32	0.71	0.71
C.D (p = 0.05)	3.08	3.01	4.99	4.78	7.18	8.04	NS	NS
(W) Weed management options								
W ₁ -Pretilachlor at 0.75 Kg ha ⁻¹ PE fb Bispyribac sodium at 20 g a.i. Ha ⁻¹ POE at 20 DAT	47.36	49.48	79.63	82.4	126.99	131.88	37.29	37.51
W ₂ -Almix 4 g a.i. ha ⁻¹ + Bispyribac sodium at 20 g a.i. ha ⁻¹ POE at 20 DAT	46.21	47.57	78.84	80.16	125.05	127.72	36.94	37.21
W ₃ - Bispyribac sodium at 25 g a.i. ha ⁻¹ POE at 20 DAT	41.17	43	71.85	75.41	113.02	118.41	36.39	36.29
W ₄ - T wo hand weedings	46.05	47.45	74.35	76.42	120.4	123.87	38.23	38.29
W ₅ - Weedy check	27.72	29.62	53.2	55.38	80.92	85	34.21	34.81
SE(m)±	0.88	0.84	1.38	1.41	2.19	2.25	0.69	0.68
C.D(p = 0.05)	2.63	2.52	4.12	4.19	6.53	6.68	2.05	2.03

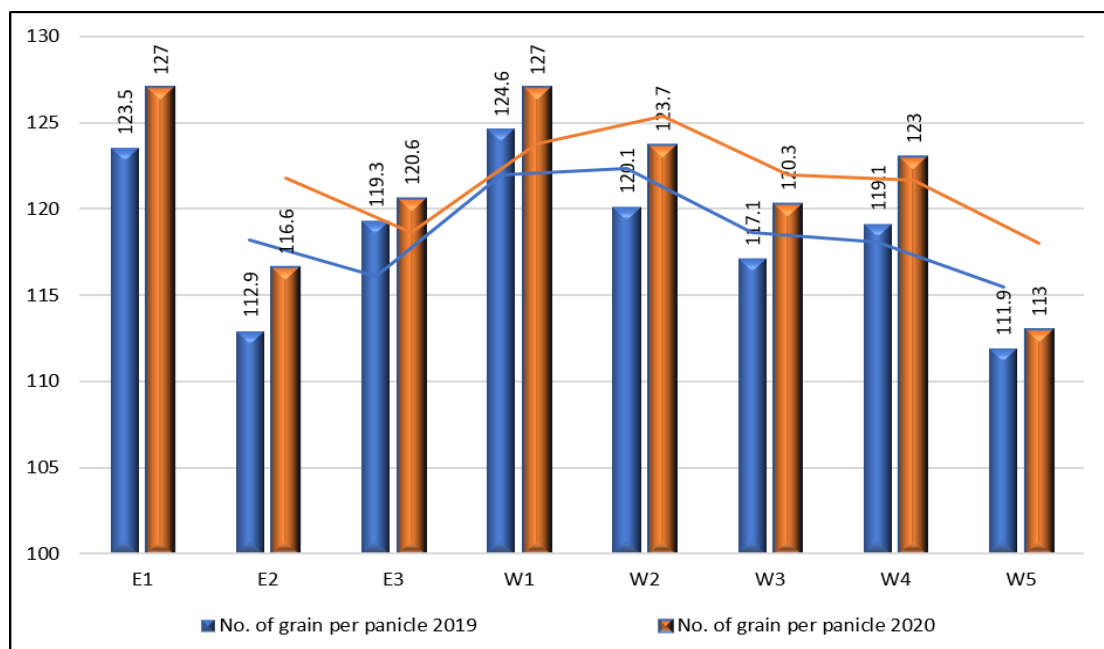


Fig. 11. Effect of Crop Establishment Methods and Weed Management Options on number of grain/Panicle.

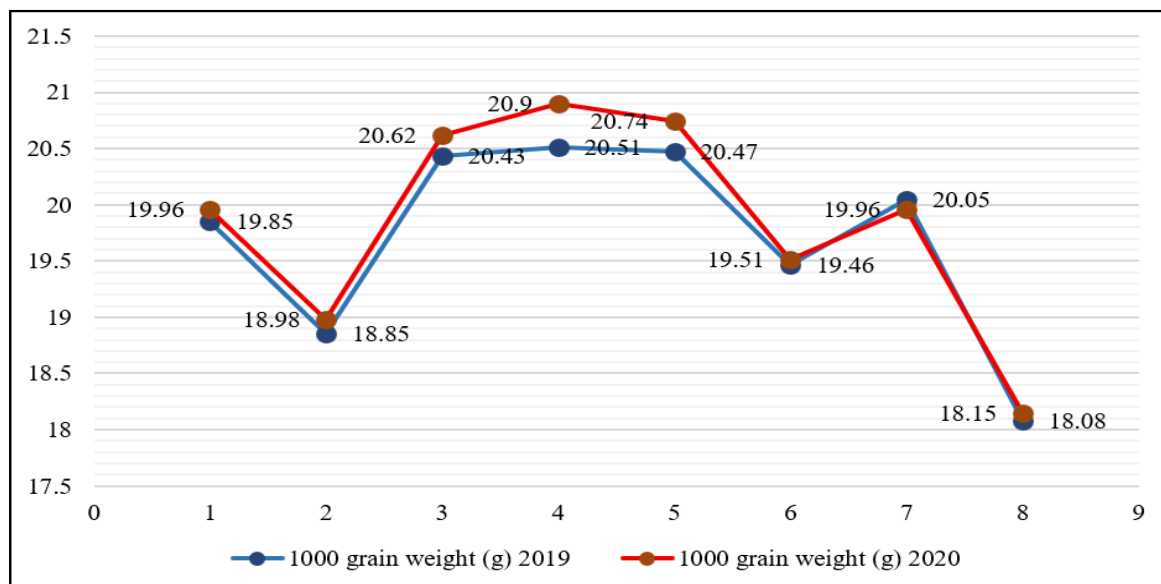


Fig. 12. Effect of crop establishment methods and weed management options on 1000 grain weight.

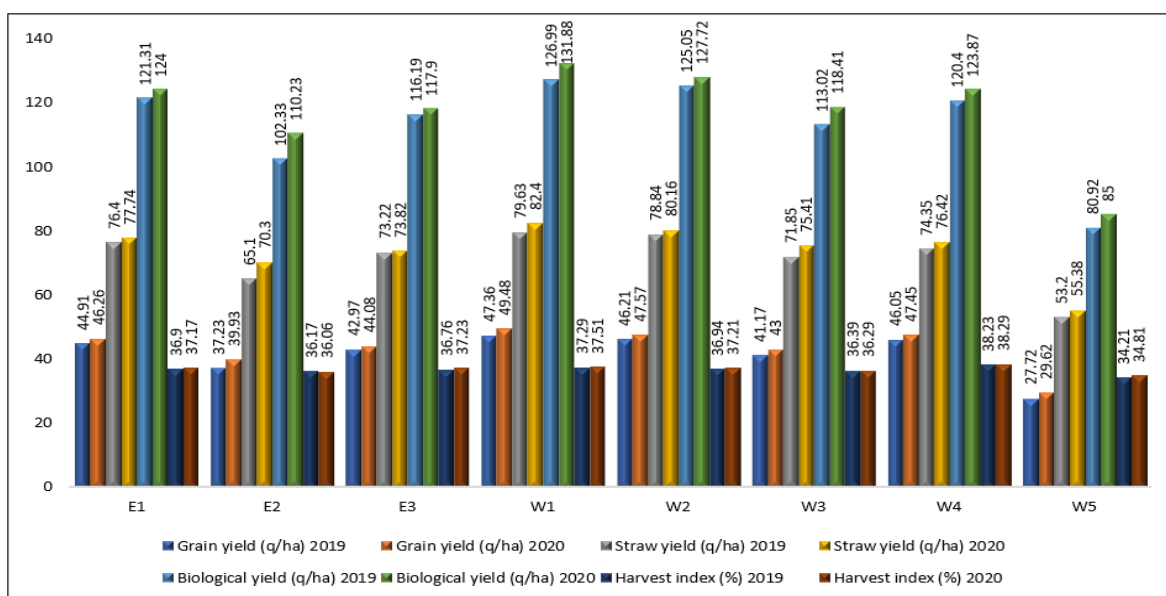


Fig. 13. Effect of crop establishment methods and weed management options on grain, straw and biological yield.

years (Fig. 13). Conventional puddled transplanting generated the maximum grain yield (44.91–46.26 q ha⁻¹), straw yield (76.4–77.74 q ha⁻¹) and biological yield (121.31–124 q ha⁻¹), followed by FIRBs, while UPF planting produced the lowest yields. Among weed control alternatives, Pretilachlor followed by Bispyribac sodium produced the highest grain (47.36–49.48 q ha⁻¹), straw (79.63–82.4 q ha⁻¹) and biological yields (126.99–131.88 q ha⁻¹), followed by two manual weeding, whereas the weedy check performed poorly. The superior yields under puddled transplanting and integrated chemical or manual weed control are attributed to reduced weed competition, higher WCE and improved nutrient utilisation, corroborating findings of previous researchers (14, 28).

Harvest index

Harvest index (HI) was slightly influenced by crop establishment and weed management practices. Among establishment methods conventional puddled transplanting (36.9–37.17 %) and furrow irrigated raised beds (36.76–37.23 %) recorded comparable HI, while UPF planting showed marginally lower values. Weed management significantly affected HI with two hand weeding producing the highest HI (38.23–38.29 %) followed by Pretilachlor followed by Bispyribac sodium, whereas the weedy check had the lowest HI

(34.21–34.81 %). The improvement in HI under effective weed control reflects better assimilate partitioning to grains due to reduced competition from weeds, consistent with previous findings (14, 28).

Effect of crop establishment methods and weed management options on nutrient content and uptake

Nutrient content of weed

Crop establishment methods and weed control approaches influenced weed nutrient content in terms of nitrogen (N), phosphorous (P) and potassium (K) in 2019 and 2020 (Fig. 14). However, there were no statistically significant variations in N, P or K content amongst crop establishment strategies. Unpuddled flat planting had slightly higher values (N: 1.024–1.044 %, P: 0.206–0.226 %, K: 1.195–1.219 %) than CPT and FIRBs, but the differences were not statistically significant. Weed management had a significant impact on weed nutrient accumulation; the weedy check (W5) had the highest nutrient content (N: 1.102–1.121 %, P: 0.238–0.257 %, K: 1.295–1.315 %), whereas successional herbicide

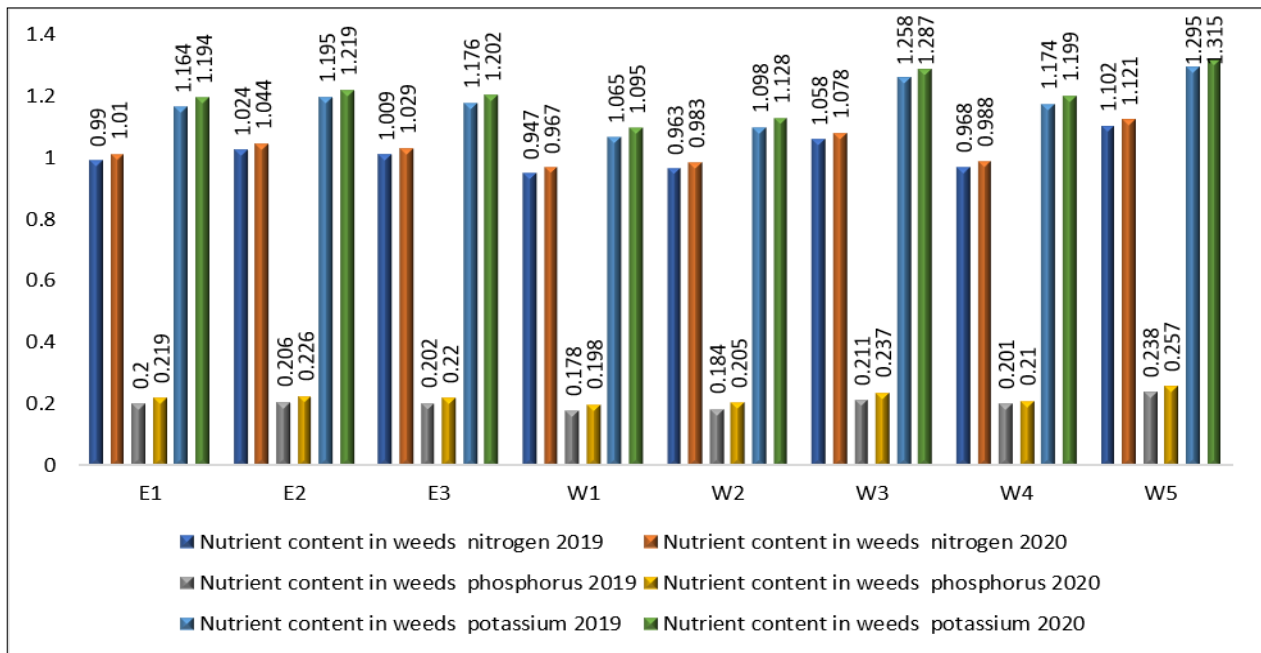


Fig. 14. Effect of crop establishment methods and weed management options on nutrient (NPK) content of weed.

application of Pretilachlor followed by Bispyribac sodium (W1) had the lowest accumulation (N: 0.947–0.967 %, P: 0.178–0.198 %, K: 1.065–1.095 %), indicating that effective weed suppression reduces nutrient removal from the system. These findings are consistent with prior research, which has shown that effective weed management reduces weed nutrient uptake, increasing crop nutrient availability (8).

Nutrient uptake by weeds

In 2019 and 2020, crop establishment methods and weed control approaches had a considerable impact on weed nutrient uptake, as measured by N, P and K (Fig. 15). Crop establishment methods showed that UPF had the highest nutrient uptake (N: 7.13–7.59 kg ha⁻¹, P: 1.44–1.65 kg ha⁻¹, K: 8.03–8.52 kg ha⁻¹) followed by FIRBs and CPT, indicating higher weed biomass accumulation in less-disturbed soils. Weed management had a significant impact on nutrient removal. The weedy check (W5) had the highest nutrient uptake (N: 13.5–14.11 kg ha⁻¹, P: 2.92–3.25 kg ha⁻¹, K: 15.78–16.44 kg ha⁻¹). However, successional herbicide application of Pretilachlor followed by Bispyribac sodium (W1) and two hand weedings (W4) significantly

reduced nutrient removal by weeds. This shows that successful weed control reduces nutrient competition, making more nutrients available to rice, which is consistent with prior research (29).

Nutrient content and uptake by rice grain and straw

Crop establishment methods and weed control approaches influenced N content and uptake in rice grain and straw in 2019 and 2020, respectively (Fig. 16 and 17). Among crop establishment methods, FIRBs and CPT had higher N content in grain (1.11–1.13 %) and straw (0.42–0.46 %) than UPF (1.07–1.08 % in grain and 0.41–0.42 % in straw), indicating better nutrient assimilation and translocation within optimised rhizosphere conditions. The FIRBs and CPT showed increased N uptake (grain: 48.47–50.19 kg ha⁻¹, straw: 33.02–34.33 kg ha⁻¹) compared to UPF. Weed management had a significant impact on N accumulation. Using Pretilachlor followed by Bispyribac sodium (W1) resulted in the highest N content and uptake (grain: 1.18–1.19 %, 55.89–58.82 kg ha⁻¹, straw: 0.49–0.50 %, 38.91–41.03 kg ha⁻¹), while the weedy check (W5) had the lowest values. This demonstrates that successful weed suppression reduces nutrient competition and improves crop nitrogen

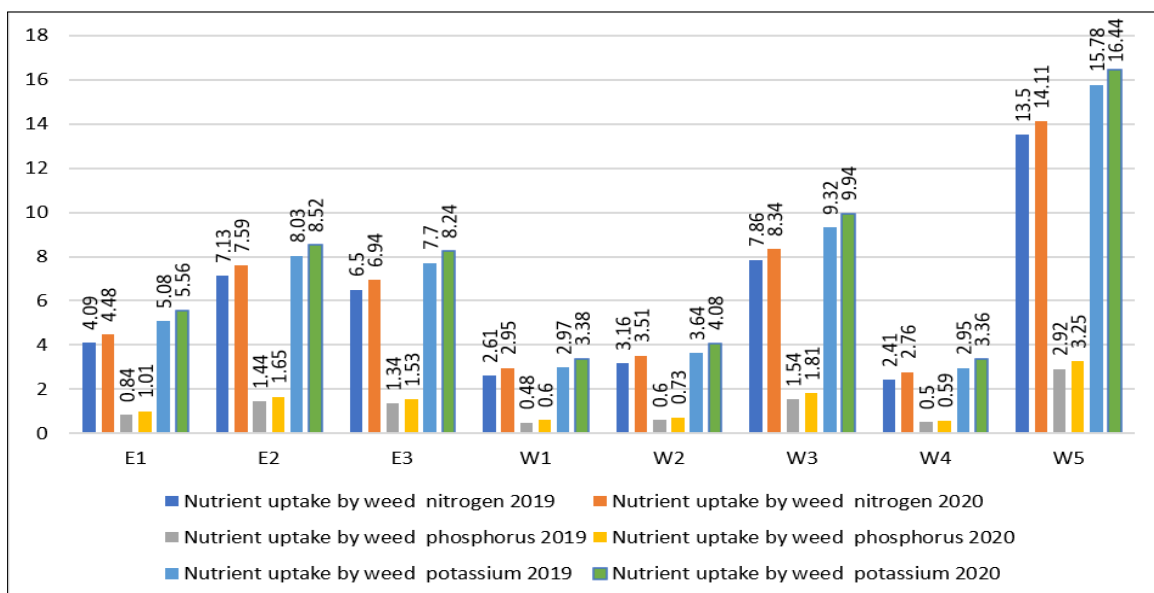


Fig. 15. Effect of crop establishment methods and weed management options on nutrient (NPK) uptake by weeds.

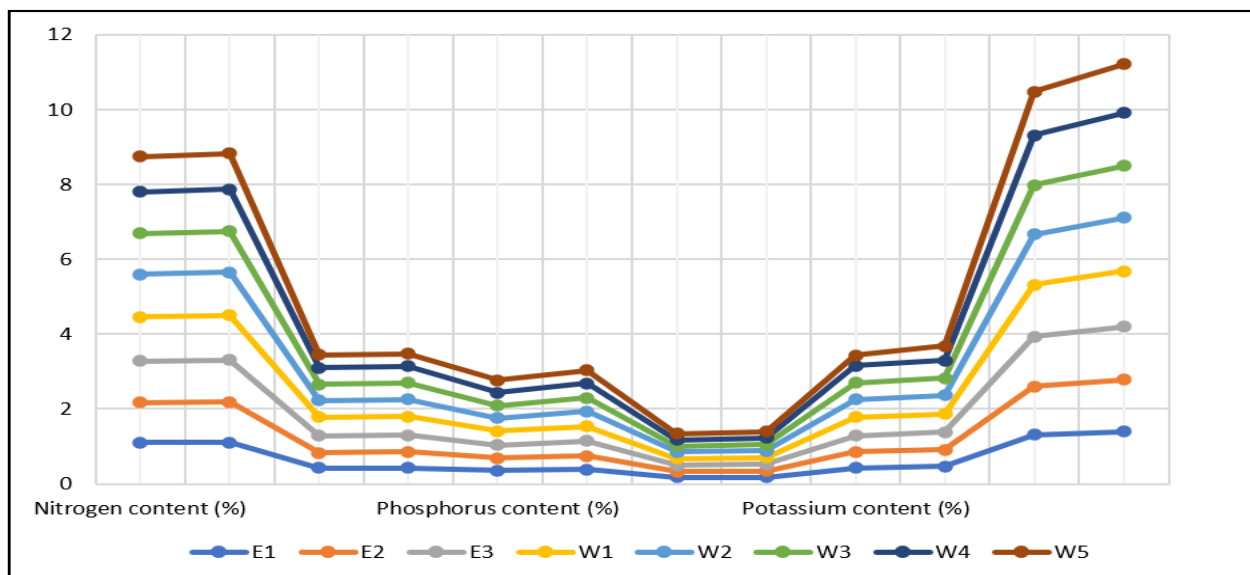


Fig. 16. Effect of crop establishment methods and weed management options on nutrient (NPK) content in rice grain and straw.

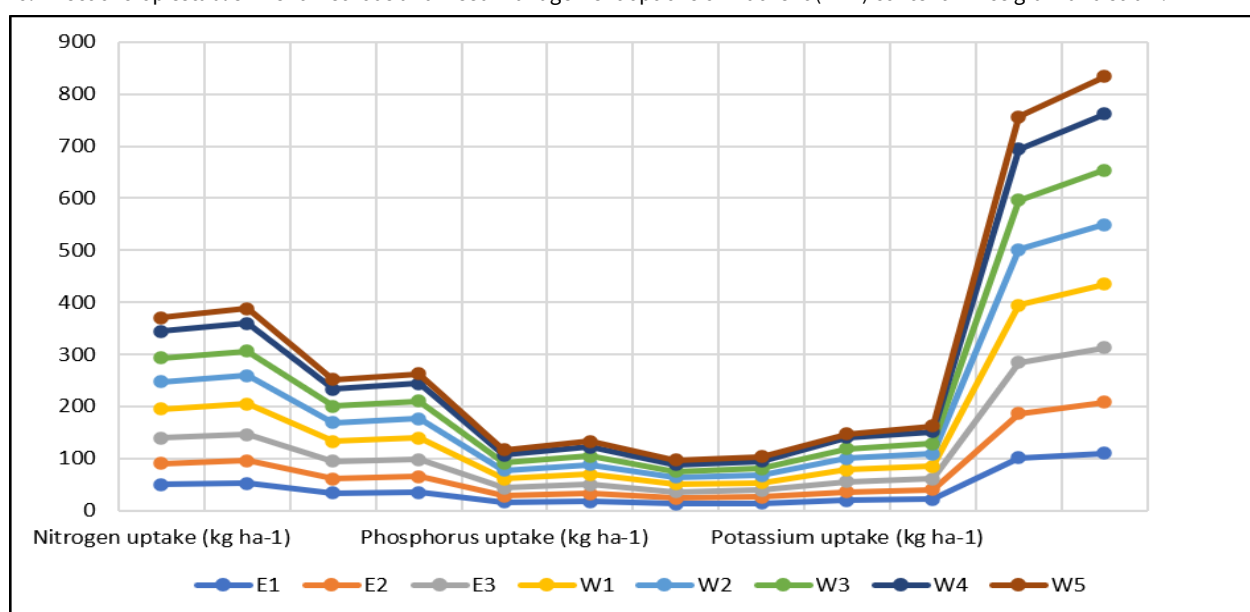


Fig. 17. Effect of crop establishment methods and weed management options on nutrient (NPK) uptake by rice grain and straw.

utilisation, which is consistent with the findings of previous researchers (30).

Crop establishment and weed control strategies greatly influenced the phosphorus concentration and uptake in rice grain and straw. Among the establishment methods CPT and FIRBs recorded higher P content in grain (0.35–0.39 %) and straw (0.17–0.18 %) compared to UPF (0.34–0.37 % in grain and 0.16–0.17 % in straw). Correspondingly, P uptake was higher in CPT and FIRBs (grain: 15.19–17.57 kg ha⁻¹, straw: 12.41–13.52 kg ha⁻¹) than in UPF. Effective weed management further enhanced P accumulation, successional application of Pretilachlor followed by Bispyribac sodium (W1) produced the highest P content and uptake (grain: 0.37–0.40 %, 17.54–20.02 kg ha⁻¹, straw: 0.18 %, 14.25–14.57 kg ha⁻¹) whereas the weedy check (W5) showed the lowest values. This indicates that controlling weeds reduces nutrient competition, facilitating better phosphorus absorption by rice, which is in line with the findings of (31, 32).

Potassium content and uptake in rice were significantly influenced by crop establishment and weed management strategies. Among establishment methods CPT and FIRBs recorded higher K content in grain (0.43–0.47 %) and straw (1.31–1.42 %),

compared to UPF (0.42–0.45 % in grain and 1.29–1.38 % in straw). Correspondingly, K uptake was greater in CPT and FIRBs (grain: 19.36–21.97 kg ha⁻¹, straw: 98.26–109.87 kg ha⁻¹) than in UPF. Among weed management treatments, successional application of Pretilachlor followed by Bispyribac sodium (W1) resulted in the highest K content and uptake (grain: 0.49 %, 23.16–24.28 kg ha⁻¹, straw: 1.39–1.48 %, 110.87–121.62 kg ha⁻¹) whereas the weedy check (W5) recorded the lowest values. This suggests that proper weed management reduces nutrient competition and promotes better potassium accumulation in rice plants, consistent with the observations of earlier researchers (31, 32).

Effect of crop establishment methods and weed management options on available soil nutrients and available soil organic carbon

The status of available soil nutrients and organic carbon was influenced by both crop establishment methods and weed management practices (Fig. 18). Among establishment methods UPF plots recorded slightly higher available N (200.36–208.38 kg ha⁻¹), P (15.73–15.84 kg ha⁻¹) and K (176.84–182.15 kg ha⁻¹) compared to CPT and FIRBs. Organic carbon was similar across methods ranging from 0.46 to 0.48 %. Weed management had a significant impact on

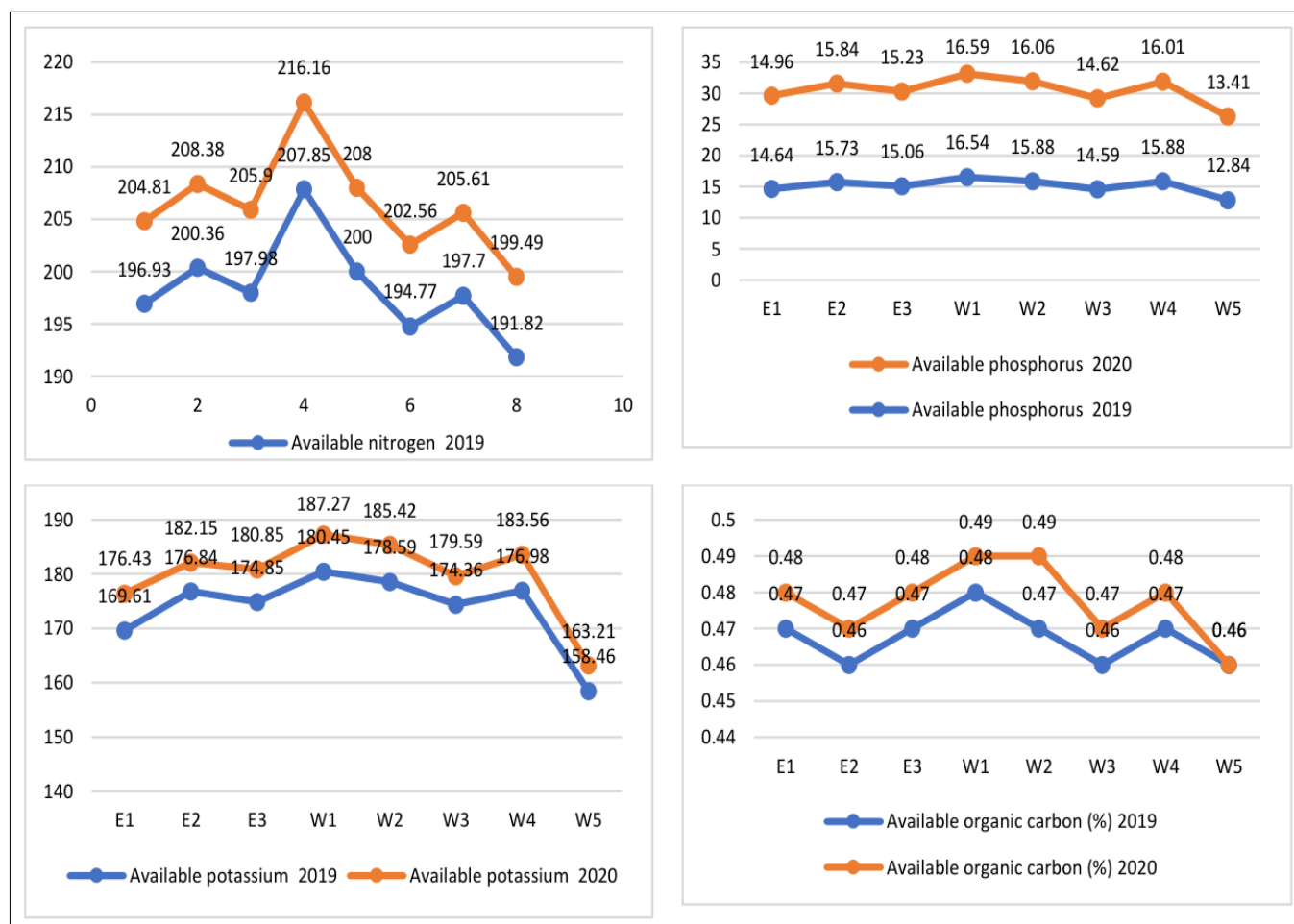


Fig. 18. Effect of crop establishment methods and weed management options on available soil nutrients and available soil organic carbon.

nutrient availability, with Pretilachlor (W1) showing the highest levels of available N (207.85–216.16 kg ha⁻¹), P (16.54–16.59 kg ha⁻¹), K (180.45–187.27 kg ha⁻¹) and organic carbon (0.48–0.49 %), while the weedy check (W5) recorded the lowest values. These results show that appropriate weed control reduces nutrient competition and improves soil nutrient retention, which supports the previous findings (33, 34).

Conclusion

Conventional puddled transplanting (CPT), when integrated with effective weed management practices, particularly the sequential application of pretilachlor followed by bispyribac-sodium or two hand weedings was found to be the most effective strategy for suppressing weed growth, enhancing weed control efficiency (WCE) and minimising crop-weed nutrient competition. Although two hand weedings recorded superior weed suppression and WCE, the herbicidal treatment was found to be statistically comparable and more economical, thereby offering a practical alternative. These practices significantly improved growth parameters, including plant height, number of tillers, dry matter accumulation, leaf area index (LAI) and panicle length, which ultimately resulted in higher grain yield, straw yield, biological yield and improved harvest index. Furthermore, nutrient uptake by rice was maximised, while nutrient depletion by weeds was minimised, leading to better preservation of soil nutrient status. Overall, the integration of appropriate crop establishment methods with timely and efficient weed management practices represents a sustainable strategy for enhancing productivity, nutrient use efficiency and profitability in Basmati rice cultivation.

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Authors' contributions

SY conceived the study, carried out the field trials and drafted the manuscript. SBS helped in the experimental design of the study. SY, RK and AS performed the statistical or mathematical analysis. PY, DK, DNY, SC and SY participated in critical revision and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

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

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