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RESEARCH ARTICLE

Cumulative effect of crop establishment method and herbicides on nutrient uptake, content and productivity of wheat in the Gird region of North India

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Abstract

A field experiment was conducted during *Rabi* 2019-20 and 2020-21 to evaluate the cumulative effects of crop establishment methods and herbicides on nutrient uptake and productivity of wheat in the Gird region of North India. Treatments comprised of three crop establishment methods viz., conventional tillage (CT), minimum tillage (MT) and zero tillage (ZT) in main plots along with seven weed control treatments as subplots. Significantly higher grain yield (4.81 t/ha) was recorded under ZT due to reduced weed density and biomass, compared to the other tillage practices. The highest grain and straw yields (5.16 and 7.50 t/ha) were obtained under two hand weeding with ZT, which was statistically at par with the application of clodinafop + metsulfuron (60+4 g/ha) under the ZT system. Significantly higher N, P and K uptake and content by wheat were recorded under CT, followed by MT and ZT. Among herbicide treatments, the lowest nutrient uptake was recorded in the weedy check, while the highest uptake was observed under two hand weeding at 30 and 60 days after sowing (DAS), which was statistically at par with clodinafop + metsulfuron-methyl (60+4 g/ha). However, weeds followed opposing trends. ZT had the highest harvest index (40.08 %) compared to MT and CT. Furthermore, among herbicide treatments the maximum harvest index was observed with two hand weeding at 30 and 60 DAS (40.85 %); which was statistically equal to clodinafop + metsulfuron-methyl (60+4) g/ha (40.30 %). Reduced tillage significantly decreased soil bulk density in ZT (1.33 g/cm^3) compared to MT (1.35 g/cm^3) and CT (1.36 g/cm^3), according to soil analysis. On the other hand, porosity and organic carbon showed the opposite trends. Available nitrogen (N), phosphorus (P) and potassium (K) in soil were recorded significantly higher under CT, followed by MT and ZT. CT recorded lower values of soil available N and higher values of soil P and K, while ZT recorded higher values of soil available N and lower values of soil P and K during the two-year study. Significantly higher values of available soil N and K were recorded under CT, followed by MT and ZT. However, ZT recorded significantly lower values of available soil nitrogen and potash accompanied by higher values of soil phosphorus. On the other hand, ZT recorded significantly lower values of available soil N and K coupled with higher values of available soil K during the pooled analysis.

Keywords: herbicides; nutrient content; nutrient uptake; tillage; weed dynamics; yield

Introduction

In India, wheat plays a crucial role in meeting the nation's food grain demands. Wheat [*Triticum aestivum* (L.) emend. Fiori & Paol)] is one of the most widely cultivated cereal crops and a key component of global food security. On average, wheat contributes around 35 % of total food grain production and 21% of cultivated areas in the country (1). The adoption of zero tillage in the rice–wheat cropping system significantly improves the soil's physical, chemical and biological properties, contributing to long-term productivity and efficient weed management (2). Weeds are the major stumbling blocks in the adoption of zero-tillage technology in wheat. Though zero tillage in wheat fields reduces the infestation of *Phalaris minor*, it aggravates the problem of *Avena ludoviciana* as well as some broad-leaf weeds (3). If weeds are not managed properly and in a timely manner, they could significantly reduce the wheat yield by as much as 10 to 50 % (4). Effective control of weeds is of utmost importance not only to check the yield losses due to weeds but also to reduce the nutrient losses from the soil. In wheat crops, weeds have been reported to deplete the levels of N, P and K by 24.3 - 28.6 %, 13.5-16.2 % and 22.3-25.2 % respectively (5). Another study has reported that there was a reduction in crop N, P and K uptake by 56 %, 45 % and 60%, respectively, when weeds were allowed to grow throughout the growing season compared to weed-free plots (6). Such yield losses may be attributed to biotic and abiotic stress factors exacerbated by environmental conditions that negatively affect plant growth, metabolism and yield (7). Among biotic factors, weeds are the foremost pests that possess the highest loss potential to wheat which can go up to 23 %, that is even greater than that of pathogens (16 %) (8). Severe weed infestation can lead to a reduction in wheat yield by 18-73 % (9). The use of herbicides not only reduces weed density but also increases nutrient uptake by wheat, thus reducing nutrient losses and increasing production (10). Effective weed control techniques combined with tillage have been demonstrated to boost yield by 40-60 % (11). In addition to directly killing weeds or dispersing weed seeds at varying soil depths, changes in tillage systems also alter the soil environment, which impacts weed seed emergence and germination (12). In this context, the current study aimed to evaluate the effects of different herbicides and crop establishment techniques on nutrient uptake by weeds and wheat crop in the Gird region of North India.

Materials and Methods

Experimental site, soil characteristics and soil analysis

The experiment was conducted at the agronomy research farm of College of Agriculture, Gwalior, Madhya Pradesh, during the *Rabi* season of 2019-20 and 2020-21. The experimental field featured uniform topography and adequate drainage. A few soil samples were randomly collected before sowing and a composite sample made after mixing all these was analyzed in the laboratory for mechanical and chemical composition. (Table 1). The soil was sandy clay loam in texture, with a p^H of 7.53, organic carbon (0.40 %), bulk density (1.34 g/cm^3), porosity (48.3 %), available N (164.5 kg/ha), P (14.3 kg/ha) and K (235.5 kg/ha)

Experimental design and treatment details

The experiment was laid out in a split-plot design with three replications. The treatments comprise 21 combinations having three tillage *viz*; zero tillage (ZT), minimum (MT) and conventional tillage (CT) as main plots and seven weed control practices i.e., sulfosulfuron (30 g/ha), metsulfuron-methyl (4 g/ha), clodinafop (60 g/ha), sulfosulfuron + metsulfuron-methyl (30 + 2 g/ha), clodinafop + metsulfuron-methyl (60+4 g/ha), two hand weeding at 30 and 60 DAS, as a subplot. Wheat cultivar RVW-4106 was sown in ZT plots on 11 November in 2019 and 06 November in 2020. Similarly, sowing was done in MT and CT plots on 5 December 2019 and 30 November 2020 with seed rate of 100 kg/ha at a row spacing of 22.5 cm. The crop was nourished with N (100 kg), P (60 kg) and K (40 kg) per hectare using urea, DAP (Diammonium Phosphate) and MOP (Muriate of Potash) as fertilizers.

Table 1. Mechanical and chemical analysis of soil before sowing and after the harvesting of wheat

Sl. No.	Soil components	Method used
1	Sand	International pipette method (49)
2	Silt	
3	clay	
4	Textural class	
5	Organic carbon (%)	Walkley and Black's rapid Titration method (49)
6	Bulk Density(g/cm^3)	Core sampler method (50)
7	Porosity (%)	Empirical method (51)
8	Available nitrogen (kg/ha)	Alkaline permanganate method (52)
9	Available phosphorus (kg/ha)	Olsen's method (53)
10	Available potassium (kg/ha)	Flame photometer (54)

Placement of crop establishment method and herbicides

After the harvesting of pearl millet, the field was set up in accordance with the experiment. Following pearl millet, no-tillage operations were carried out in ZT. After its harvest, ZT plots were watered to promote the germination of wheat seeds that had been sown and after four weeks, the plot was treated with post-emergence herbicides to manage weeds. The corresponding plots were prepared for the MT with one disc harrowing and one rotavator pass. In contrast, CT plots required one disc plough pass, two passes with a cultivator and one pass with a Planker to level the field. The post–emergence herbicides was applied using spray volume of 500 liters/ha at 28 DAS with knapsack sprayer after first irrigation. Herbicides were sprayed on the date of the ZT plot on 08 December 2019 and 04 December 2020. Similarly, in MT and CT plots, herbicides were applied on 02 January 2020 and 28 December 2020, respectively. After 30 and 60 days of sowing, hand weeding was carried out in ZT, MT and CT.

Collection and analysis of crop and weed samples

Observations on broad and narrow-leaved weed density were made by using the quadrate count method, from each plot at 20, 40 and 60 DAS as well as at harvest. Quadrates (1 m^2) were placed in each plot at random to determine the weed density. The information was then converted as (no./m^2). The weedy check plot was used to evaluate the percentage composition of weed flora. Relative weed density was calculated according to the formula previously described (13). To normalize the distribution of the total weed density, square root transformation was applied (14).

$$\text{Relative Density\%} = \frac{\text{Number of individuals of the same species}}{\text{Total number of individuals of all species}} \times 100 \qquad \text{(Eqn. 01)}$$

Biomass of broad and narrow leaved weeds were taken at 20, 40, 60 DAS and at harvest. Species-wise associated weeds were removed from the four different locations within each plot using the quadrate methodology, to record the dry weight of broad-leaved weeds. The weeds were first sun-dried, placed in paper bags, then dried in an oven at 60 °C for 48 hrs. Dry biomass measurements were carried out until a stable weight was reached. The information was later converted to g/m^2.

After harvest, the crop from net plots' was threshed and the grains that were left over were weighed. The yield per plot was adjusted to 12 % moisture content and after sun-drying the straw for 5-6 days, both grain and straw weights were converted to (t/ha) using appropriate conversion factors. The biological yield was calculated according to Donal CM, 1963 (15) and the harvest index following Donal CM, 1976 (16). It measures the partitioning of photosynthetic towards grains and is expressed in percentages (%). The formulas were as;

$$\text{Harvest index \%} = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100 \qquad \text{(Eqn. 02)}$$

$$\text{Biological Yield} = (\text{Grain} + \text{Straw}) \text{ Yield} \qquad \text{(Eqn. 03)}$$

The analysis for N, P and K were done in crop and weed plants at harvest stage by adopting micro-kjeldahl, vanado-molybdate yellow colour method (17) and flame emission photometry method (18) respectively. Nutrient uptake by grain, straw and weeds was estimated by following the algebraic equation stated below;

$$\text{Nutrient uptake (kg/ha)} = [\text{Nutrient (\%)} \times \text{yield}] \text{ (kg/ha)}] / 100 \qquad \text{(Eqn. 04)}$$

Statistical analysis

The data were statistically analyzed by OPSTAT (Operational Statistics) software as per the method provided previously (19) to determine the significance of differences. Wherever the "F" test was significant at 5 % significance level, significant differences were calculated to evaluate the significance of treatment means. There was no significant ($p<0.05$) effect of years on various parameters and therefore, pooled analysis was performed for the two-year mean and interpreted accordingly.

Results and discussion

Weed density and biomass

In the pearl millet-wheat cropping system, the major narrow-leaved weeds (NLWs) observed were *P. minor* and *Avena fatua*, whereas the broad-leaved weeds (BLWs) included *Chenopodium album*, *Rumex dentatus*, *Fumaria parviflora*, *Convolvulus arvensis* and *Anagallis arvensis* during 2019-20 and 2020-21. Weed density and biomass were significantly reduced ($p<0.05$) by herbicides under various crop establishment methods. The relative population of narrow leaved weeds to the overall weed population in terms of density was larger in all stages of crop growth. *P. minor* was the most dominant weed at harvest, contributing 31 % of total weed population (Fig. 1). Among broad-leaved weeds, *C. album* was the most dominant (29 %), followed by *R. dentatus* (9 %). *P. minor*, *Rumex* spp. and *C. album* are reported earlier (20) as the major weeds of wheat in the pearl millet-wheat cropping system. Total weed density was lower in ZT (61.1/m^2) and MT (87.4/m^2) when compared to CT (106.7/m^2). Furthermore, the lowest biomass was recorded in ZT (38.27 g/m^2) and MT (59.55 g/m^2) in contrast to CT (72.73 g/m^2), respectively. Lower total weed density under zero tillage (ZT) compared to conventional tillage (CT) aligns with our findings from (21-22). Following pearl millet harvest, the density of *P. minor* in wheat sown under ZT was much lower when compared to those sown under CT. During all the stages, weed density and biomass of each weed were higher in CT. This may be attributed to its pulverized soil, which provided congenial growth environment such as optimum moisture and nutrients in the rhizosphere of the crop (23). While CT brings the weeds seeds from deeper depths and scarify and breaks the dormancy of weed seeds resulting in enhanced germination and emergence (24). For instance, studies have shown that ZT can lead to a 52 % reduction in weed density compared to CT (25). Similarly, the previous findings from Jabalpur confirmed a reduction in the density of Phalaris minor and Chenopodium album under zero tillage (ZT) conditions (20). Weed count was mainly in decline due to absence of sunlight and loss of viable seeds buried deep in the soil profile. Also, in the absence of tillage under ZT, they could not emerge, while weed counts were almost twice and thrice under MT and CT.

Among herbicides, the highest weed density was recorded under weedy check (241.5/m^2) while it was lowest in two hand weeding 30 and 60 DAS, i.e., 98.21 % followed by clodinafop + metsulfuron-methyl (60+4 g/ha) application resulted in 94.8 % at harvest, respectively. The highest biomass was recorded in weedy check (159.45 g/m^2) and the lowest in two hand weeding at 30 and 60 DAS, while it was comparable with clodinafop propargyl 15 % WP + metsulfuron methyl 20 % WP (60 + 4) g/ha (94.34 %). Increase in weed control efficiency is a result of improved weed management, which reduced the accumulation of biomass. Additionally, uniform placement of previous crop residues also inhibited the emergence and growth of weeds. These results align with earlier reports indicating that clodinafop offers superior control of grasses compared to sulfosulfuron-methyl, especially for resistant biotypes of *P. minor* (26-27). Metsulfuron-methyl was shown to be more effective against dicot weeds as suggested earlier (28). The application of clodinafop propargyl 15 % WP+ metsulfuron methyl 20 % WP (60+4) g/ha at 28 DAS provided broad-spectrum weed control controlling 97.3 % of grasses and 96.5 % of BLWs (29).

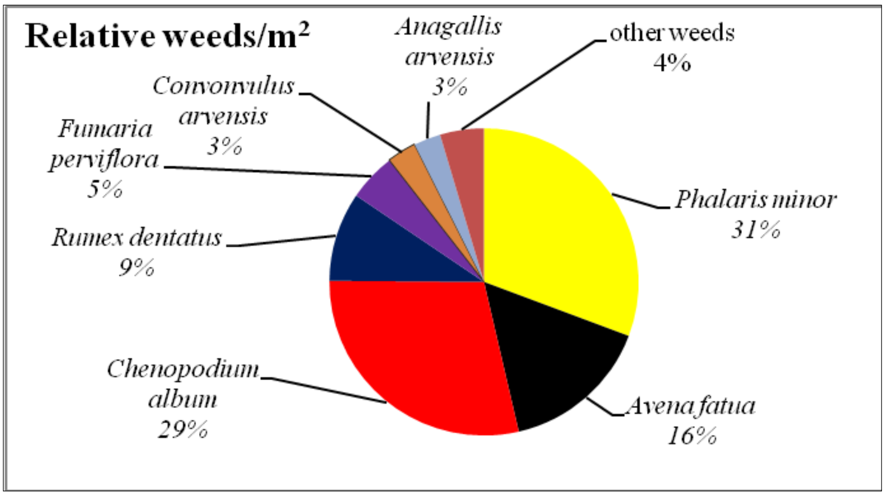

Fig. 1. Relative weed flora in wheat (%/m^2).

Nutrient content in wheat and weeds

Based on pooled analysis, the N, P and K contents of wheat and weeds were affected significantly (p<0.05) by tillage and herbicides in the pearl millet-wheat system (Table 2, Fig. 2). The highest significant (p<0.05) N, P and K content was recorded in ZT (2.24, 0.38, 0.36% in grain and 0.44, 0.06, 1.75 % in straw), followed by MT (2.20, 0.37, 0.34 % in grain and 0.43, 0.05, 1.65 % in straw) and CT (2.17, 0.35, 0.33 % in grain and 0.42, 0.05, 1.56 in straw), respectively. CT (2.31, 0.45, 2.30 %) resulted in significantly higher N, P and K content of weeds than MT (2.23, 0.43, 2.25 %) and ZT (2.17, 0.40, 2.20 %). Among herbicides, the lower N, P and K content were recorded in weedy check (2.05, 0.30, 0.29 % in grain and 0.36, 0.046, 1.51 % in straw). While higher recorded in two hand weeding 30 and 60 DAS (2.29, 0.40, 0.38 % in grain and 0.47, 0.07, 1.8 % in straw). This was at par with clodinafop + metsulfuron-methyl (60+4) g/ha (2.26, 0.40, 0.37 % in grain and 0.46, 0.06, 1.75 % in straw), respectively. In the early stages, there are several ways that conservation tillage techniques such as reduced tillage (RT) and no-tillage (NT), affect the dynamics of soil nutrients and weed control. By increasing soil organic matter and microbial biomass, NT and RT improve soil structure and nutrient cycling (30). NT systems also aid in moisture retention by reducing soil disturbance, which can increase wheat's nutrient absorption efficiency (31). Moreover, by creating a physical barrier and modifying the soil's temperature as well as light availability; crop residues left

Table 2. Nutrient content and uptake in wheat and weeds as influenced by various crop establishment methods and herbicides (pooled data)

	Content (%)									Uptake (kg/ha)								
Treatments	Grain			Straw			Weed			Grain			Straw			Weed		
A. Tillage	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
Zero tillage	2.24	0.38	0.36	0.448	0.064	1.757	2.17	0.40	2.20	105.7	17.97	17.18	31.63	4.72	123.89	8.68	1.60	8.69
Minimum tillage	2.20	0.37	0.34	0.436	0.056	1.646	2.23	0.43	2.25	99.9	16.80	15.78	29.78	4.34	112.17	13.74	2.60	13.81
Conventional tillage	2.17	0.35	0.33	0.425	0.050	1.565	2.31	0.45	2.30	92.9	15.36	14.45	27.57	3.92	101.35	17.40	3.32	17.15
S.E. m (d)	**0.01**	**0.01**	**0.003**	**0.002**	**0.001**	**0.018**	**0.02**	**0.00**	**0.01**	**0.96**	**0.20**	**0.22**	**0.25**	**0.05**	**1.81**	**0.66**	**0.15**	**0.80**
C.D. (at 5%)	**0.04**	**0.01**	**0.010**	**0.006**	**0.005**	**0.059**	**0.06**	**0.01**	**0.04**	**3.13**	**0.66**	**0.707**	**0.83**	**0.17**	**5.92**	**2.15**	**0.48**	**2.61**
B. Weed control practices																		
Sulfosulfuron (25g\ha)	2.22	0.35	0.35	0.445	0.046	1.538	2.14	0.40	2.17	92.3	14.65	14.71	26.88	3.54	92.91	9.87	1.86	9.99
Metsulfuron -methyl (4g/ha)	2.19	0.36	0.33	0.432	0.051	1.596	2.19	0.41	2.21	94.5	15.48	14.34	28.23	4.09	104.11	17.91	3.36	18.09
Clodinafop(60g\ha)	2.16	0.37	0.34	0.423	0.056	1.653	2.25	0.43	2.26	97.8	17.09	15.61	29.16	4.51	113.71	20.56	3.94	20.53
Sulfosulfuron+Metsulfuron- methyl (30+2) g/ha	2.24	0.38	0.36	0.455	0.063	1.711	2.31	0.44	2.31	105.5	18.09	17.02	32.04	4.85	120.37	2.77	0.53	2.77
Clodinafop + Metsulfuron-methyl (60+4) g/ha	2.26	0.40	0.37	0.464	0.069	1.757	2.37	0.45	2.35	112.0	19.74	18.29	34.07	5.35	128.84	2.14	0.40	2.12
Two hand weeding (30&60DAS)	2.29	0.40	0.38	0.475	0.074	1.827	0.00	0.00	0.00	117.1	20.72	19.40	35.72	5.71	137.08	0.00	0.00	0.00
Weedy check	2.05	0.30	0.29	0.361	0.036	1.510	2.44	0.46	2.39	77.1	11.21	11.22	21.52	2.25	90.26	39.14	7.36	38.47
S.E. m (d)	**0.03**	**0.004**	**0.004**	**0.003**	**0.002**	**0.020**	**0.02**	**0.01**	**0.02**	**2.23**	**0.35**	**0.330**	**0.53**	**0.09**	**2.22**	**0.83**	**0.16**	**0.93**
C.D. (at 5%)	**0.08**	**0.010**	**0.010**	**0.009**	**0.005**	**0.057**	**0.06**	**0.02**	**0.06**	**6.30**	**0.99**	**0.929**	**1.50**	**0.25**	**6.25**	**2.35**	**0.46**	**2.62**

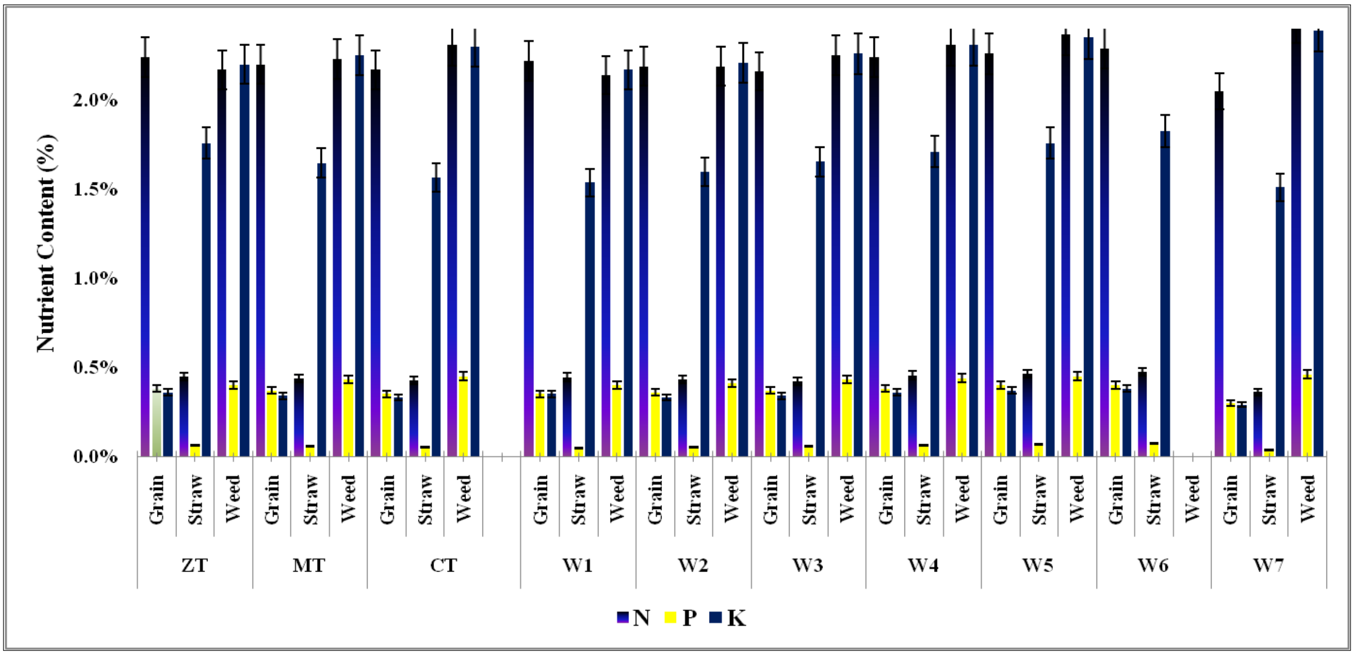

Fig. 2. Impact of crop establishment methods and herbicides on percentage N, P and K content by grain, straw and weeds.

ZT	Zero tillage
MT	Minimum tillage
CT	Conventional tillage
W1	Sulfosulfuron (25g/ha)
W2	Metsulfuron–methyl (4g/ha)
W3	Clodinafop (60g\ha)
W4	Sulfosulfuron+metsulforon-methyl((30+2)g/ha
W5	Clodinafop+metsulfuron-methyl(60+4)g/ha
W6	Two hand weeding (30&60DAS)
W7	Weedy check

on the surface in NT systems can inhibit the growth of weeds (32). By bringing buried weed seeds to the surface, conventional tillage (CT) re-distributes nutrients within the soil profile and may increase weed pressure (33). Herbicides that effectively control weeds also lessen the competition for vital nutrients, giving wheat plants more access to N, P and K for increased development and production (34).

Nutrient uptake by wheat and weeds

Based on pooled analysis, the N, P and K uptake of wheat and weeds were affected significantly (p<0.05) by tillage and herbicides (Table 2, Fig. 3). The significantly (p<0.05) highest N, P and K uptake was recorded in ZT (105.7, 17.97, 17.18 kg/ha in grain and 31.63, 4.72, 123.8 kg/ha in straw) followed by MT (99.9,16.80, 15.78 kg/ha in grain and 29.78, 4.34, 112.17 kg/ha in straw) and CT (92.9, 15.36, 14.45 kg/ha in grain and 27.57, 3.92, 101.35 kg/ha in straw), respectively. CT (17.40, 3.32, 17.15 kg/ha) resulted significantly (p<0.05) higher N, P and K uptake of weeds than MT (13.74, 2.60, 13.81 kg/ha) and ZT (8.68, 1.60, 8.69 kg/ha). Among herbicides, the lowest N, P and K uptake was recorded in weedy check (77.1, 11.21, 11.22 kg/ha in grain and 21.52, 2.25, 90.26 kg/ha in straw). While highest recorded in two hand weeding 30 and 60 DAS (117.1, 20.72, 19.40 kg/ha in grain and 35.72, 5.71, 137.08 kg/ha in straw) followed by clodinafop + metsulfuron-methyl (60 + 4) g/ha (112.0, 19.74, 18.29 kg/ha in grain and 34.07, 5.35, 128.84 kg/ha in straw), respectively. However, N, P and K uptake in weeds were found highest in CT (17.40, 3.32, 17.15 kg/ha) followed by MT (13.74, 2.60, 13.81 kg/ha) and ZT (8.68, 1.60, 8.69 kg/ha). Among herbicides, the significantly higher N, P and K uptake was observed in weedy check (39.14, 7.36, 38.47 kg/ha) while lower in two hand weeding 30 and 60 DAS (0.00) followed by clodinafop + metsulfuron-methyl (60+4) g/ha (2.14, 0.40 and 2.12 kg/ha), respectively. Weeds are more efficient competitors for nutrients, water, space utilization as compared to wheat, which ultimately have negative effects on crop yield and nutrient uptake by crop (35). The lower density of weeds under the treatments might be another valid reason for higher nutrient uptake by crop plants (10). Application of clodinafop + metsulfuron-methyl (60+4) g/ha reduced the nutrient losses due to weeds owing to control of both grassy as well as broad-leaf weeds compared with the weedy check. A study reported reduction in N, P and K depletion by adopting suitable weed-control practices (5). Enhanced uptake of nitrogen, phosphorus and potassium under weed-free and integrated treatments can be attributed to improved nutrient availability and enhanced crop vigour. These management practices reduce nutrient losses through leaching and volatilization, thereby increasing nutrient use efficiency (36). Moreover, reduced weed competition during critical growth stages promotes better crop development and yield, leading to higher overall nutrient uptake due to improved access to light, space and essential resources (37).

Yield parameters

Based on pooled analysis, the yield parameters of wheat were significantly influenced by both tillage and herbicide treatments (Table 3). ZT has been recorded significantly (p≤0.05) higher grain yield (4.81 t/ha) followed by MT (4.56 t/ha) compared to CT (4.26 t/ha). Among weed control treatments, two hand weeding 30 and 60 DAS resulted in the highest grain production (5.16 t/ha), equivalent to clodinafop + metsulfuron-methyl (60+4) g/ha (5.01 t/ha). The reduced yield observed under the CT may be attributed to increased weed density, particularly *P. minor*, along with greater nitrogen leaching and nutrient immobilization resulting from crop residue incorporation. These factors likely impaired nutrient availability and crop development. In contrast, the ZT system effectively suppressed weed emergence, minimized nitrogen and moisture losses and reduced crop-weed competition. These improvements created more favourable conditions for wheat growth, leading to increased tiller production and enhanced ear development. These findings align with previous studies demonstrating the agronomic benefits of ZT practices in improving wheat productivity under conservation agriculture systems (25, 38-39). Higher grain yields in herbicide-treated plots may be due to effective weed control. These results are near those reported earlier (40-42) where herbicides increased crop productivity based on weed control efficacy.

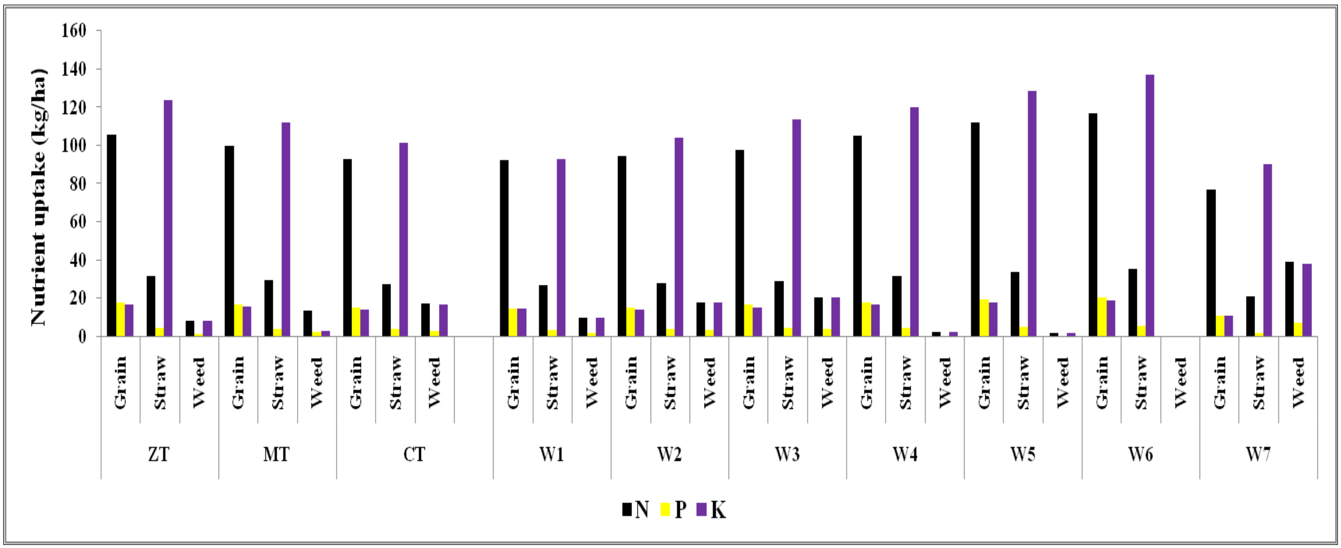

Fig. 3. Effect of crop establishment methods and herbicides on N, P and K uptake (kg/ha) in grain, straw and weeds.

ZT	Zero tillage	W3	Clodinafop (60g\ha)
MT	Minimum tillage	W4	Sulfosulfuron+metsulfuron-methyl (30+2)g/ha
CT	Conventional tillage	W5	Clodinafop+metsulfuron-methyl(60+4)g/ha
W1	Sulfosulfuron (25g/ha)	W6	Two hand weeding (30&60DAS)
W2	Metsulfuron–methyl (4g/ha)	W7	Weedy check

Table 3. Impact of crop establishment methods and herbicides on yield attributes and weed parameters of wheat (pooled data)

	Yield Attributes				Weed Parameters						
					Weed Density (no/m²)			Weed Biomass (g/m²)			
A. Tillage	**Grain (t/ha)**	**Straw (t/ha)**	**Biological (t/ha)**	**HI (%)**	**NLW**	**BLW**	**Total**	**NLW**	**BLW**	**Total**	**WCE (%)**
Zero tillage	4.81	7.09	11.73	40.08	0.98 (22.5)	1.195 (34.0)	1.48 (61.1)	25.07	14.16	38.27	63.03
Minimum tillage	4.56	6.81	11.29	39.99	1.14 (39.7)	1.31 (47.4)	1.62 (87.4)	34.55	26.69	59.55	63.54
Conventional tillage	4.26	6.49	10.71	39.81	1.21 (49.9)	1.37 (60.4)	1.68 (106.7)	42.80	32.18	72.73	64.90
S.E. m (d)	**4.1**	**7.1**	**9.5**	**0.07**	**0.04**	**0.028**	**0.03**	**0.96**	**1.95**	**3.23**	
C.D. (at 5%)	**13.3**	**23.2**	**30.9**	**0.23**	**NS**	**NS**	**0.10**	**3.14**	**6.37**	**10.54**	
B. Weed control practices											
Sulfosulfuron (25g\ha)	4.20	6.39	10.18	40.74	0.74 (5.9)	1.66 (49.7)	1.71 (54.7)	41.94	3.8	45.85	63.21
Metsulforon -methyl(4g/ha)	4.36	6.53	10.84	39.83	1.93 (103.4)	1.148 (14.9)	2.04 (122.3)	11.52	69.5	81.15	39.50
Clodinafop(60g\ha)	4.55	6.82	11.37	39.62	1.48 (32.7)	2.024 (115.4)	2.13 (143.6)	38.34	16.0	90.56	66.05
Sulfosulfuron + Metsulforon-methyl (30+2) g/ha	4.75	7.03	11.73	40.04	0.67 (5.0)	1.051 (11.9)	1.20 (16.5)	9.02	3.1	11.94	85.51
Clodinafop + Metsulforon-methyl (60+4) g/ha	5.01	7.33	12.28	40.30	0.56 (3.9)	0.925 (8.7)	1.08 (12.4)	6.18	2.4	9.01	92.49
Two hand weeding (30 & 60DAS)	5.16	7.50	12.62	40.85	0.71 (0.0)	0.71 (0.0)	0.62 (4.3)	0.00	0.00	0.00	100.00
Weedy check	3.79	5.99	9.69	38.65	1.99 (108.3)	2.070 (128.6)	2.36 (241.5)	68.78	75.6	159.45	0.00
S.E. m (d)	**6.9**	**13.4**	**18.0**	**0.21**	**0.04**	**0.037**	**0.03**	**0.94**	**3.7**	**3.54**	
C.D. (at 5%)	**19.3**	**37.9**	**50.8**	**0.59**	**0.11**	**0.105**	**0.08**	**2.65**	**10.5**	**9.97**	

Post-harvest physic-chemical properties of the soil

Based on pooled data, the physic-chemical properties of soil were affected significantly ($p<0.05$) by tillage and herbicide treatments (Table 4). Soil analysis showed that organic carbon, bulk density, porosity and available soil N, P and K were affected significantly ($p \le 0.05$) after harvest. Tillage significantly reduced soil bulk density under ZT (1.33g/cm³) compared to MT (1.35g/cm³) and CT (1.36g/cm³). Significantly higher organic carbon (0.47 %) and porosity (48.16 %) were observed under ZT compared to MT (0.45 %, 48.14 %) and CT (0.42 %, 48.13 %). The higher available N, P and K was recorded in CT (146.47, 52.83, 142.83 kg/ha) followed by MT (141.87, 51.72, 135.05 kg/ha) and ZT (138.86, 50.86, 126.51 kg/ha). Among herbicides, the highest available N, P and K were recorded under sulfosulfuron (25g/ha) (154.82, 54.92, 157.67 kg/ha), followed by the weedy check (153.74, 53.75, 141.69 kg/ha). The minimum available N, P and K were recorded in two hand weeding 30 and 60 DAS (132.13, 48.65, 120.20 kg/ha) which was at par with clodinafop + metsulfuron-methyl (60 + 4) g/ha (135.84, 49.66, 126.56 kg/ha). Settling of soil particles can increase bulk density under zero tillage systems (43). ZT increased plant-available N by enhancing surface organic matter and stimulating microbial-driven mineralization of organic N into NH_4^+ and NO_3^-. This improved nitrogen availability supports short-term yield gains without additional fertilizer, reinforcing the benefits of ZT in conservation agriculture (44). However, CT depletes soil organic matter, leading to reduced soil fertility and structural stability. In contrast, ZT helps retain higher levels of organic matter in the surface soil (45). Significantly greater available soil P and K were recorded in CT as found by (46).

Table 4. Impact of crop establishment methods and herbicides on physicochemical properties and available nutrients of soil after harvest

Treatments	Physico-chemical properties					
				Available Nutrients (kg/ha)		
A. Tillage	**OC (%)**	**BD g/cm³**	**Porosity (%)**	**N**	**P**	**K**
Zero tillage	0.47	1.33	48.16	138.86	50.86	126.51
Minimum tillage	0.45	1.35	48.14	141.87	51.72	135.05
Conventional tillage	0.42	1.36	48.13	146.47	52.83	142.83
S.E. m (d)	0.002	0.002	0.01	1.32	0.33	2.43
C.D. (at 5%)	0.008	0.008	0.03	NS	NS	NS
B. Weed control practices						
Sulfosulfuron (25g\ha)	0.43	1.37	48.12	154.82	54.92	157.67
Metsulfuron - methyl(4g/ha)	0.44	1.36	48.13	141.22	52.15	136.47
Clodinafop(60g\ha)	0.45	1.36	48.13	135.23	49.71	125.79
Sulfosulfuron + Metsulfuron-methyl (30+2) g/ha	0.44	1.35	48.14	143.83	51.76	135.19
Clodinafop + Metsulfuron-methyl (60+4) g/ha	0.44	1.35	48.15	135.84	49.66	126.56
Two hand weeding (30&60DAS)	0.45	1.34	48.19	132.13	48.65	120.20
Weedy check	0.46	1.34	48.17	153.74	53.75	141.69
S.E. m (d)	0.005	0.01	0.02	2.77	0.44	2.54
C.D. (at 5%)	NS	NS	NS	7.81	1.24	7.15

Regression studies

Regression analysis for weed density, biomass, nutrient content and uptake (in both crops weed) and wheat grain yield were performed for two years (2019-20, 2020-21) and pooled value (Fig. 4-8). Where, the weed density, biomass, nutrient content and uptake (crop and weeds) were taken as independent variables and yield as the dependent variable. Linear regression analysis showed that with the increase in weed density, biomass, nutrient content and uptake by weed, the yield decreased significantly and followed a strong negative linear relationship. However, the enhanced nutrient content and uptake by both grain and straw were strongly correlated with increased yields, exhibiting a significant positive linear relationship. The weed biomass (64.4 %), density (63.3 %), N content and uptake by grain and straw (75.6 %, 74.6 % and 98.3 %, 97.1 %); P content and uptake by grain and straw (85.7 %, 97.7 % and 97.5 %, 94.4 %); K content and uptake by grain and straw (83.2 %, 87.1 % and 97.2 %, 94.3 %); N content and uptake by weed (29.3, 67.1 %); P content and uptake by weed (26.9, 67.1 %); K content and uptake by weed (23.5, 67.4 %) variation was noted in the weed data and nutrient levels found in grain, straw and weeds during the combined value analysis, respectively. R^2 (coefficient of determination) was obtained with weed density, biomass (R^2=0.644), N, P and K content by grain (R^2=0.756, 0.857, 0.832), N, P and K content by straw (R^2=0.746, 0.977, 0.871), N, P and K content by weed (R^2=0.293,0.269, 0.235) and N, P and K uptake by grain (R^2=0.983, 0.975, 0.972), N, P and K uptake by straw (R^2=0.971, 0.944, 0.943) along with N, P and K uptake by weeds (R^2=0.671, 0.671, 0.674), respectively. A Similar trend was reported from research conducted in Jammu and Kashmir, India (47, 48).

Conclusion

In Central India, most farmers use intense tillage to develop fine seedbeds for wheat establishment following *Kharif* season harvests. According to the current study, ZT was shown to have reduced weed pressure when combined with clodinafop + metsulfuron-methyl, which improved crop development. This combination results in higher grain yield, increased soil organic matter, lower bulk density and minimum soil disturbance. It also encouraged more vigorous wheat growth, modified the soil's physical environment and enhanced the wheat crop's ability to utilize water and nutrients more efficiently through rhizosphere. Enhanced dry matter accumulation during the early vegetative stage, facilitated by improved root development, significantly increased nutrient uptake, thereby contributing to higher wheat grain yield. This early vigour not

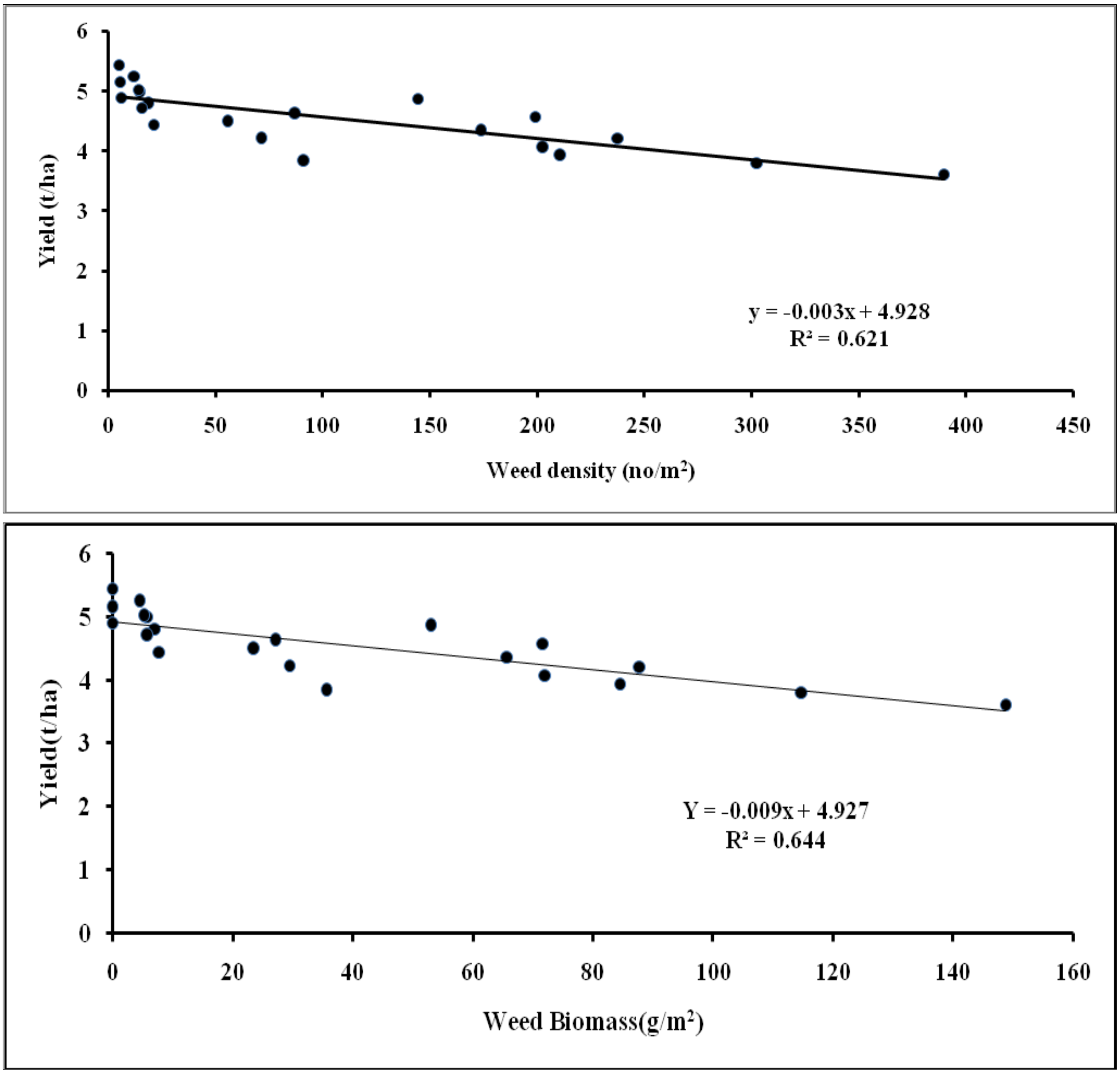

Fig. 4. Linear relationship between grain yield of wheat with weed density (no/m²) and biomass (g/m²) under the crop establishment methods and herbicides (pooled data).

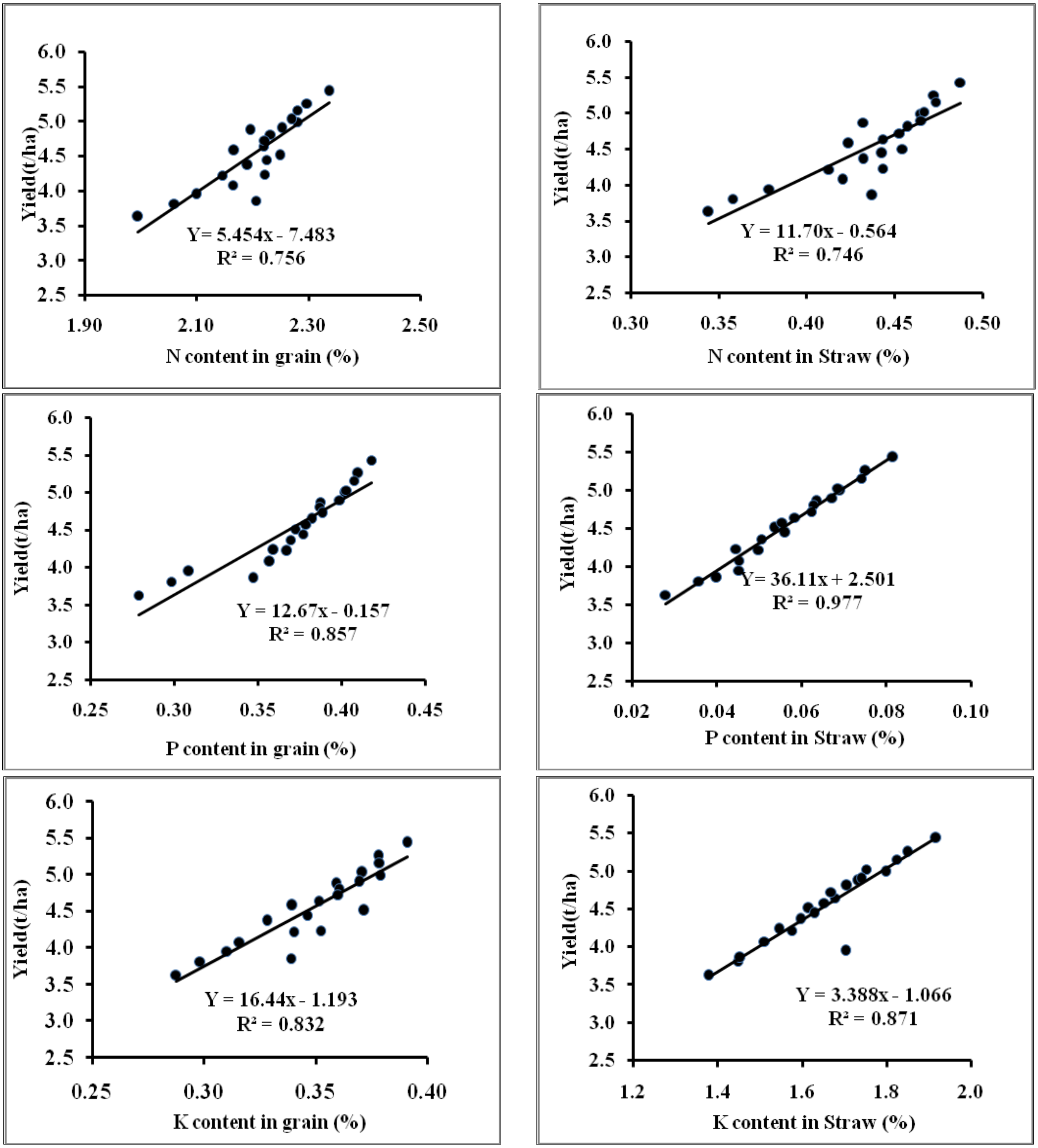

Fig. 5. Linear relationship between yield of wheat with crop nutrient content under the crop establishment methods and herbicides (pooled data).

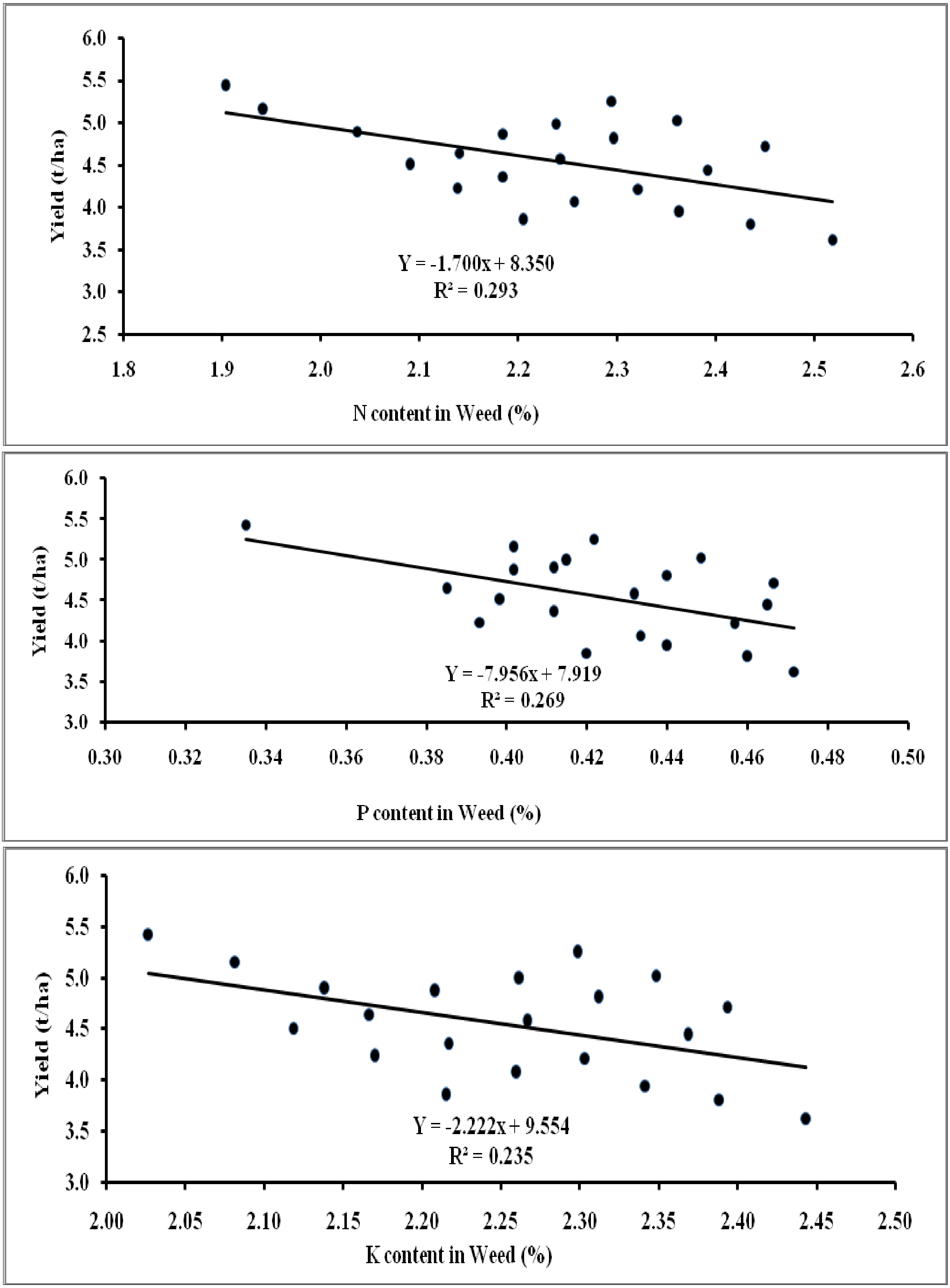

Fig. 6. Linear relationship between crop yield and weed nutrient content under crop establishment methods and herbicides (pooled data).

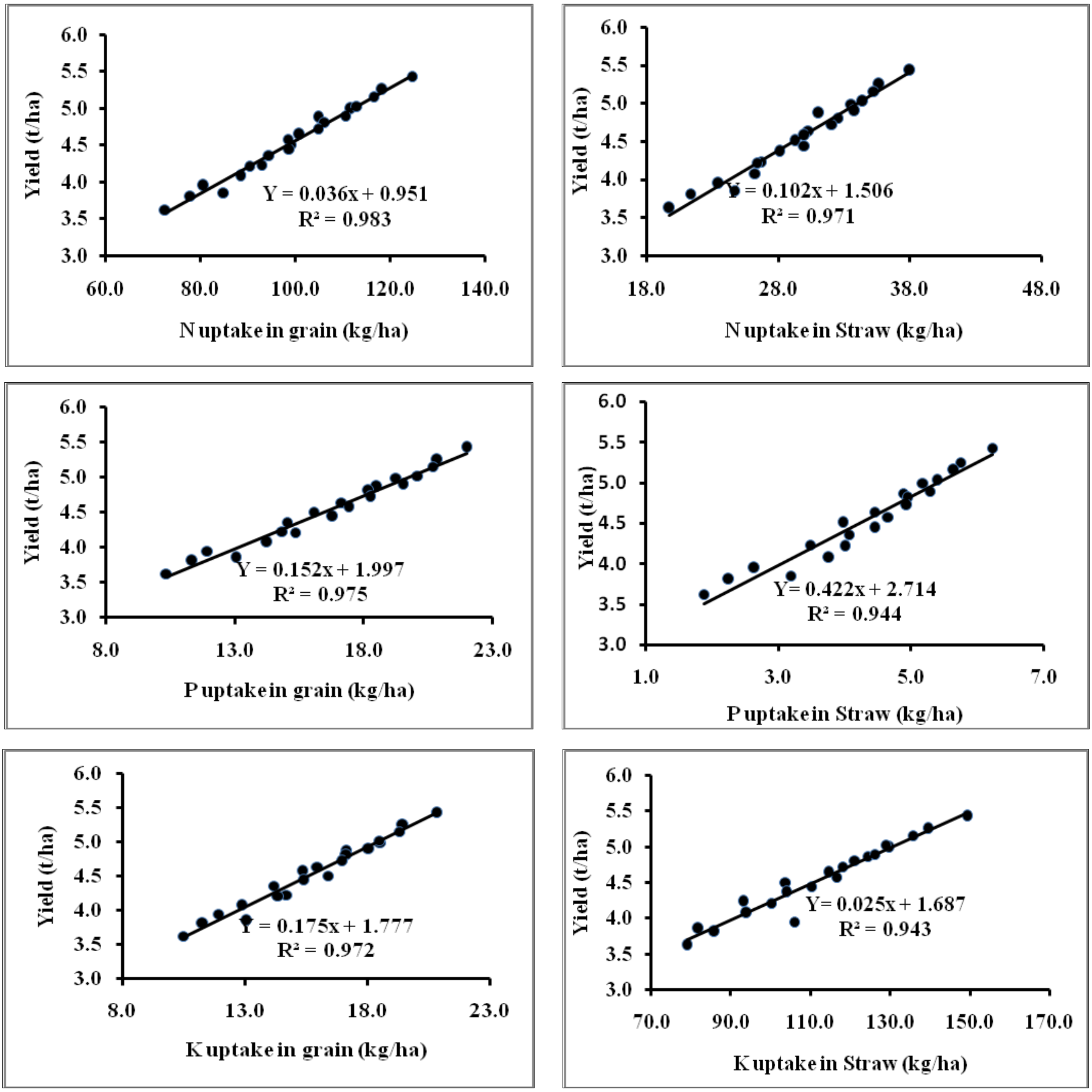

Fig. 7. Linear relationship between yield of wheat with crop nutrient uptake under the crop establishment methods and herbicides (pooled data).

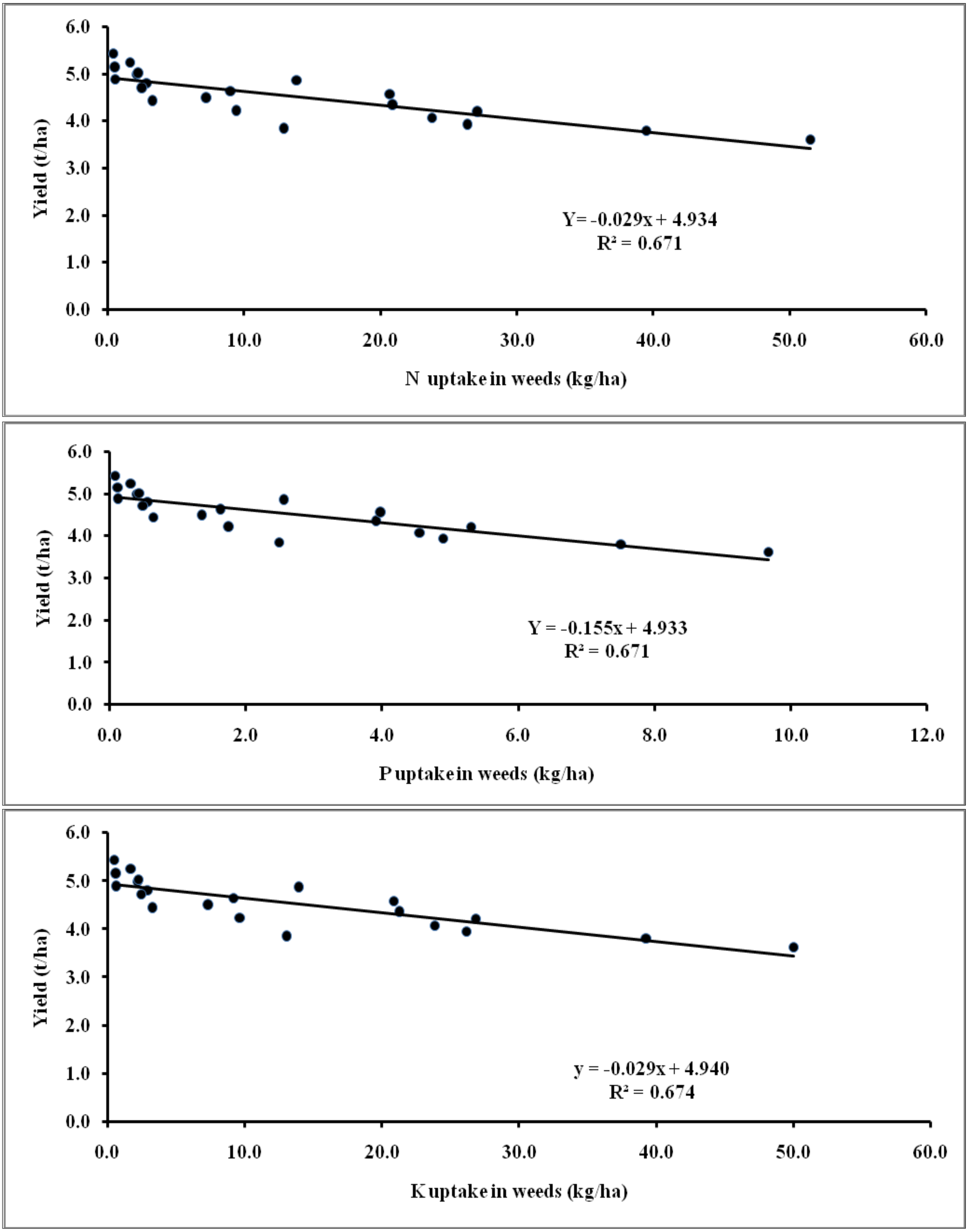

Fig. 8. Linear relationship between yield of wheat with weeds' nutrient uptake under the crop establishment methods and herbicides (pooled data).

only bolstered nutrient absorption but also optimized the partitioning of biomass, leading to improved grain filling and overall yield. The weed control measure clodinafop + metsulfuron-methyl (60+4 g/ha) under ZT was found to be an efficient strategy, significantly enhancing nutrient uptake and producing the highest yield among various treatment combinations. Therefore, post emergence application of clodinafop + metsulfuron-methyl (60+4 g/ha) can be recommended as an effective measure for weed control giving a higher productivity and nutrient uptake in wheat followed by two hand weeding (30 and 60 DAS). Total N, P and K absorption increased by 31.16 %, 43.21 % and 38.65 % in grain and 36.83 %, 57.94 % and 29.94 % in straw, respectively. Additionally, grain and straw yields increased by 24.35 % and 18.28 %, respectively. Therefore, it is possible to suggest that this treatment combination of ZT with clodinafop + metsulfuron-methyl is highly effective in enhancing weed control, nutrient uptake and yield in wheat production systems of Central India.

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Authors' contributions

PKP was responsible for carrying out the lab and field research work, manuscript preparation and SK communication of the manuscript. PKP, KSS, TKR, SA, SK and SB conceptualized, conceived and designed the experiment. KSS, TKR, TR and SK analyzed the data and interpreted the results. KSS, PKP and VK drafted the manuscript. PKP, KSS, TKR, SB, SK and SA critically revised and edited the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest: The authors have no conflicts of interest to declare and no financial interest to report.

Ethical issues: None

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