

Article

Comparative Analysis of Rice and Weeds and Their Nutrient Partitioning under Various Establishment Methods and Weed Management Practices in Temperate Environment

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Abstract: A research trial was conducted at Agronomy Farm (SKUAST-K, Wadura, Jammu & Kashmir), during *kharif* 2017 and 2018 to evaluate nutrient removal in rice under various rice establishment methods and weed control measures. The study comprised of two factors: rice establishment techniques {Transplanting (TPR); Direct seeding (DSR) and System of rice intensification (SRI)} as main plot treatments and weed control measures {Butachlor @ 1500 g a.i ha⁻¹ (B); Penoxsulam @ 22.5 g a.i ha⁻¹ (P); Pyrazosulfuron ethyl + Pretilachlor @ 15 and 600 g a.i ha⁻¹ (PP); Bensulfuron methyl + Pretilachlor @ 60 and 600 g a.i ha⁻¹ (BP); 2 Conoweeding/Hand Weeding (CW/HW); Weed free (WF) and weedy check (WC)} as sub-plot treatments meant to evaluate the best establishment method and weed management practice for rice. Over DSR and transplanted rice, the SRI technique yielded a significant increase in dry biomass accumulation (17.04 and 17.20 t ha⁻¹) and grain (7.92 and 8.17 t ha⁻¹) and straw (9.60 and 10.17 t ha⁻¹) yields. Penoxsulam herbicide significantly showed higher grain and straw yield of 8.19 and 8.28 t ha⁻¹ and 10.13 and 10.44 t ha⁻¹, respectively, than other weed management measures by comparing the means using critical difference. TPR excelled in reducing dry weed biomass more than other established methods. All herbicides considerably reduced dry weed biomass, but Penoxsulam herbicide showed the greatest reduction in dry weed biomass and proved superior against complex weed flora. Weeds showed maximum contribution towards total Biomass under DSR, among rice establishment techniques. In contrast, among different weed control measures, it was maximum in weedy check treatment (Untreated Control) and minimum in penoxsulam treatment. SRI significantly excelled in crop (grain and straw) nutrient uptake compared to the DSR and TPR method, although different crop establishment techniques non-significantly influenced nutrient concentrations. Furthermore, penoxsulam treatment demonstrated higher crop (grain

and straw) nutrient uptake among the various weed management measures. However, available soil nutrients were observed among establishment techniques, highest in DSR and lowest in SRI. Moreover, direct-seeded rice excelled SRI and transplanted rice in weed nutrient uptake, and among the different herbicidal treatments, penoxsulam recorded the lowest uptake in weeds. Nutrient budgeting demonstrated that DSR showed the maximum percentage of nutrient removal by weeds, and the minimum ratio was in TPR. In contrast, the lowest rate of nutrients removed via weeds were seen in penoxsulam application under various weed management measures.

Keywords: biomass; herbicide; Himalayas; nutrient uptake; penoxsulam; rice; SRI; weed; yield

1. Introduction

Rice production is the agricultural sector's backbone in sub-tropical and tropical countries, including India, the world's 2nd-largest producer and consumer [1]. By the end of 2025, demand for rice, the world's most important staple food, is predicted to reach 800 metric tons [2,3]. As the world's population expands, developing countries must focus on producing sufficient rice on limited arable land through crop genetic improvement, managerial optimization, and socioeconomic factors. Doubling of production on a sustainable basis is required to feed more than 9 billion people by 2050. Although more than 75 percent of rice production comes from 79 m ha of irrigated lowland area, it is assumed that 17 m ha of Asia's irrigated rice crop will face water scarcity. In contrast, 22 m ha will face economic water scarcity [4,5], raising concerns about the sustainability of rice production under flooded conditions. Furthermore, transplanted rice has higher greenhouse gas emissions (CH₄ and N₂O emissions), contributing to global warming [6]. As a result, alternative rice cultivation techniques should be executed to reduce rice-related hazardous gas emissions. The direct-seeded rice (DSR) is gaining importance in recent years to minimize water and labour scarcity issues while retaining a sustainable output. As a result, adopting DSR has several benefits, including minimal use of irrigation water, time consumption, reduced labour scarcity, mitigation of climate change, increased output of succeeding crops, and so on [6]. Many variables and weeds that limit DSR productivity are the most severe biological constraints causing economic losses. Due to maximum plant density and biomass production during the vegetative phase, DSR has a higher nutritional requirement than a transplanted crop; hence, senescence occurs earlier as a nutrient deficiency is developed at the reproductive phase [7]. To make more efficient water use, rice-growing practises transitioning from traditional rice to other alternative rice techniques. The system of rice intensification (SRI) involves alternate wetting and drying rice fields [5,8]. More than half of the nitrogen used in flooded rice production is lost to the environment through volatilization, leaching, surface runoff, and denitrification, polluting freshwater and marine habitats. Changes in soil physical, chemical, and biological features caused by puddling and submergence, on the other hand, have some positive effects on soil quality, which influences the availability of some macro- and micronutrients, nutrient content, and crop uptake pattern. The transition from traditional rice production to aerobic rice has increased micronutrient deficiency, particularly in Fe, posing a new challenge to iron availability. Micronutrient deficiencies, such as Fe and Zn, are a severe hazard to the world's population's health. The SRI is a water-conserving production system that increases fame and interest as it improves rice productivity and improves nutrient uptake and nutrient usage efficiency [9,10]. For water-saving rice techniques, nutrient management tools are critical because changes in soil redox potential significantly impact the availability of soil nutrients, transport in soil, and removal by crop plants. Flooded condition in rice results in an anoxic condition as the soil is submerged, while aerobic rice soil develops a completely different soil environment than traditional flooded rice soil. Because of the early weed emergence under favourable soil conditions, crops and weeds compete for different factors viz. nutrients, space, water, and light [11]. Weeds cause various losses,

fluctuating from 50% to complete failure of crops [7], and weeds can absorb up to nine times more nutrients in the unweeded plot. Fertilizer use and consumption in rice have risen dramatically in recent decades [12]. It has been reported that weeds absorb more than 60% of applied fertilizers, resulting in poorer nutrient availability for crops [13]. Weed nutrient removal is dependent on the period of their growth, but due to labour scarcity and increased wages, controlling weeds in transplanted rice at critical stages by manual weeding alone is very difficult. Herbicides with a single mechanism of action will not be effective against a wide range of weeds. So, to control these broad-spectrum weeds, herbicide formulations with various modes of action combined with hand weeding will result in effective weed control, lesser nutrient loss via weeds, accompanied by more crop nutrient uptake. Many herbicides, successfully used to control weeds in rice crops, with diverse compositions are recommended to avoid residue buildup, weed flora shifts, and the increase of herbicide-resistant weeds [14]. The current herbicide use trend is to identify an efficient weed control measure by using low dose high-efficiency herbicides, which will reduce overall herbicide use and make application easier and more cost-effective. Given the above, this research experiment was conducted to find suitable crop establishment techniques and weed control strategies for rice to minimize nutrient losses, reducing the cost of cultivation and making rice cultivation as profitable as possible.

2. Materials and Methods

2.1. Experimental Site Description

A research trial was studied at Agronomy Farm, SKUAST-K, Wadora-Sopore, J&K, in the 2 consecutive *kharif* seasons (2017 and 2018). Wadora is situated at 34°34' North latitude, 74°40' East longitude, and at 1587 m altitude from mean sea level. In the mid-latitude temperate zone, the research farm has 812 mm mean annual precipitation. During the experimental years, the total rainfall of 339.4 and 352.5 mm was received in 2017 and 2018, respectively, with minimum temperatures fluctuating from 5.25 to 19.30 °C and 5.41 to 18.6 °C. Maximum temperatures fluctuated from 24.5 to 32.7 °C and 22.0 to 31.8 °C, respectively (Figures 1 and 2), and mean relative humidity (R.H) ranged from 67.3 to 90.8% and 60.1 to 92.1% (maximum R.H) and 32.1 to 64.4 percent and 33.3 to 70.4 percent (minimum R.H), respectively. This location has a cold temperate climate, with minus winter temperatures and moderate temperatures in the summer. The rice crop in this area has a growth period of 140–150 days. Samples from the top 20 cm of the soil profile were taken to assess initial nutrients. The texture of soil was silty-clay-loam, with a neutral pH and medium range of organic carbon (O.C), medium in available nitrogen (N), phosphorus (P) and potassium (K) (Table 1).

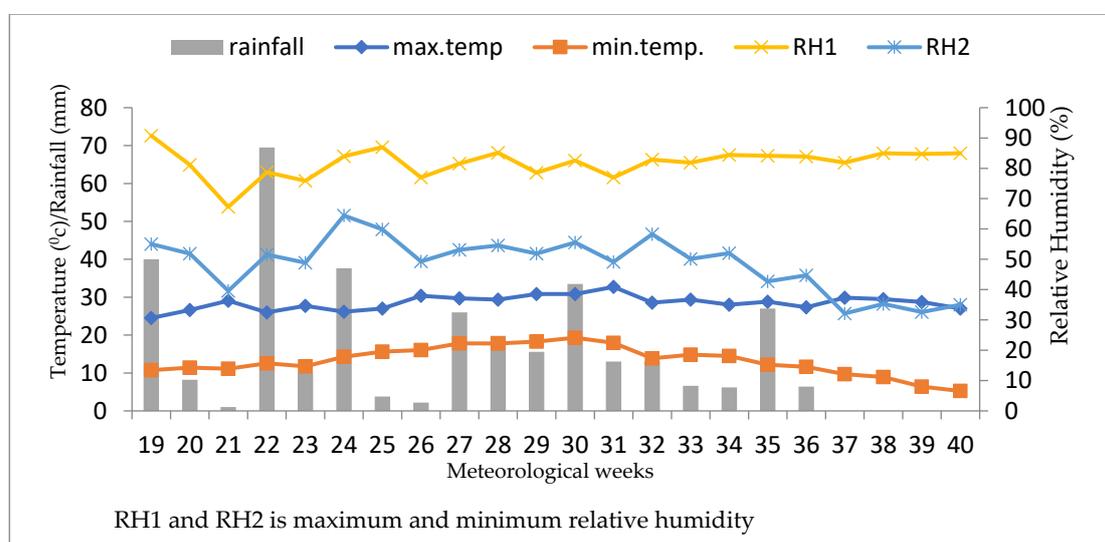


Figure 1. Average weekly meteorological data (2017).

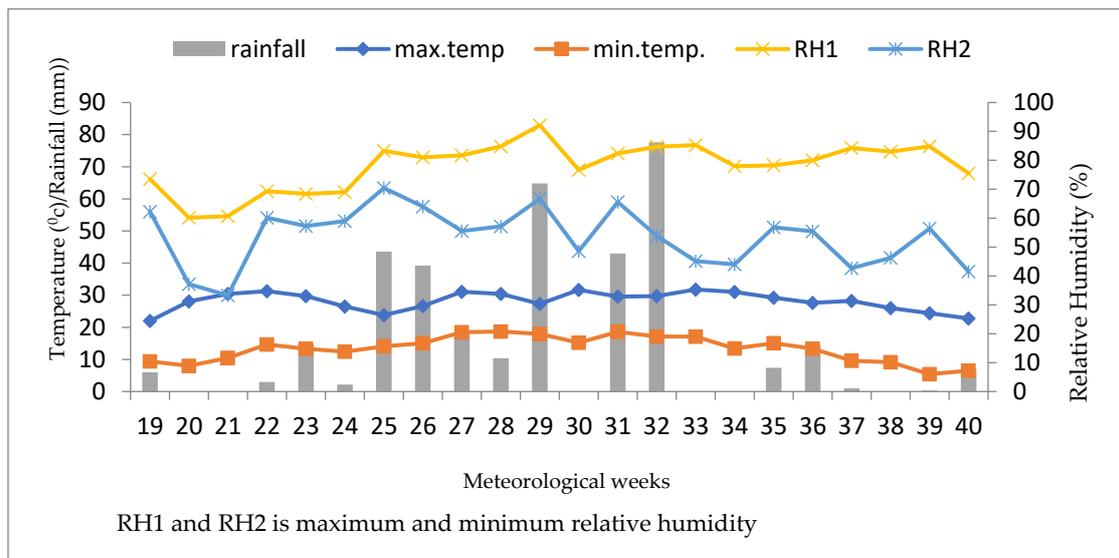


Figure 2. Average weekly meteorological data (2018).

Table 1. Initial soil status of experimental field.

Characteristics	Status	Range	Method Used
A. Physical			
Texture		Silty-clay-loam	International Pipette Method [15]
B. Chemical			
pH	6.9	Neutral	Blackman's glass electrode pH meter [16]
O.C (%)	0.99%	Medium	Walkely and Black rapid titration method [16]
Available N	380 (kg ha ⁻¹)	Medium	Alkaline Potassium permanganate method [17]
Available P	19.7 (kg ha ⁻¹)	Medium	Extraction with 0.5 M NaHCO ₃ [18]
Available K	280 (kg ha ⁻¹)	Medium	Flame photometer method [16]

2.2. Design of Experiment

A split-plot design with three replications was used to carry out the experiment with three rice establishment techniques in main plots and seven weed control measures as a sub-factor. The treatments of the main plot consisted of (i) TPR (Transplanting), (ii) DSR (Direct Seeding), (iii) SRI (System of Rice Intensification) and sub-plot treatments comprised of (i) Butachlor @ 1500 g a.i. ha⁻¹ (B), (ii) Penoxsulam @ 22.5 g a.i. ha⁻¹ (P), (iii) Pyrazosulfuron ethyl + pretilachlor @ 15 and 600 g a.i. ha⁻¹ (PP), (iv) Bensulfuron methyl + pretilachlor @ 60 and 600 g a.i. ha⁻¹ (BP), (v) 2 Cono-weeding/Handweeding (CW/HW), (vi) Weed free (WF) and (vii) Weedy check (WC). No manual weeding was followed in the weedy check treatment, but in the weed-free treatment, multiple manual weedings were received.

2.3. Crop Management Practices

Pre-germinated rice seeds were sown with a row spacing of 20 cm in DSR on 17 May and were also used for growing nursery in case of transplanting (TPR) method. 25 days old seedlings were used for transplanting, with 20 cm × 10 cm spacing. In the last week of May, 12-day-old seedlings (SR-4) were transplanted for the SRI method with 25 cm × 25 cm spacing. In experiment plots, well-decomposed 10 t ha⁻¹ of FYM was mixed during field preparation. N, P₂O₅, and K₂O were applied in the proportion of 120:60:30 kg ha⁻¹. At transplanting, full quantity of P₂O₅ and K₂O, as well as 1/2 N, were involved; however,

at active tillering and panicle initiation phase the rest $1/2$ N was given in two splits. The herbicides butachlor, pyrazosulfuron-ethyl + pretilachlor, and bensulfuron methyl + pretilachlor were applied as pre-emergent at three DAS/DAT penoxsulam as post-emergent at 10 DAS/DAT in each establishment method as per treatment. In SRI and DSR, no continuous standing water was maintained throughout the vegetative stage, but a thin water layer was continued from flowering to soft dough stage; however, up to the dough stage, 2–3 cm of water was maintained under TPR.

2.4. Collection and Processing

2.4.1. Rice (Grain + Straw)

Plants in a $0.5\text{ m} \times 0.5\text{ m}$ quadrant from each plot of treatment were collected at 15-day intervals and sun-dried (3–4 days), oven-dried ($60\text{--}65\text{ }^{\circ}\text{C}$) to attain a constant weight. The crop's dry biomass noted in grams was transformed into t ha^{-1} . The crop was harvested in the second week of October grain, and straw yields were measured in kg ha^{-1} and were later converted into t ha^{-1} . For analysis purposes, rice grain and straw samples were collected from different treatments separately, oven-dried ($60\text{--}65\text{ }^{\circ}\text{C}$) until the attainment of constant weight, and grinded with Yarco grinder in the laboratory.

2.4.2. Weeds

Weeds uprooted from each plot at harvest were sundried, followed by oven drying ($60\text{--}65\text{ }^{\circ}\text{C}$) until they reached a constant weight. For analysis, the Yarco grinder was used to grind the oven-dried plant samples. The weight of weed biomass was measured in t ha^{-1} .

2.5. Nitrogen (N), Phosphorus (P) and Potassium (K) Estimation

Chemical analysis was performed on the ground samples placed in labelled bags. A 0.5 g sample was digested with concentrated H_2SO_4 @ 10 mL plus digestion-mixture ($\text{H}_2\text{SO}_4 + \text{HClO}_4 + \text{HNO}_3$) to assess the nitrogen content. The micro Kjeldahls method was used to determine total nitrogen (N). Phosphorus content was evaluated with a spectrophotometer by the Vanads-Molybdo-phosphoric yellow method by digestion in a tri acid-mixture ($\text{HNO}_3:\text{HClO}_4:\text{H}_2\text{SO}_4 = 10:4:1$). A flame photometer was used to quantify the plant sample's potassium concentration (percent) [16]. The uptake of N, P and K by weeds, straw, and crop grain, estimated by multiplying dry matter production with their respective content values, was expressed as kg ha^{-1} . After the crop was harvested, soil samples were obtained from each plot up to a depth of 15 cm and were shade dried and labelled. After drying, the soil samples were crushed, then sieved through a 2 mm screen, and for lab analysis, the composite sample was collected. For each soil sample, the available soil nitrogen was estimated in kg ha^{-1} using the alkaline potassium permanganate method [17]. The available P of soil samples noted in kg ha^{-1} was assessed using 0.5 N NaHCO_3 at a pH of 8.5 [18]. The K content of samples was measured in kg ha^{-1} using an extraction method with 1N ammonium acetate at a pH of 7.0 [16].

2.6. Statistical Analysis

The recorded data were analyzed statistically using analysis of variance subjected to split-plot design with the help of R software. At a significance level of 0.05 , the treatment averages were compared using the critical difference (C.D) test. Regression analysis of yield with crop and weed dry matter and nutrient uptake by crop and weeds was computed, and regression equations were fitted to estimate the response of yield explained by dry matter and nutrient uptake.

3. Results

3.1. Dry Matter Accumulation

Rice establishment techniques and weed control measures illustrated significant influence on dry Biomass production in rice. Dry matter accumulation improved exponentially up to 100 days after sowing (DAS), then decreased at a declining rate until maturity

(Table 2). SRI performed better than TPR and DSR, with dry matter accumulation of 17.04 and 17.20 t ha⁻¹ at harvest, respectively. In contrast, direct-seeded rice had the lowest dry matter accumulation of 12.31 and 12.65 t ha⁻¹ at 2017 and 2018 (Table 1). SRI showed a 13.48 and 27.75 percent increase in dry matter accumulation than transplanted and direct-seeded rice at harvest in 2017, and the comparable figures for 2018 were 12.83 and 26.43 percent, respectively. However, as compared to other herbicides, the plots under Penoxsulam herbicide significantly recorded the higher dry matter accumulation of 15.73 and 116.30 t ha⁻¹, with a percentage increase of 18.59 and 17.94 percent when compared to weedy check during 2017 and 2018, respectively.

Table 2. Dry biomass (qha⁻¹) of rice crop as influenced by rice establishment techniques and weed control measures.

Treatments	40 (DAS)		55 (DAS)		70 (DAS)		85 (DAS)		100 (DAS)		115 (DAS)		130 (DAS)		Maturity	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Rice establishment techniques																
TPR	1.09	1.42	7.7	8.2	53.4	54.4	110.3	112.8	124.7	127.8	140.4	144.0	145.1	148.5	147.4	149.9
DSR	1.00	1.26	6.3	6.7	45.8	45.5	98.5	100.7	108.8	110.6	117.8	118.4	120.6	122.1	123.1	126.5
SRI	1.17	1.57	8.5	9.2	55.8	57.9	118.1	120.8	136.3	139.3	151.3	154.8	166.1	169.3	170.4	172.0
SE (m) ±	0.003	0.01	0.06	0.04	0.19	0.19	0.34	0.31	1.12	0.95	0.80	0.74	1.39	1.41	1.48	1.49
C.D. (<i>p</i> ≤ 0.05)	0.01	0.04	0.26	0.19	0.79	0.79	1.37	1.25	4.53	3.85	3.22	3.01	5.60	5.69	5.98	6.01
Weed control measures																
B	1.01	1.34	6.9	7.5	46.5	47.4	103.9	105.4	117.4	121.0	124.2	129.1	131.1	136.8	134.1	139.8
P	1.17	1.5	8.1	8.6	56.5	57.4	116.5	118.0	134.6	138.2	144.7	150.6	154.3	160.0	157.3	163.0
PP	1.14	1.47	7.8	8.3	54.1	55.0	112.5	115.0	129.8	133.4	138.2	144.1	148.6	154.3	151.6	157.3
BP	1.09	1.42	7.5	8.0	51.7	52.6	109.4	111.9	127.4	131.1	135.2	140.1	141.7	147.4	144.7	150.4
2 CW/HW	1.04	1.37	7.2	7.8	49.4	50.3	106.1	108.5	122.2	125.8	129.7	134.6	137.2	142.9	140.2	145.9
WF	1.22	1.55	8.4	8.9	60.0	60.9	118.9	121.4	139.0	143.6	152.0	157.9	160.3	166.0	163.3	169.0
WC	0.94	1.28	6.7	7.2	43.8	44.7	96.6	102.1	110.6	112.3	117.2	123.1	125.1	130.8	128.1	133.8
SE (m) ±	0.01	0.01	0.01	0.02	0.10	0.12	0.13	0.16	1.55	1.53	1.92	1.85	1.36	1.53	1.30	1.47
C.D. (<i>p</i> ≤ 0.05)	0.05	0.05	0.05	0.06	0.31	0.36	0.40	0.47	4.67	4.43	5.76	5.35	4.10	4.43	3.90	4.25

AS = Days after sowing, TPR = Transplanting, DSR = Direct seeding, SRI = System of rice intensification, B = Butachlor (1500 g a.i. ha⁻¹), P = Penoxsulam (22.5 g a.i. ha⁻¹), PP = Pyrazosulfuron ethyl + pretilachlor (15 and 600 g a.i. ha⁻¹), BP = Bensulfuron methyl + pretilachlor (60 and 600 g a.i. ha⁻¹), 2CW/HW = 2 Cono-weeding/Hand-weeding, WF = Weed free and WC = Weedy check.

3.2. Yield of Rice (Grain + Straw)

Rice yield (grain + straw) was affected significantly under different rice establishment approaches and weed control measures (Table 3). SRI produced a maximum grain yield of 7.92 and 8.17 t ha⁻¹ and straw yield of 9.60 and 10.17 t ha⁻¹, followed by TPR, whereas DSR produced significantly lower grain yield (6.01 and 6.24 t ha⁻¹) and straw yield (8.00 and 8.32 t ha⁻¹). SRI method excelled transplanting and DSR method in grain yield by 24.11 and 10.47 percent and 23.62 and 12.23 percent, respectively. During 2017 and 2018, Penoxsulam herbicide produced significantly more grain yield (8.19 and 8.28 t ha⁻¹) and straw yield (10.13 and 10.44 t ha⁻¹) than WC and other weed control techniques.

3.3. Weed Dry Matter

Significant differences were noticed during the study period in weed biomass and its contribution to total Biomass. Rice establishment techniques and weed control approaches influenced significantly dry weed biomass (Table 3). Compared to SRI and DSR, dry weed biomass was found less under transplanted rice at harvest, with reductions of 9.22 and 43.10 percent in 2017 and 10.04 and 45.06 percent in 2018. On contrary, DSR had recorded maximum dry weed biomass. Among the different herbicidal treatments, Penoxsulam herbicide significantly lowered dry weed biomass (0.25 and 0.23 t ha⁻¹), reducing 67.08 and 69.38 percent in dry weed biomass at harvest compared to weedy check, respectively.

Table 3. Yield (t ha^{-1}) of rice, weed biomass (t ha^{-1}) and biomass share of weeds as influenced by rice establishment techniques and weed control measures.

Treatments	Grain—Yield (t ha^{-1})		Straw—Yield (t ha^{-1})		Weed—Biomass (t ha^{-1})		Total—Biomass (Rice + Weeds) (t ha^{-1})		Weeds Share of Total Biomass (%)	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Rice establishment techniques										
TPR	7.09	7.17	8.88	9.21	0.22	0.20	16.19	16.58	1.36	1.21
DSR	6.01	6.24	8.00	8.32	0.69	0.68	14.70	15.24	4.69	4.46
SRI	7.92	8.17	9.60	10.17	0.27	0.25	17.79	18.59	1.52	1.34
SE (m) \pm	0.25	0.28	0.26	0.29	0.01	0.01	0.52	0.49	-	-
C. D. ($p \leq 0.05$)	0.75	0.84	0.79	0.87	0.03	0.04	1.51	1.48	-	-
Weed control measures										
B	6.04	6.43	8.23	8.67	0.47	0.45	14.74	15.55	3.19	2.89
P	8.19	8.28	10.13	10.44	0.25	0.23	18.57	18.95	1.35	1.21
PP	7.59	7.77	9.31	9.51	0.27	0.25	17.17	17.53	1.57	1.43
BP	7.27	7.45	9.03	9.37	0.29	0.27	16.59	17.09	1.75	1.58
2 CW/HW	7.06	7.14	8.72	8.96	0.34	0.32	16.12	16.42	2.11	1.95
WF	9.00	9.29	10.75	11.19	0.00	0.00	19.75	20.48	0.00	0.00
WC	4.10	4.39	6.06	6.50	1.15	1.12	11.31	12.01	10.17	9.33
SE (m) \pm	0.24	0.28	0.23	0.21	0.01	0.01	0.55	0.52	-	-
C. D. ($p \leq 0.05$)	0.72	0.84	0.69	0.61	0.04	0.04	1.66	1.61	-	-

3.4. Weeds Share of Total Biomass

The findings of our experiment revealed that weeds contributed significantly to total biomass production under various establishment methods and weed control measures. As a result, the maximum share (%) of weeds (4.69 and 4.46%) towards total biomass production was observed under DSR treatment among different methods of crop establishment during 2017 and 2018, respectively (Table 3). However, under various weed management approaches the maximum contribution of weeds to total biomass production was 10.17 and 9.33%, noted under weedy check treatment.

3.5. Uptake of Nitrogen (N), Phosphorus (P) and Potassium (K) in Rice

Crop establishment techniques and weed control measures showed non-significant influence on NPK concentration in rice. In contrast, establishment methods and weed management practices affected the uptake of nitrogen, phosphorus, and potassium. During both years, SRI significantly improved nitrogen, phosphorus, and potassium uptake by rice over transplanting and DSR. SRI achieved the maximum N-uptake of 83.95 and 89.05 kg ha^{-1} in grain, followed by TPR and DSR, among the methods of rice establishment (Table 4). Uptake of phosphorus and potassium in grain followed the same trend. The higher phosphorus uptake (Table 5) and potassium (Table 6) noted 19.01 and 20.42 kg ha^{-1} and 23.76 and 24.51 kg ha^{-1} , respectively in grain under SRI. In straw, the highest nitrogen, phosphorus and potassium uptake were 47.04 and 50.85 kg ha^{-1} , 6.72 and 7.12 kg ha^{-1} and 150.77 and 164.80 kg ha^{-1} , respectively, under SRI, being significantly superior to transplanted rice and DSR. During 2017 and 2018, SRI's advantages in increasing total nitrogen, phosphorus and potassium uptake than transplanted rice were 18.37 and 20.72 percent N, 15.89 and 16.70 percent P, and 9.88 and 11.78 percent K, respectively, while its superiority over direct seeded rice was 28.6 and 29.07 percent N, 29.96 and 32.06 percent P, 21.70 and 24.06 percent K, respectively.

During 2017 and 2018, among the various weed control measures, penoxsulam noted the maximum N uptake by grain (83.54 and 86.11 kg ha^{-1}), and straw (48.62 and 51.16 kg ha^{-1}) (Table 4). The highest phosphorus uptake achieved under SRI in rice was 18.84 and 19.86 kg ha^{-1} (grain) and 6.08 and 7.30 kg ha^{-1} (straw), respectively (Table 5). Similarly, a significantly higher uptake of K i.e., 24.57 and 24.83 kg ha^{-1} by grain and 157.95

and 166.96 kg ha⁻¹ by straw, was observed under SRI (Table 6). During 2017, penoxsulam @ 22.5 g a.i. excelled WC and B treatments in increasing total nitrogen, phosphorus and potassium uptake by 50.66 and 27.61 percent N, 49.23 and 21.99 percent P, and 44.38 and 22.73 percent K. At the same time, the corresponding values for 2018 were 47.99 and 24.57 percent N, 50.11 and 24.07 percent P, and 41.88 and 20.63 percent K, respectively.

Table 4. Influence of rice establishment techniques and weed control measures on nitrogen content (%) and uptake (kg ha⁻¹) of rice.

Treatment	Grain N Content (%)		Straw N Content (%)		Grain N Uptake (kg ha ⁻¹)		Straw N Uptake (kg ha ⁻¹)		Total N Uptake (kg ha ⁻¹)	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Rice establishment techniques										
TPR	0.93	0.95	0.47	0.47	65.18	67.61	41.74	43.29	106.92	110.9
DSR	0.98	0.99	0.44	0.45	58.90	61.78	35.20	37.44	94.1	99.22
SRI	1.06	1.09	0.49	0.5	83.95	89.05	47.04	50.85	130.99	139.9
SE (m) ±	0.001	0.007	0.002	0.001	0.90	1.30	1.87	1.81	3.73	3.63
C. D. (<i>p</i> ≤ 0.05)	N.S	N.S	N.S	N.S	3.54	5.08	5.42	5.45	11.20	10.90
Weed control measures										
B	0.97	0.99	0.47	0.45	58.59	63.66	37.08	39.88	95.67	103.54
P	1.02	1.04	0.50	0.48	83.54	86.11	48.62	51.16	132.16	137.27
PP	1.0	1.02	0.50	0.48	75.90	79.25	44.69	45.65	120.59	124.9
BP	0.99	1.01	0.49	0.47	71.97	75.25	42.31	44.04	114.28	119.29
2 CW/HW	0.97	0.99	0.48	0.46	68.48	70.69	40.11	42.11	108.59	112.8
WF	1.03	1.05	0.51	0.49	92.70	97.55	49.37	55.95	142.07	153.5
WC	0.94	0.96	0.46	0.44	38.54	42.14	26.66	29.25	65.2	71.39
SE (m) ±	0.007	0.007	0.002	0.002	0.93	0.95	1.34	1.67	3.53	4.03
C. D. (<i>p</i> ≤ 0.05)	* N.S	N.S	N.S	N.S	2.66	2.74	4.03	5.02	10.60	12.10

* N.S means non-significant.

Table 5. Influence of rice establishment techniques and weed control measures on phosphorus content (%) and uptake (kg ha⁻¹) of rice.

Treatment	Grain P Content (%)		Straw P Content (%)		Grain P Uptake (kg ha ⁻¹)		Straw P Uptake (kg ha ⁻¹)		Total P Uptake (kg ha ⁻¹)	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Rice establishment techniques										
TPR	0.23	0.23	0.06	0.07	16.31	16.49	5.33	6.45	21.64	22.94
DSR	0.22	0.22	0.06	0.06	13.22	13.72	4.80	4.99	18.02	18.71
SRI	0.24	0.25	0.07	0.07	19.01	20.42	6.72	7.12	25.73	27.54
SE(m) ±	0.003	0.003	0.0001	0.0003	0.25	0.27	0.22	0.25	0.93	1.06
C.D. (<i>p</i> ≤ 0.05)	N.S	N.S	N.S	N.S	0.99	1.13	0.87	0.77	2.80	3.20
Weed control measures										
B	0.24	0.24	0.46	0.06	14.50	15.42	4.94	5.20	19.44	20.62
P	0.23	0.24	0.49	0.07	18.84	19.86	6.08	7.30	24.92	27.16
PP	0.23	0.23	0.48	0.07	17.45	17.88	5.59	6.66	23.04	24.54
BP	0.23	0.23	0.47	0.07	16.71	17.14	5.42	6.56	22.13	23.7
2 CW/HW	0.23	0.23	0.47	0.06	16.23	16.43	5.23	5.38	21.46	21.81
WF	0.23	0.24	0.5	0.07	20.70	22.28	7.52	7.83	28.22	30.11
WC	0.22	0.22	0.45	0.06	9.02	9.65	3.63	3.90	12.65	13.55
SE (m) ±	0.004	0.004	0.0003	0.0003	0.32	0.33	0.15	0.16	1.16	1.20
C. D. (<i>p</i> ≤ 0.05)	* N.S.	N.S.	N.S	N.S	0.93	0.96	0.45	0.49	3.50	3.62

* N.S means non-significant.

Table 6. Influence of rice establishment techniques and weed control measures on potassium content (%) and uptake (kg ha^{-1}) of rice.

Treatments	Grain K Content (%)		Straw K Content (%)		Grain K Uptake (kg ha^{-1})		Straw K Uptake (kg ha^{-1})		Total K Uptake (kg ha^{-1})	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Rice establishment techniques										
TPR	0.29	0.30	1.54	1.58	20.56	21.51	136.72	145.49	157.28	167.00
DSR	0.29	0.29	1.49	1.51	17.42	18.09	119.23	125.66	136.65	143.75
SRI	0.30	0.30	1.57	1.62	23.76	24.51	150.77	164.80	174.53	189.31
SE(m) \pm	0.002	0.002	0.004	0.005	0.26	0.16	4.43	3.63	4.77	4.60
C.D. ($p \leq 0.05$)	N.S.	N.S.	N.S.	N.S.	1.05	1.10	12.13	11.01	14.33	13.90
Weed control measures										
B	0.29	0.29	1.50	1.54	17.52	18.64	123.51	133.58	141.03	152.22
P	0.30	0.30	1.56	1.60	24.57	24.83	157.95	166.96	182.52	191.79
PP	0.31	0.31	1.55	1.59	23.51	24.09	144.37	151.27	167.88	175.36
BP	0.29	0.30	1.54	1.58	21.07	22.36	139.09	148.08	160.16	170.44
2 CW/HW	0.29	0.29	1.52	1.56	20.47	20.72	132.56	139.79	153.03	160.51
WF	0.30	0.30	1.58	1.61	26.99	27.86	169.77	180.08	196.76	207.94
WC	0.29	0.29	1.48	1.52	11.88	12.72	89.63	98.74	101.51	111.46
SE(m) \pm	0.004	0.004	0.005	0.005	0.35	0.24	3.45	3.26	4.26	4.88
C.D. ($p \leq 0.05$)	N.S.	* N.S.	N.S.	N.S.	1.03	0.72	10.21	9.73	12.80	14.66

* N.S means non-significant.

3.6. Nitrogen (N), Phosphorus (P) and Potassium (K) Concentration and Uptake in Weeds

During both years of the experiment, the results demonstrated that weeds in rice cultivated using the direct seeding approach had greater nutritional N, P and K concentrations. As compared to other herbicidal treatments, Weedy check increased the concentration of nitrogen, phosphorus, and potassium in weeds in both years (Table 7), yet all herbicidal treatments remained at par in terms of N, P and K concentrations. Nitrogen, phosphorus, and potassium uptake of weeds under different crop establishment approaches were affected significantly.

Table 7. Influence of rice establishment techniques and weed control measures on nutrient concentration (%) of weeds.

Treatments	N		P		K	
	2017	2018	2017	2018	2017	2018
Rice establishment techniques						
TPR	1.5 (1.32)	1.50 (1.31)	1.37 (0.91)	1.36 (0.89)	1.52 (1.38)	1.52 (1.38)
DSR	1.51 (1.33)	1.51 (1.32)	1.37 (0.91)	1.37 (0.90)	1.53 (1.40)	1.53 (1.40)
SRI	1.51 (1.32)	1.50 (1.32)	1.37 (0.91)	1.37 (0.90)	1.53 (1.40)	1.53 (1.40)
SE (m) \pm	0.0003	0.0003	0.0005	0.0005	0.002	0.002
C. D. ($p \leq 0.05$)	0.001	0.001	0.0018	0.0018	0.006	0.006
Weed control measures						
B	1.59 (1.55)	1.59 (1.54)	1.44 (1.07)	1.43 (1.07)	1.62 (1.64)	1.62 (1.64)
P	1.59 (1.54)	1.59 (1.53)	1.43 (1.06)	1.43 (1.04)	1.62 (1.63)	1.61 (1.60)
PP	1.59 (1.54)	1.59 (1.53)	1.43 (1.06)	1.43 (1.04)	1.61 (1.59)	1.62 (1.63)
BP	1.59 (1.54)	1.59 (1.53)	1.43 (1.07)	1.43 (1.05)	1.62 (1.63)	1.62 (1.64)
2 CW/HW	1.59 (1.54)	1.59 (1.53)	1.43 (1.06)	1.42 (1.04)	1.62 (1.62)	1.62 (1.62)
WF	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)
WC	1.60 (1.57)	1.60 (1.56)	1.44 (1.07)	1.43 (1.05)	1.62 (1.64)	1.62 (1.64)
SE (m) \pm	0.0006	0.0006	0.0005	0.0005	0.004	0.004
C. D. ($p \leq 0.05$)	0.0017	0.0017	0.0015	0.0015	0.012	0.012

Note: Data in parenthesis are square root transformed values.

During both years, DSR excelled SRI and TPR in weed nutrient uptake. The highest uptake of N by weeds recorded under DSR (Table 8) was 10.85 and 10.50 kg ha⁻¹. When related to direct seeding, the transplanting method resulted in 38.12 percent less depletion of N uptake by weeds in 2017 and 39.68 percent in 2018. P uptake by weeds demonstrated a similar pattern as it was noticed under DSR, the uptake of P was higher among the different treatments of rice establishment techniques. Likewise, significantly the uptake of K remained higher under DSR as compared to SRI and TPR.

Table 8. Influence of rice establishment techniques and weed control measures on nutrient uptake of weeds (kg ha⁻¹).

Treatments	N		P		K	
	2017	2018	2017	2018	2017	2018
Rice establishment techniques						
TPR	1.98 (3.39)	1.90 (3.09)	1.74 (2.32)	1.67 (2.09)	2.01 (3.55)	1.94 (3.26)
DSR	3.20 (10.85)	3.15 (10.50)	2.72 (7.47)	2.67 (7.14)	3.27 (11.42)	3.23 (11.14)
SRI	2.14 (4.17)	2.07 (3.87)	1.87 (2.87)	1.81 (2.63)	2.18 (4.39)	2.11 (4.10)
SE (m) ±	0.01	0.01	0.02	0.01	0.01	0.01
C. D. (<i>p</i> ≤ 0.05)	0.04	0.03	0.06	0.03	0.04	0.03
Weed control measures						
B	2.80 (7.28)	2.73 (6.91)	2.39 (5.02)	2.33 (4.71)	2.87 (7.69)	2.81 (7.35)
P	2.12 (3.80)	2.03 (3.46)	1.85 (2.61)	1.77 (2.35)	2.15 (3.97)	2.07 (3.64)
PP	2.20 (4.15)	2.11 (3.80)	1.91 (2.85)	1.83 (2.57)	2.24 (4.38)	2.16 (4.04)
BP	2.26 (4.44)	2.18 (4.08)	1.97 (3.08)	1.90 (2.80)	2.32 (4.71)	2.24 (4.37)
2 CW/HW	2.44 (5.26)	2.37 (4.91)	2.11 (3.62)	2.04 (3.34)	2.50 (5.56)	2.43 (5.22)
WF	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)
WC	4.25 (18.04)	4.19 (17.60)	3.56 (12.35)	3.50 (11.90)	4.34 (18.87)	4.30 (18.54)
SE (m) ±	0.02	0.02	0.03	0.02	0.03	0.02
C. D. (<i>p</i> ≤ 0.05)	0.07	0.06	0.10	0.06	0.08	0.07

Note: Data in parenthesis are square root transformed values.

During the study, weedy check significantly enhanced weed nitrogen, phosphorus, and potassium uptake from the rest of weed control plots, followed by butachlor, illustrating superiority significantly among herbicidal treatments (Table 8). Uptake of nitrogen i.e., 3.80 and 3.46 kg ha⁻¹ by weeds, was lower in penoxsulam treated plots. In 2017, 24.28 and 50.11 percent of weeds N uptake was less depleted under penoxsulam treatment, and the corresponding values for 2018 were 25.64 and 51.55 percent. The uptake of P by weeds showed a similar pattern as it was found that P uptake was lowest under penoxsulam treatment that recorded 22.59 and 48.03 percent less depletion in P uptake by weeds in 2017. The corresponding figures for 2018 were 24.03 and 49.42 percent. Similarly, the lowest K uptake by weeds was realized under penoxsulam that, demonstrated 22.08 and 50.46 percent less depletion in potassium uptake via weeds in 2017. The corresponding values for 2018 were 26.33 and 51.86% than butachlor and weedy check, respectively.

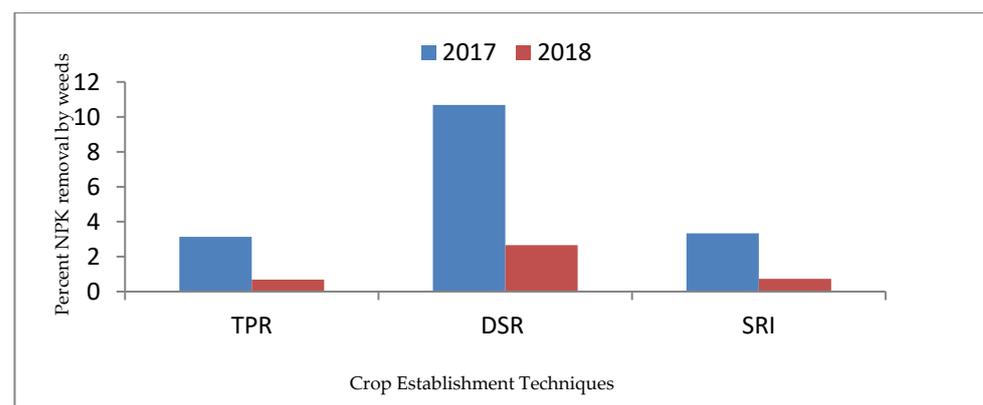
3.7. Nutrients Budgeting (Rice + Weeds) for Removal of Nitrogen (N), Phosphorus (P) and Potassium (K)

Total nitrogen, phosphorus, and potassium uptake (Table 9) in rice was significantly affected under different crop establishment techniques, and the maximum uptake was found under SRI (331.25 and 356.75 kg ha⁻¹) followed by TPR (285.84 and 300.84 kg ha⁻¹) and DSR (248.77 and 261.68 kg ha⁻¹). Weed control practices also significantly influenced the total nitrogen, phosphorus, and potassium uptake by crop. The maximum values of 339.6 and 356.22 kg ha⁻¹ under weed control measures were recorded under penoxsulam treated plots, apart from weed-free plots.

Table 9. Influence of rice establishment techniques and weed control measures on total nutrient uptake of the crop ($\text{kg}\cdot\text{ha}^{-1}$).

Treatment	Total N + P + K Crop Uptake ($\text{kg}\cdot\text{ha}^{-1}$)		Total N + P + K Weed Uptake ($\text{kg}\cdot\text{ha}^{-1}$)		N + P + K Uptake Weeds Share (%)	
	2017	2018	2017	2018	2017	2018
Rice establishment techniques						
TPR	285.84	300.84	9.26	2.09	3.14	0.69
DSR	248.77	261.68	29.74	7.14	10.68	2.66
SRI	331.25	356.75	11.43	2.63	3.34	0.73
Weed control measures						
B	256.14	276.38	19.99	4.71	7.24	1.68
P	339.6	356.22	10.38	2.35	2.97	0.66
PP	311.51	324.8	11.38	2.57	3.52	0.79
BP	296.57	313.43	12.23	2.8	3.96	0.89
2 CW/HW	283.08	295.12	14.44	3.34	4.85	1.12
WF	367.05	391.55	0.00	0.00	0.00	0.00
WC	179.36	196.4	49.26	11.9	21.55	5.71

Weeds also compete for nutrients and recorded significant uptake of total nitrogen, phosphorus and potassium under various establishment techniques and weed control practices. Maximum uptake by weeds under different crop establishment treatments was observed under DSR (29.74 and 7.14 $\text{kg}\cdot\text{ha}^{-1}$), then was followed by SRI (11.43 and 2.63 $\text{kg}\cdot\text{ha}^{-1}$) and TPR (9.26 and 2.09 $\text{kg}\cdot\text{ha}^{-1}$). Under different weed control measures, the maximum NPK total uptake was noticed in WC treatment by weeds (Table 9). Percent of nutrients removed via weeds indicated that significantly more significant amounts of nitrogen, phosphorus, and potassium were removed during the study period. The maximum contribution of 10.68 and 2.66% by weeds was noticed under DSR among different establishment techniques (Figure 3; Table 9). However, under various weed management measures, a weedy check showed a maximum contribution of 21.55 and 5.71% towards removing nutrients by weeds during our research (Figure 4).

**Figure 3.** Proportion of nutrient uptake by weeds from total uptake (plants + weeds NPK uptake) under crop establishment techniques.

3.8. Soil Nutrient Status

3.8.1. Available Nitrogen (N)

During the period of study, the available nitrogen status of 235.76 and 219.76 $\text{kg}\cdot\text{ha}^{-1}$, respectively, under SRI was seen lowest, which significantly differed compared to TP and DSR, demonstrating that SRI removed more N from the soil than transplanted and

direct-seeded rice (Table 10). However, the highest values of available N status of soil were registered highest under DSR (266.41 and 250.41 kg ha⁻¹). All the weed control measures significantly affected the soil available N status, but the highest status of available N (273.93 and 257.94 kg ha⁻¹) was recorded under weedy check. The lowest available N status of 239.55 and 223.55 kg ha⁻¹ in soil was observed under penoxsulam treatment, revealing that penoxsulam treatment removed more N from the soil among the different weed control measures which possibly is due to higher Biomass resulting in more extraction of nitrogen from soil.

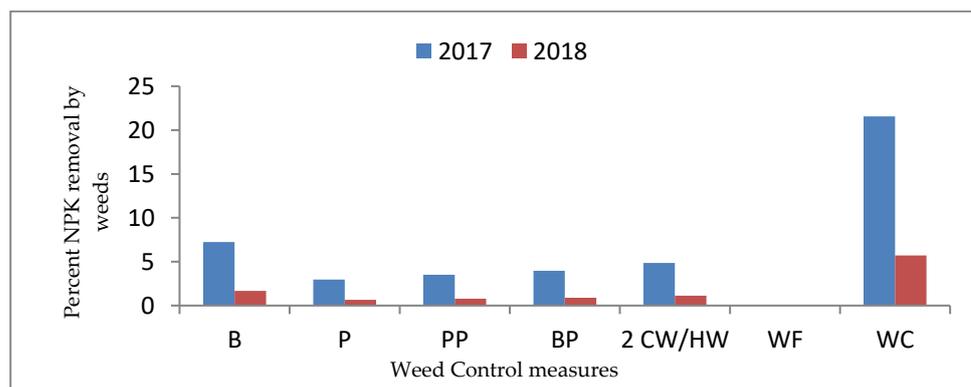


Figure 4. Proportion of nutrient uptake by weeds from total uptake (plants + weeds NPK uptake) under different weed control measures.

Table 10. Influence of rice establishment techniques and weed control measures on available nutrient status of soil (kg ha⁻¹).

Treatments	Available N		Available P		Available K	
	2017	2018	2017	2018	2017	2018
Rice establishment techniques						
TPR	255.7	239.7	20.08	19.85	143.8	135.5
DSR	266.4	250.4	23.31	26.56	159.2	153.4
SRI	235.7	219.7	17.82	15.60	134.2	124.5
SE(m) ±	1.71	2.07	0.34	0.35	1.64	1.91
C. D. ($p \leq 0.05$)	5.21	6.21	1.01	1.05	4.94	5.72
Weed control measures						
B	263.8	247.8	22.16	24.57	157.9	150.2
P	239.5	223.5	18.18	16.03	132.0	123.7
PP	246.24	230.2	19.25	18.18	138.2	130.1
BP	253.0	237.0	20.35	20.42	145.6	137.6
2 CW/HW	259.3	243.3	21.52	22.78	152.9	145.1
WF	232.5	216.5	16.99	14.19	124.5	116.1
WC	273.9	257.9	24.39	28.54	169.2	161.7
SE(m) ±	2.63	2.21	0.30	0.29	1.93	2.28
C. D. ($p \leq 0.05$)	7.90	6.73	0.90	0.88	5.80	6.84

3.8.2. Available Phosphorus (P)

The study revealed that among different crop establishment methods, the available P status of soil recorded under SRI (17.82 and 15.60 kg ha⁻¹) was lowest than transplanted and direct seeded rice, respectively illustrating that more P from the soil was removed under SRI than transplanted and DSR (Table 10). Under DSR, the highest status of available P (23.31 and 26.56 kg ha⁻¹) in soil was demonstrated during the two consecutive years of study. Concerning herbicidal applications, the available phosphorus in the soil, recorded lowest under penoxsulam was 18.18 and 16.03 kg ha⁻¹, respectively, than remaining

herbicidal treatments, while highest values (24.39 and 28.54 kg ha⁻¹) in soil were observed under weedy check treatment, indicating that more P from the soil has been removed in Penoxsulam treatment.

3.8.3. Available Potassium (K)

Among different crop establishment methods, the available soil K recorded under SRI (134.27 and 124.54 kg ha⁻¹) was lowest among other rice establishment techniques, while DSR excelled in demonstrating the higher values of available K (159.27 and 153.40 kg ha⁻¹) in soil (Table 10), confirming more removal of K from the soil in SRI than transplanted and direct-seeded rice. For weed management practices, the lowest available K status in soil recorded under penoxsulam was 132.03 and 123.75 kg ha⁻¹, indicating that more K has been removed in penoxsulam treatment from the soil. Among weed control treatments. However, weedy check treatment registered higher availability of K (169.22 and 161.79 kg ha⁻¹) in the soil during research.

3.9. Regression and Correlation Studies

Among rice establishment techniques and weed control measures, crop attributes viz. crop dry matter, and total N uptake by crop illustrated a positive correlation with rice grain yield. The coefficient of determination was highly significant for rice grain yield with dry crop matter (0.18 and 0.26) (Figure 5) and total N uptake (0.87 and 0.91) (Figure 6) in rice establishment techniques. The variations in dry crop matter and total N uptake could be attributed to 18 and 26% and 87 and 91% during 2017 and 2018, respectively. Among the different weed management measures, the coefficient of determination for grain yield with crop dry matter (0.05 and 0.50) (Figure 7) and total N uptake (0.99 and 0.99) (Figure 8) was noted significant. The deviations in dry crop biomass and total N-uptake could be attributed to 5 and 50% and 99 and 99% during 2017 and 2018, respectively. Among the various crop establishment methods, rice grain yield and weed parameters viz. weed dry matter and NPK uptake by weeds demonstrated a negative correlation. Coefficient of determination among rice grain yield and dry matter of weeds (0.92 and 0.96) (Figure 9), N uptake by weeds (0.70 and 0.61) (Figure 10), P uptake by weeds (0.70 and 0.61) (Figure 11) and K uptake by weeds (0.70 and 0.61) (Figure 12) was found significant in various rice establishment techniques. In conclusion, variations in weed dry matter and NPK uptake by weeds could be explained to 92 and 96%, 70 and 61%, 70 and 61%, and 70 and 61%, during 2017 and 2018, respectively. Furthermore, there was a negative correlation between weed biomass with weed NPK uptake and grain yield among the different weed management approaches. The coefficient of determination for grain yield with weed dry matter (0.92 and 0.96) (Figure 13), N uptake by weeds (0.95 and 0.97) (Figure 14), P uptake by weeds (0.95 and 0.97) (Figure 15) and K uptake by weeds (0.95 and 0.97) (Figure 16) was recorded significant. Conclusion: variations in weed dry matter and NPK uptake by weeds could be explained to 92 and 96%, 95 and 97%, 95 and 97%, and 95 and 97% during 2017 and 2018, respectively.

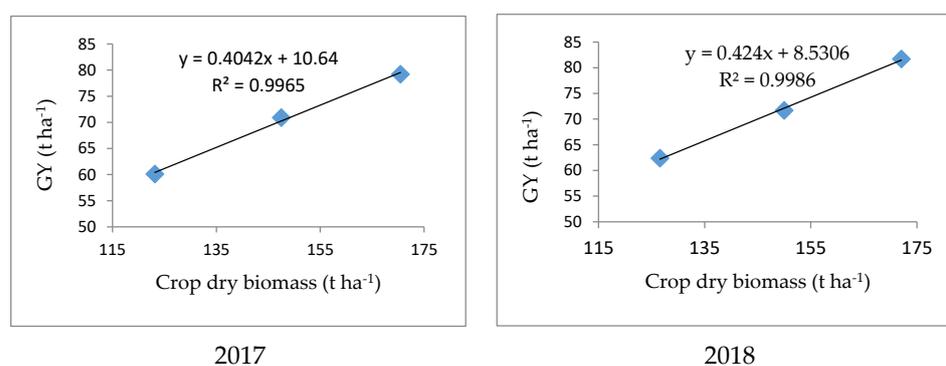


Figure 5. Linear regression line among crop establishment methods between dry matter accumulation vs. Grain yield (GY).

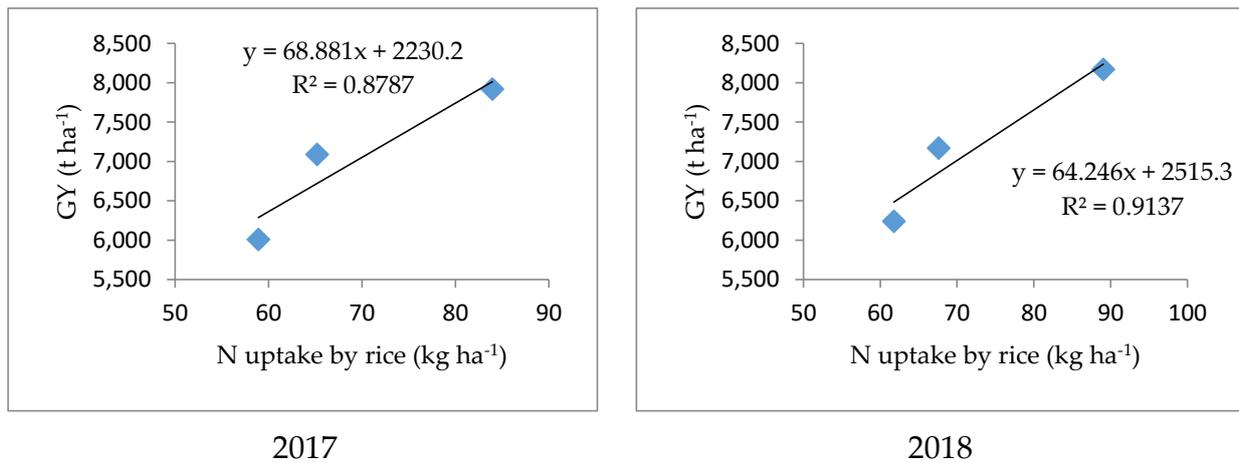


Figure 6. Linear regression line among crop establishment methods between N uptake vs. Grain yield (GY).

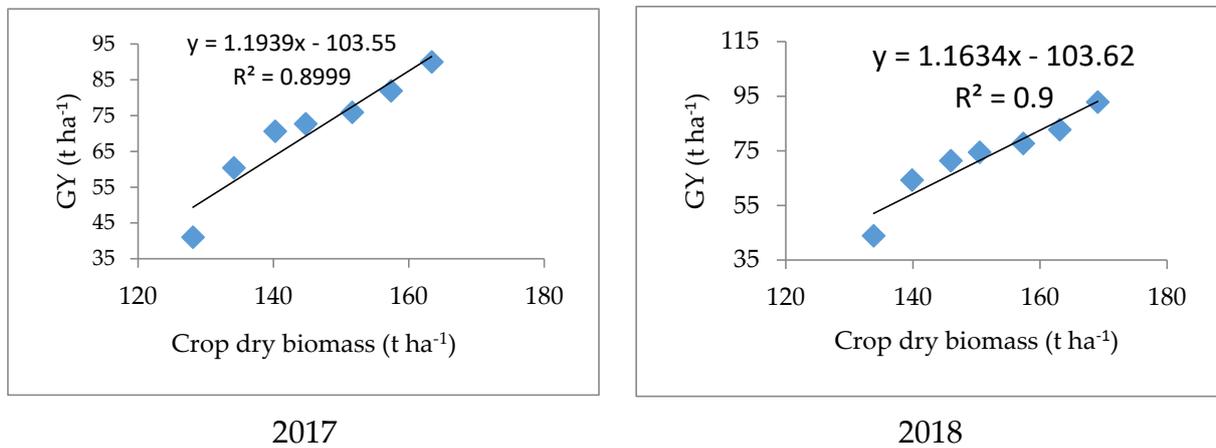


Figure 7. Linear regression line among weed management practices between dry matter accumulation vs. Grain yield (GY).

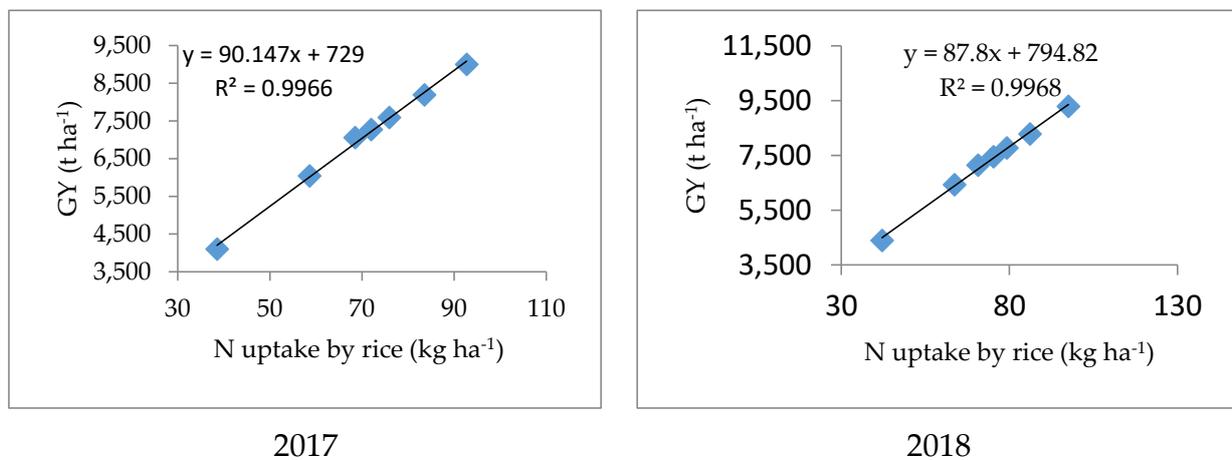


Figure 8. Linear regression line among weed management practices between N uptake vs. Grain yield (GY).

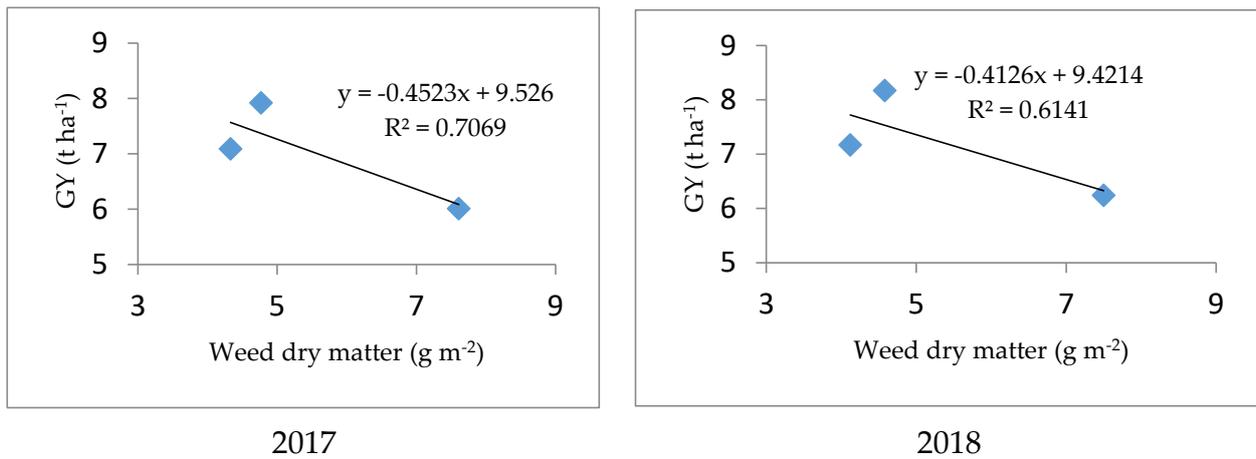


Figure 9. Linear regression line among crop establishment methods between weed dry matters vs. Grain yield (GY).

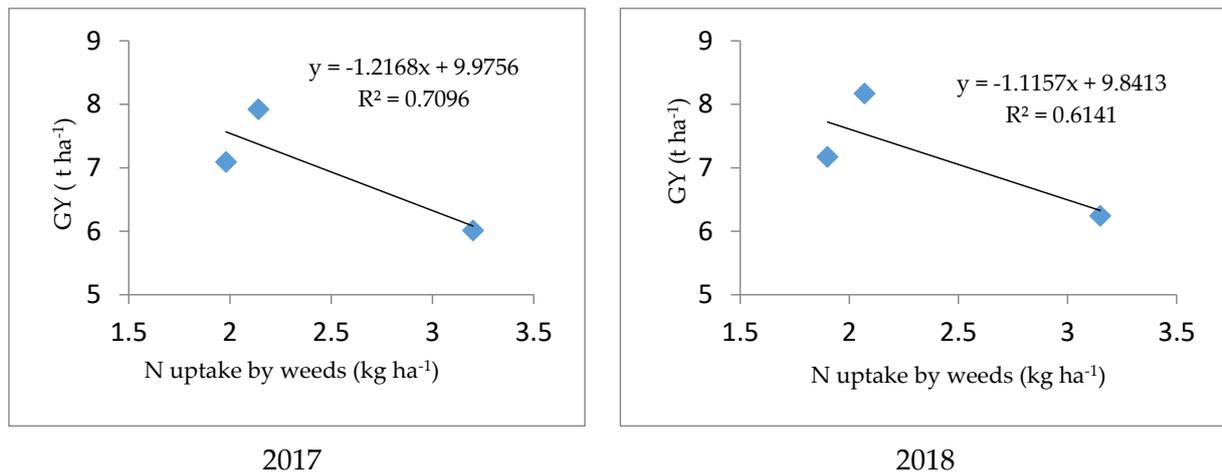


Figure 10. Linear regression line among crop establishment methods between N uptake by weeds vs. Grain yield (GY).

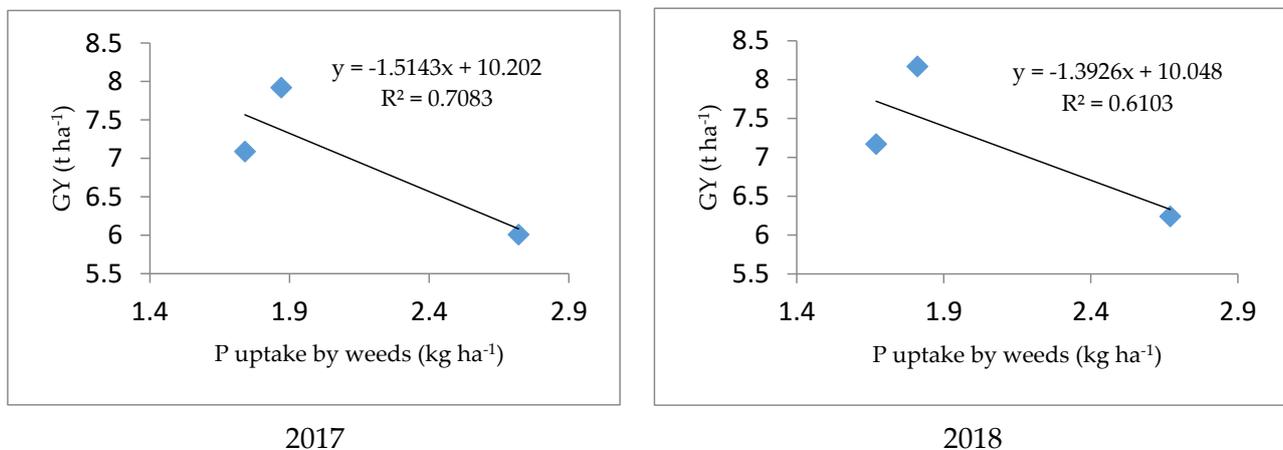


Figure 11. Linear regression line among crop establishment methods between p uptake by weeds vs. Grain yield (GY).

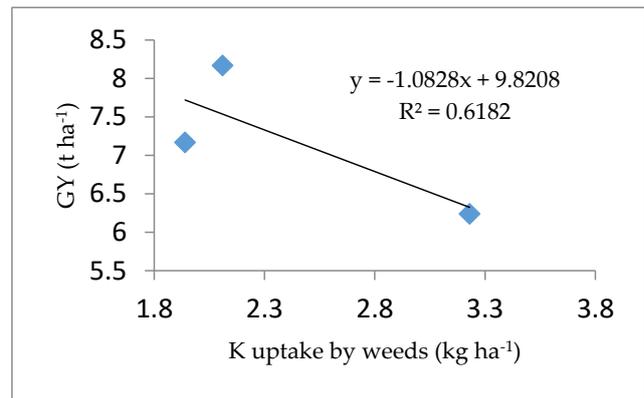
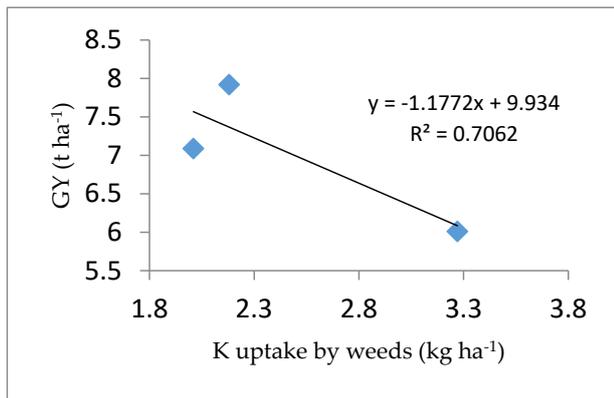


Figure 12. Linear regression line among crop establishment methods between K uptake by weeds vs. Grain yield (GY).

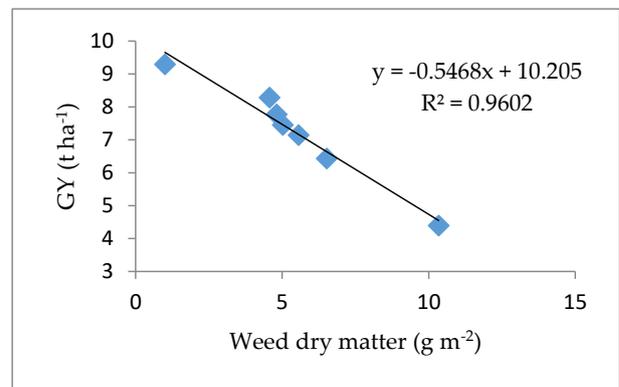
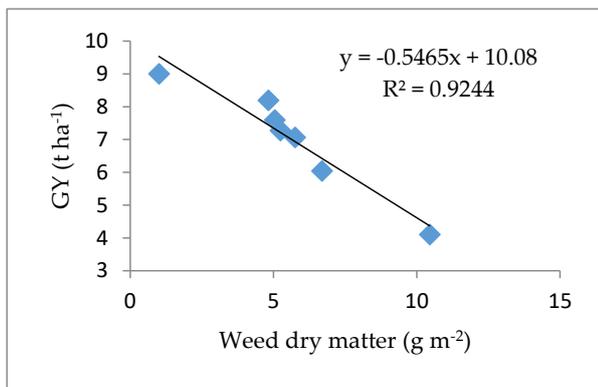


Figure 13. Linear regression line among weed management practices between weed dry matter vs. Grain yield (GY).

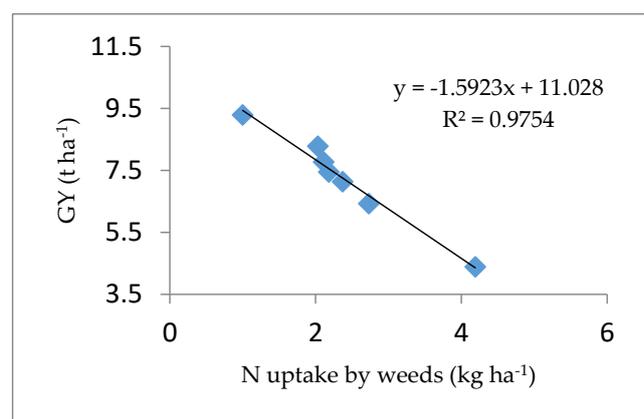
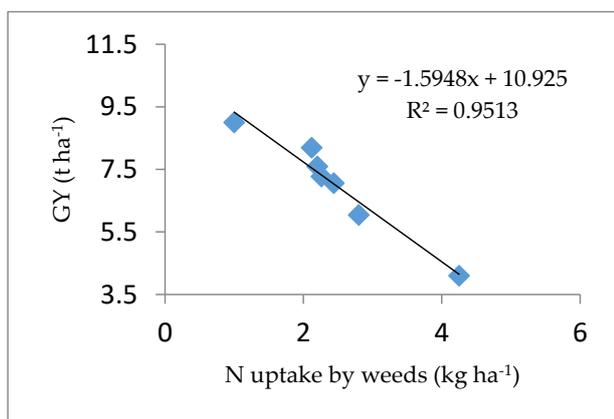


Figure 14. Linear regression line among weed control measures between N-uptake by weeds vs. Grain yield (GY).

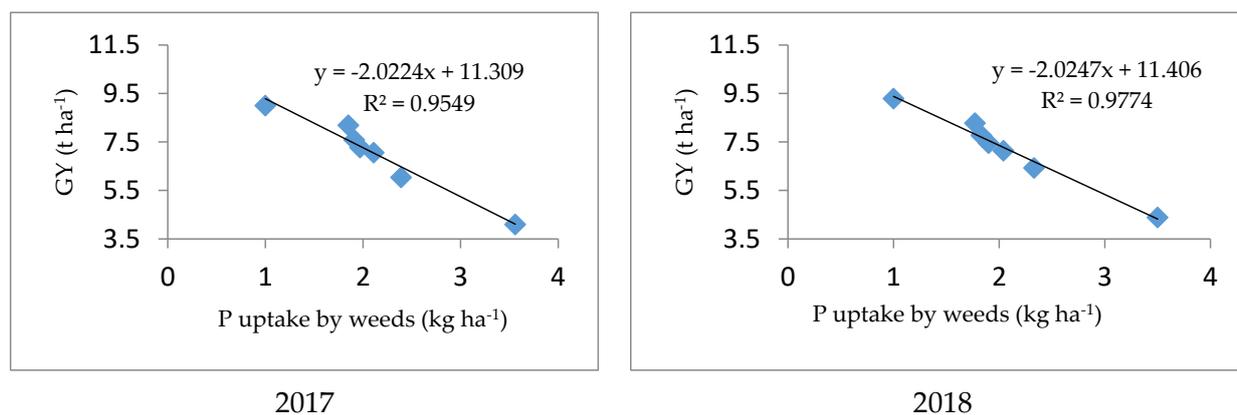


Figure 15. Linear regression line among weed control measures between P-uptake by weeds vs. Grain yield (GY).

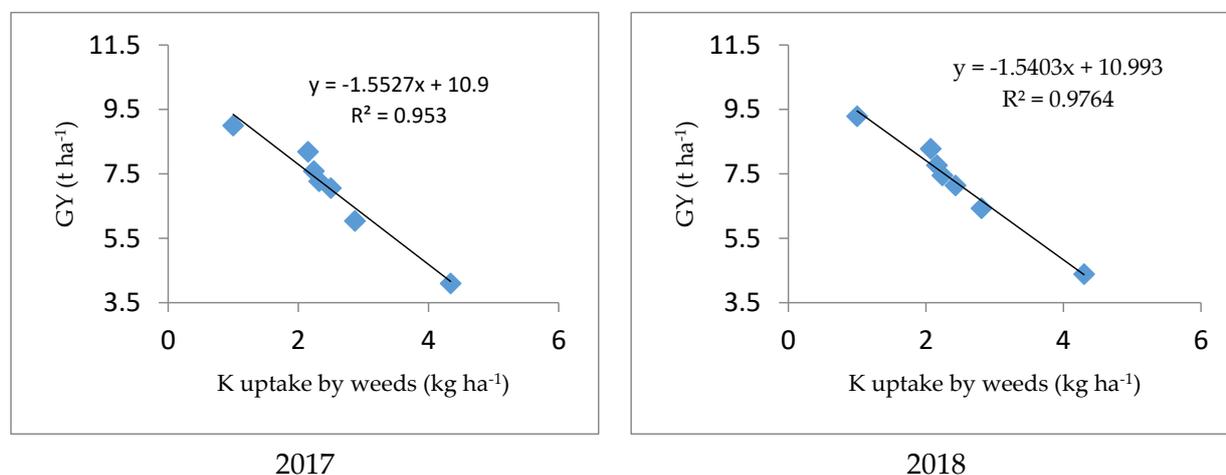


Figure 16. Linear regression line among weed control measures between K-uptake by weeds vs. Grain yield (GY).

4. Discussion

Under SRI, the dry matter was observed highest compared to other crop establishment techniques. This could be described as soils becoming more robust due to broader spacing, which improves soil's organic matter retention, nutrient cycling, and biological fertility, boosting crop development such as dry matter output. Increased plant height and other growth characteristics such as LAI may be responsible for higher dry matter output under the SRI approach [19–21]. Under different weed control measures, the maximum dry matter was achieved in penoxsulam treated plots. Less weed competition led to better crop growth during the initial growth period, which boosted nutrient availability and light, favouring better photosynthate buildup. Herbicide use reduced weed growth and allowed the crop to reach its full potential, resulting in higher dry matter accumulation [20–22].

The highest yield (grain + straw) observed in SRI is described due to the enhanced expression of yield attributes. Under SRI, transplanting young seedlings promotes better tillering and rooting, resulting in greater root volume, improved tillers, more filled spikelets, and maximum grain weight. In addition, wider spacing (25 cm × 25 cm) encourages canopy and root growth, enhancing grain filling [23–25]. Several scientists support our research findings [20,21,26,27]. Penoxsulam treatment demonstrated higher values of grain and straw yield. Herbicide application inhibited weed growth and permitted the rice crop to receive adequate nutrient supply. Production of more photosynthates via more effective tillers per metre⁻² and proper dry matter partitioning (source to sink) resulted in higher grain and straw yields [28,29]. Several studies demonstrated similar findings [20,21,30].

Maximum weed biomass noticed in DSR is attributed to hospitable environment received in DSR by weeds, compared to SRI and TPR rice methodologies. Puddling under TPR provided favourable environments at an initial stage for short crop growth, responsible for weed smothering. Preparation of land in standing water destroys the existing weed flora. However, puddling promotes rice growth, resulting in the suppression of weeds [24,31,32]. Under DSR, dry tillage, aerobic environment due to absence of flooding [33] resulted in higher weed biomass. Penoxsulam application resulted in a maximum reduction in dry weed biomass. Penoxsulam is an excellent herbicide that effectively controls weeds and has low toxicity to rice seedlings [34–36].

Under different crop establishment techniques, the maximum share (%) of weeds towards total Biomass observed in DSR demonstrated that weeds received favourable environmental conditions due to dry tillage and aerobic conditions since flooding was absent, resulting in a maximum share of weeds to total Biomass [7]. However, under different weed control measures, the percentage of weeds to total biomass production obtained in weedy check could be illustrated due to vast weed flora and higher dry weed biomass [7].

SRI proved to be most efficient technology of rice production for better nutrient content and uptake than DSR and TPR as SRI has excellent potential for better use of resources. Further, the findings of our study revealed that removal of total nitrogen, phosphorus and potassium by rice were noted highest in SRI, under rice establishment methods. This could be attributed to the square geometry of the hills, wider spacing, and the planting of a single seedling under SRI that improved the interception of photosynthetically active radiation and uptake of nutrients. Plants with increased root growth under SRI have access to utilize subsoil nutrients. It's also possible that SRI soil and water management strategies, such as alternate wetting and drying, can boost microbial P solubilization [37,38]. The crop's nutrient uptake is determined by nutrient status and yield. Rice establishment techniques illustrated a significant impact on yield. Hence uptake of nutrients varied significantly despite the non-significant nutrient content variation. Percentage of nutrients removed by weeds illustrated that lower amounts of nitrogen, phosphorus, and potassium by weeds were accumulated in TPR due to the smothering of weeds due to continuous submergence. However, dry tillage and aerobic environment due to lack of flooding conditions contributed to maximum percent removal of nitrogen, phosphorus, and potassium by weeds under DSR [7].

Among the different herbicidal treatments, penoxsulam resulted in maximum nutrient content and uptake by the crop. Since weeds compete for macronutrient uptake thereby demonstrated a significant effect on total uptake. The nutrient uptake by the crop is determined by its nutrient content and above-ground biomass, which indicates the crop's better growth due to less weed interaction [38,39]. Further, the percent (%) removal of N, P and K due to weeds demonstrated that significantly lower amounts of N, P and K were accumulated in penoxsulam treated plots due to maximum reduction in weed biomass since it effectively controlled complex weed flora. However, N, P and K were removed maximum in weedy check due to weeds under various weed control measures, illustrating complex weed flora and higher dry weed biomass [7].

Available soil nitrogen, phosphorus and potassium observed lowest in SRI under establishment methods might be attributed to more removal of N, P and K from soil than TPR and DSR, since SRI recorded higher yield and maximum uptake of nutrients [7]. Under weed control treatments, the available N, P and K status of soil was found lowest under penoxsulam treatment, illustrating that penoxsulam, because of higher biomass production, removed more nutrients from the soil among other weed control treatments and could be ascribed to effective weed control provided by penoxsulam herbicide, favoured the crop growth and resulted in higher crop biomass followed by maximum crop nitrogen, phosphorus and potassium uptake [7,40].

5. Conclusions

At the outset of our detailed experiment, we can conclude that among the crop establishment methods, SRI demonstrated the higher accumulation of dry matter, yield (grain + straw) and maximum nutrient (N, P and K) uptake by rice. In contrast, the dry weed biomass and removal of nitrogen, phosphorus and potassium by weeds were illustrated higher in DSR. Under weed control measures, penoxsulam treatment showed the highest accumulation of dry matter, rice yield and maximum nutrient (N, P and K) removal by rice, however, weed biomass and nutrient removal by weeds were observed highest in weedy check plots. The contribution of weeds towards nitrogen, phosphorus and potassium removal was illustrated highest under DSR. In contrast, penoxsulam application contributed the lowest in nutrient removal by weeds as far as weed control treatments were studied. Among crop establishment techniques and weed control measures, the treatment with penoxsulam application under SRI resulted in minimum uptake of nitrogen, phosphorous and potassium by weeds as compared to other treatment combinations, which indicate that the above-mentioned treatment combination can be employed in the Northwestern region of India for optimum resource utilization to boost rice productivity.

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