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Optimizing NPK Uptake in Basmati Rice through Organic Nutrient Management across Contrasting Water Management Regimes

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Abstract

Basmati rice is a superior aromatic variety grown extensively in North India. It is challenged in cultivation by the use of a lot of water and excessive dependency on chemical fertilizers, impacting soil health and ecosystem balance. The present research was conducted to assess the influence of organic sources of nutrients on nitrogen, phosphorus, and potassium uptake by Basmati rice under two water management regimes: puddled and aerobic. The experiment was carried out in the 2021 and 2022 Kharif seasons at Shri Guru Ram Rai University, Dehradun, and Uttarakhand. The experiment followed split-plot layout having two major water treatments, puddled and aerobic, and six nutrient treatments, i.e., poultry manure, night soil, press mud, farmyard manure, and 100% recommended dose of fertilizers. The findings indicated that rice under puddled conditions had greater uptake of nutrients. The highest performance was observed in 75% night soil and 25% poultry manure treatment, which showed the highest nutrient uptake in the grain with 61.53 kilograms per hectare nitrogen, 18.92 kilograms per hectare phosphorus, and 19.86 kilograms per hectare potassium. Organic treatments were superior to chemical fertilizers in nutrient build-up in both grain and straw. The research points out that application of organic nutrients in combination with water management can enhance nutrient utilization, maintain soil health, and provide clean grain production. It is beneficial in sustainable cultivation of Basmati rice, particularly in hilly areas, and also in line with global objectives such as the Sustainable Development Goals and the National Mission for Sustainable Agriculture.

Keywords: Amendments, Certification, Ecosystem, Efficiency, Residues.

Introduction

Rice (*Oryza sativa* L.) is the staple food security for over half of the world's population. Rice is grown on about 159.81 million hectares of land globally and yields some 740.96 million tonnes per annum (1). Rice is a staple food in most of Asia and sub-regions of Africa and Latin America and provides a lot of calories, rural livelihood, and agricultural income. India is the second leading producer of rice in the world, producing 150.79 million tonnes on approximately 45.5 million hectares and providing approximately 24% of global production (2). Amongst several rice varieties, Basmati rice occupies a unique position due to its characteristic aroma, elongation of grain, and premium price in the market. As over 70% of Basmati exports globally come from India (3), it is cultivated with crucial contributions from the states of Haryana, Punjab, Uttar Pradesh, and Uttarakhand. Though being an economically powerful region, its sustainability as a rice-producing belt is increasingly confronted with dwindling water resources and unsustainable agricultural methods. Traditional puddled transplanted rice, although efficient, uses 3000–5000 mm of water per year, which is unviable in the context of prevailing climate and resource stress situations (4). Under such circumstances, aerobic rice cultivation, whereby the crop is directly sown in non-puddled, well-drained soils, has found favour as an efficient water-saving strategy with the potential to save 30–50% of irrigation water (5). Although optimizing water application is essential, nutrient efficiency of uptake, of major macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), is crucial for sustaining yield and grain quality in both puddled and aerobic conditions. Farmers have traditionally used excess synthetic fertilizers to satisfy crop nutrient requirements. However, the excessive and indiscriminate application of these inputs has resulted in severe environmental

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impacts, such as leaching of nutrients, soil erosion, and reduced microbial diversity (6). Nitrogen use efficiency in Indian rice systems is surprisingly low, with a mere 30–40% of the applied nitrogen being consumed by crops and the remaining lost through leaching and volatilization (7). In addition, repetitive use of chemical fertilizers has led to secondary nutrient deficiencies as well as decreased soil organic carbon. Consequently, organic nutrient management has emerged as a sustainable, environmentally friendly means, particularly for high-value crops such as Basmati rice, where market demand increasingly inclines towards residue-free, organically grown grains (8). Organic sources of nutrients like farmyard manure (FYM), poultry manure, press mud, night soil, and urban compost are known to improve soil structure, water holding capacity, and biological activity, while releasing the nutrients slowly over the course of the crop growth period (9, 10). Research has demonstrated that organic inputs like poultry manure, rich in nitrogen and phosphorus, mineralize rapidly to meet early crop demands, while inputs like FYM improve soil physical properties and support microbial activity, benefits particularly pronounced under water-variable conditions such as those found in aerobic systems (11). The dynamic interplay between organic inputs and water management regimes directly influences nutrient transformations and uptake. For instance, under puddled (anaerobic) conditions, decomposition of organic matter is slower, affecting nitrogen mineralization and phosphorus availability. In contrast, aerobic conditions foster faster decomposition and microbial activity but may also increase nutrient leaching risks (12). Despite these insights, there remains a paucity of site-specific studies examining how diverse organic nutrient sources perform under puddled versus aerobic conditions in terms of NPK uptake in Basmati rice, particularly in hill ecosystems like those of Uttarakhand. Some past studies (13) suggest that nutrient management in organic systems is highly context-dependent, necessitating localized experimentation and validation to guide farmer recommendations and policy interventions effectively (14). The current research fills this knowledge gap by assessing NPK uptake in Basmati rice under different water management regimes (puddled vs. aerobic), employing a variety of organic nutrient combinations. Carried out in the Dehradun zone of Uttarakhand, where Basmati is conventionally cultivated under puddled conditions with minimal chemical inputs, the study is well-timed and pertinent. With rainfall unpredictability, increased labour cost, and decreased soil organic content propelling farmers to more sustainable directions, there is a great imperative to examine the extent to which organic amendments can maximize nutrient acquisition under both conventional and future cultivation systems (15). The originality of this research is in its integrated strategy, contrast between several organic nutrient sources under two divergent water regimes in a high-value crop, and the potential implications for resource-use efficiency, soil health, and organic certification. The research would contribute towards national initiatives such as the National Mission on Sustainable Agriculture (NMSA) and global plans such as the Sustainable Development Goals (SDGs), specifically those that target responsible production and renewal of soils (16). The results provide evidence-based recommendations for policymakers, extension services, and farmers seeking to balance yield maximization with environmental sustainability in the context of regenerative hill agriculture. This research complements and extends the results of the earlier work (17-19) by presenting new facts under different irrigation regimes in the Dehradun area. In contrast to their many other previous studies that assessed organic nutrient sources under a uniform water regime, our research examines the combined effect of organic amendments with puddled and aerobic systems. The results support the beneficial effects of organic mixtures such as poultry manure and night soil on nutrient acquisition and align with national sustainability targets. Therefore, the research adds to existing literature with region-specific, quantified information that can be used to guide future agronomic advice. The principal innovation of this study is the integration of varied organic nutrient sources with contrasting water regimes, providing a unified framework to evaluate their combined influence on nutrient uptake in Basmati rice.

Methodology

The field trials were conducted at the School of Agricultural Sciences, Shri Guru Ram Rai

University, Dehradun, Uttarakhand, during the 2021 and 2022 Kharif seasons. Dehradun has latitude of 30.3165° N and a longitude of 78.0322° E with an altitude of 640 m above mean sea level. The site is located in the Himalayan foothills, between the Ganges River in the east and the Yamuna River in the west. The experimental area had a pH of 6.46, which is slightly acidic soil reaction, as ascertained with the 1:2 soil water suspension electrode pH meter technique (20). The electrical conductivity (EC) was 0.21 dS/m, as measured with a systronic conductivity meter (21), reflecting that the soil was non-saline and crop cultivation favourable. Organic carbon content was determined to be 0.28%, analysed using the wet oxidation technique (22), indicating low organic matter, which might need organic amendments for enhanced soil fertility. The available nitrogen in the soil was 243.04 kg/ha, as estimated by the alkaline potassium permanganate method (23), reflecting a moderate nitrogen status. The available phosphorus was 59.36 kg/ha, as determined by Olsen's method (24), making the soil rich in phosphorus availability. The available potassium was 267.3 kg/ha, as determined by the ammonium acetate method reflecting an adequate supply of potassium for plant growth (25). Table 1, Shows the soil's physical and chemical properties at the experimental site.

Table 1: Soil Status of the Experimental Site

Parameter	Test Values	Method Used
pH	6.46	1:2 soil water suspension electrode pH meter (20)
EC (dS/m)	0.21	Systronic conductivity meter (21)
Organic Carbon (%)	0.28	Wet oxidation method (22)
Available Nitrogen (kg/ha)	243.04	Alkaline $KMnO_4$ method (23)
Available Phosphorus (kg/ha)	59.36	Olsen's method (24)
Available Potassium (kg/ha)	267.3	Ammonium acetate method (25)

The experiment was conducted in a split-plot arrangement with three replications. The main plot treatments were two cultivation practices: puddled rice culture (M1) and aerobic rice culture (M2). The treatments of the sub-plot were six nutritional management practices: 100% Recommended Dose of Fertilisers (T1), 75% Farmyard Manure + 25% Poultry Manure (T2), 75% Press Mud + 25% Poultry Manure (T3), 100% Poultry Manure (T4), 75% Night Soil + 25% Poultry Manure (T5), and 75% Urban Compost + 25% Poultry Manure (T6). The rice crop employed in the experiment was 'Pusa Basmati 1718,' transplanted on 7th July 2021 and 10th July 2022 in the first and second years, respectively. To assess the nutrient dynamics in Basmati rice under varying nutrient and water management regimes, plant samples were collected and analysed for nitrogen (N), phosphorus (P), and potassium (K) content and uptake at different growth stages. At 30, 60, and 90 days after transplanting/sowing, and at harvest, five plants were randomly taken out and uprooted from the row near the border of each experimental plot. These development phases at 30, 60, and 90 days from transplanting /sowing, and at harvest, which are equivalent to the tillering, panicle initiation, grain filling, and maturity phases of rice. This method enabled to quantify the nutrient uptake during physiologically critical periods of the crop. Careful uprooting was done with a Hand-Hoe to prevent injury to the root system. Adhering soil particles were dislodged by washing the roots under a weak stream of water. The plant samples were oven-dried to a constant weight at 78 ± 2°C. Dry samples were ground with a mechanical grinder and sieved through a 40-mesh sieve for further chemical analysis. Total nitrogen content in finely ground plant samples of leaves, stems, grains, and straw at each stage of sampling was measured with the micro-Kjeldahl digestion and distillation technique (26), and nitrogen uptake was computed as the product of nitrogen content and corresponding dry matter weight of each plant part. Phosphorus content in the plant tissues was estimated by the molybdovanadate yellow colour method after tri-acid mixture (HNO_3:H_2SO_4:$HClO_4$) digestion, the absorbance was read spectrophotometrically, and phosphorus content was calculated accordingly (27), while uptake values were obtained by multiplying phosphorus concentration by corresponding dry matter yields. Potassium concentration was determined using the flame photometric method after digesting the plant samples with a tri-acid mixture, and potassium uptake was computed by correlating the concentration with the dry weight of grains and straw.

Results

Nitrogen, phosphorus, and potassium concentrations in Basmati grains were highly variable under a range of irrigation practices and organic nutrient management. Grain nitrogen concentration was higher under puddled rice cultivation (1.30%) compared to aerobic cultivation (1.25%). This could be attributed to increased retention of nitrogen and reduced volatilization losses in flooded situations, which permit increased uptake and translocation of nitrogen into the grain at critical stages of growth. The findings conform to previous work where puddled systems exhibited greater nutrient availability and provided better vegetative and reproductive growth through lesser nitrogen leaching (28). Phosphorus and potassium concentrations in grain were also in similar line, puddled rice registering pooled mean contents of 0.28% P and 0.28% K and the aerobic system 0.25% P and 0.27% K. The increased phosphorus concentration in puddled rice is likely due to increased phosphorus solubility in low soil conditions, promoting increased availability for root uptake. Similarly, enhanced moisture retention in puddled systems promotes increased potassium uptake, explaining the marginal benefit observed over aerobic rice (29). Data have been tabulated in Table 2.

Table 2: Influence of Organic Nutrient Sources and Irrigation Methods on NPK Content in Basmati Rice Grain under Puddled and Aerobic Conditions (Pooled over 2021–22 and 2022–23)

Treatment Details	NPK Content in grain								
	Nitrogen (N)			Phosphorous (P)			Potassium (K)		
	2021-22	2022-23	Pooled Mean	2021-22	2022-23	Pooled Mean	2021-22	2022-23	Pooled Mean
Main plot – Irrigation method (03)									
M_1: Puddled rice cultivation	1.29	1.31	1.30	0.27	0.29	0.28	0.28	0.29	0.28
M_2: Aerobic rice cultivation	1.24	1.26	1.25	0.24	0.26	0.25	0.26	0.27	0.27
Sem (±)	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CD (5%)	0.04	0.01	0.03	0.01	0.02	0.00	0.01	0.01	0.01
Sub plot – Nutrient management									
T_1: 100 % RDF.	1.22	1.24	1.23	0.23	0.25	0.24	0.25	0.26	0.26
T_2: 75% FYM + 25% poultry manure.	1.26	1.28	1.27	0.25	0.27	0.26	0.26	0.27	0.27
T_3: 75% Press mud + 25% poultry manure.	1.29	1.31	1.30	0.27	0.29	0.28	0.28	0.29	0.29
T_4: 100% poultry manure.	1.28	1.30	1.29	0.26	0.28	0.27	0.27	0.28	0.28
T_5: 75% Night soil + 25% poultry manure.	1.30	1.32	1.31	0.27	0.29	0.28	0.28	0.29	0.29
T_6: 75% Urban compost + 25% poultry manure	1.27	1.29	1.28	0.26	0.28	0.27	0.27	0.28	0.28
Sem (±)	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01
CD (5%)	NS	NS	0.05	0.02	0.02	0.02	0.02	0.02	0.02
Interaction									
M_1T_1	1.22	1.24	1.23	0.23	0.25	0.24	0.25	0.26	0.26

M_1T_2		1.28	1.30	1.29	0.26	0.28	0.27	0.27	0.28	0.28
M_1T_3		1.31	1.33	1.32	0.28	0.30	0.29	0.29	0.30	0.30
M_1T_4		1.30	1.32	1.31	0.27	0.29	0.28	0.28	0.29	0.29
M_1T_5		1.32	1.34	1.33	0.28	0.30	0.29	0.29	0.30	0.30
M_2T_6		1.29	1.31	1.30	0.27	0.29	0.28	0.28	0.29	0.29
M_2T_1		1.21	1.23	1.22	0.23	0.25	0.24	0.25	0.26	0.26
M_2T_2		1.23	1.25	1.24	0.24	0.26	0.25	0.25	0.26	0.26
M_2T_3		1.26	1.28	1.27	0.25	0.27	0.26	0.27	0.28	0.28
M_2T_4		1.25	1.27	1.26	0.24	0.26	0.25	0.26	0.27	0.27
M_2T_5		1.27	1.29	1.28	0.25	0.27	0.26	0.27	0.28	0.28
M_2T_6		1.24	1.26	1.25	0.24	0.26	0.25	0.26	0.27	0.27
	Sem (±)	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01
	CD (5%)	NS	NS	NS	NS	NS	NS	NS	NS	NS
	CV (%)	4.90	3.39	3.05	7.13	6.49	6.11	5.97	5.91	5.58

Among the treatments of nutrient management, the greatest NPK concentration in grains was found in T5 (75% Night Soil + 25% Poultry Manure) with 1.31% nitrogen, 0.28% phosphorus, and 0.29% potassium. This was closely followed by T3 (75% Press Mud + 25% Poultry Manure) with 1.30% N, 0.28% P, and 0.29% K. Conversely, the lowest values of grain NPK were recorded in T1 (100% RDF), which had 1.23% nitrogen, 0.24% phosphorus, and 0.26% potassium. The interaction effects indicated that under puddled conditions, T5 (M1T5) had the highest NPK content (1.33% N, 0.29% P, and 0.30% K), followed by M1T3 and M1T4, which all included poultry manure in combination. Even when grown in aerobic conditions, T5 and T3 had comparatively higher nutrient content in grain, though lower compared to their puddled counterparts, reaffirming the promise of these organic formulations under water-limited conditions. Nitrogen, phosphorus, and potassium levels in Basmati rice straw differed across various irrigation systems and organic nutrient management regimes. The mean straw under puddled rice cultivation contained higher levels of nitrogen (0.49%), phosphorus (0.10%), and potassium (1.00%) than aerobic cultivation, with the latter having 0.48% nitrogen, 0.08% phosphorus, and 0.98% potassium. Data has been summarized in Table 3.

Table 3: Influence of Organic Nutrient Sources and Irrigation Methods on NPK Content (%) in Straw of Basmati Rice under Puddled and Aerobic Conditions (Pooled over 2021–22 and 2022–23)

Treatment Details		NPK content in Straw								
	Nitrogen (N)			Phosphorous (P)			Potassium (K)			
		2021-22	2022-23	Pooled Mean	2021-22	2022-23	Pooled Mean	2021-22	2022-23	Pooled Mean
Main plot – Irrigation method (03)										
M_1: Puddled rice cultivation		0.49	0.50	0.49	0.09	0.10	0.10	0.99	1.00	1.00
M_2: Aerobic rice cultivation		0.47	0.48	0.48	0.08	0.09	0.08	0.98	0.99	0.98
	Sem (±)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CD (5%)	NS	NS	0.02	0.00	0.00	0.00	NS	NS	NS
Sub plot – Nutrient management										
T_1: 100 % RDF.		0.46	0.47	0.47	0.07	0.08	0.08	0.97	0.98	0.98
T_2: 75% FYM + 25% poultry manure.		0.47	0.48	0.48	0.08	0.09	0.09	0.98	0.99	0.99
T_3: 75% Press mud + 25% poultry manure.		0.49	0.50	0.50	0.09	0.10	0.10	0.99	1.00	1.00
T_4: 100% poultry manure.		0.48	0.49	0.49	0.09	0.10	0.10	0.99	1.00	1.00

T_5: 75% Night soil + 25% poultry manure.	0.49	0.50	0.50	0.10	0.11	0.10	1.00	1.01	1.00
T_6: 75% Urban compost + 25% poultry manure	0.48	0.49	0.49	0.09	0.10	0.09	0.99	1.00	0.99
Sem (±)	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01
CD (5%)	NS	NS	NS	0.01	0.01	0.01	NS	NS	NS
Interaction									
M_1T_1	0.46	0.47	0.47	0.07	0.08	0.08	0.97	0.98	0.98
M_1T_2	0.48	0.49	0.49	0.09	0.10	0.10	0.99	1.00	1.00
M_1T_3	0.50	0.51	0.51	0.10	0.11	0.11	1.00	1.01	1.01
M_1T_4	0.49	0.50	0.50	0.10	0.11	0.11	1.00	1.01	1.01
M_1T_5	0.50	0.51	0.51	0.10	0.11	0.11	1.00	1.01	1.01
M_2T_6	0.49	0.50	0.50	0.09	0.10	0.10	0.99	1.00	1.00
M_2T_1	0.46	0.47	0.47	0.07	0.08	0.08	0.97	0.98	0.98
M_2T_2	0.46	0.47	0.47	0.07	0.08	0.08	0.97	0.98	0.98
M_2T_3	0.48	0.49	0.49	0.08	0.09	0.09	0.98	0.99	0.99
M_2T_4	0.47	0.48	0.48	0.08	0.09	0.09	0.98	0.99	0.99
M_2T_5	0.48	0.49	0.49	0.09	0.10	0.10	0.99	1.00	1.00
M_2T_6	0.47	0.48	0.48	0.08	0.09	0.09	0.98	0.99	0.99
Sem (±)	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.01
CD (5%)	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	4.56	3.60	3.75	9.55	10.24	8.02	1.70	2.08	1.84

Among the nutrient management treatments, T5 (75% Night Soil + 25% Poultry Manure) recorded the maximum NPK absorption by grain with pooled mean estimates of 58.68 kg/ha nitrogen, 17.62 kg/ha phosphorus, and 19.94 kg/ha potassium. T3 (75% Press Mud + 25% Poultry Manure) and T4 (100% Poultry Manure) followed with higher nutrient uptake. The minimum uptake values were recorded in T1 (100% RDF), wherein nitrogen, phosphorus, and potassium uptake was 47.59 kg/ha, 12.13 kg/ha, and 13.76 kg/ha respectively. The interaction between nutrient treatment and irrigation practices brought to the surface the efficiency of organic sources under puddled conditions. The M1T5 treatment (Puddled + Night Soil + Chicken Manure) posted the greatest grain nutrient uptake with 61.53 kg/ha nitrogen, 18.92 kg/ha phosphorus, and 19.86 kg/ha potassium, far exceeding other treatments. Nutrient uptake by Basmati rice straw also differed greatly by irrigation regimes and nutrient management practices. The pooled mean values for puddled conditions were 45.27 kg/ha nitrogen, 13.48 kg/ha phosphorus, and 73.08 kg/ha potassium, and for aerobic conditions, the values were 36.99 kg/ha, 10.86 kg/ha, and 63.35 kg/ha, respectively. The findings show the significant impact of integration of plant water-saving practices with nutrient-rich organic amendments on enhancing the overall recovery of all nutrients in grain and straw. The findings are given in detail in Table 4.

Table 4: Effect of Organic Nutrient Management and Irrigation Practices on NPK Uptake (kg/ha) in Basmati Rice Grain under Puddled and Aerobic Conditions (Pooled over 2021–22 and 2022–23)

Treatment Details	NPK uptake in grain								
	Nitrogen (N)			Phosphorous (P)			Potassium (K)		
	2021-22	2022-23	Pooled Mean	2021-22	2022-23	Pooled Mean	2021-22	2022-23	Pooled Mean
Main Plot – Irrigation Method (03)									
M_1: Puddled rice cultivation	56.80	58.56	57.68	15.92	18.23	17.08	18.92	19.84	19.38
M_2: Aerobic rice cultivation	50.78	52.67	51.73	13.33	15.52	14.43	15.08	16.90	15.99

Sem (±)	0.43	0.53	0.39	0.14	0.44	0.27	0.07	0.28	0.11
CD (5%)	2.64	3.25	2.39	0.87	2.65	1.62	0.41	1.73	0.69
Sub Plot – Nutrient Management									
T_1: 100 % RDF.	46.54	48.64	47.59	11.32	12.94	12.13	12.55	14.97	13.76
T_2: 75% FYM + 25% poultry manure.	52.35	54.41	53.38	14.10	16.32	15.21	16.16	17.89	17.03
T_3: 75% Press mud + 25% poultry manure.	56.67	58.54	57.60	15.85	18.26	17.05	18.63	19.64	19.14
T_4: 100% poultry manure.	55.18	56.83	56.01	15.34	17.70	16.52	17.96	19.00	18.48
T_5: 75% Night soil + 25% poultry manure.	58.07	59.28	58.68	16.36	18.88	17.62	19.57	20.32	19.94
T_6: 75% Urban compost + 25% poultry manure	53.94	56.00	54.97	14.79	17.17	15.98	17.14	18.41	17.78
Sem (±)	1.61	1.74	1.45	0.70	0.72	0.31	0.89	1.03	0.76
CD (5%)	4.75	5.12	4.28	2.06	2.12	0.92	2.63	3.04	2.25
Interaction									
M_1T_1	47.85	49.52	48.69	11.60	13.42	12.51	12.85	15.63	19.02
M_1T_2	56.52	58.36	57.44	15.78	18.31	17.04	18.68	19.36	21.10
M_1T_3	59.85	61.25	60.55	17.22	19.65	18.43	20.79	21.41	20.46
M_1T_4	58.61	60.74	59.68	16.85	19.07	17.96	20.16	20.75	21.62
M_1T_5	60.73	62.33	61.53	17.72	20.13	18.92	21.31	21.92	19.86
M_2T_6	57.25	59.15	58.20	16.39	18.78	17.58	19.75	19.96	13.28
M_2T_1	45.23	47.75	46.49	11.04	12.45	11.74	12.25	14.31	15.03
M_2T_2	48.17	50.46	49.32	12.42	14.32	13.37	13.64	16.42	17.17
M_2T_3	53.49	55.82	54.66	14.49	16.86	15.67	16.47	17.87	16.50
M_2T_4	51.75	52.92	52.34	13.84	16.33	15.09	15.75	17.24	18.27
M_2T_5	55.41	56.23	55.82	15.01	17.62	16.32	17.82	18.71	15.70
M_2T_6	50.63	52.84	51.74	13.20	15.55	14.38	14.53	16.86	**1.08**
Sem (±)	2.28	2.46	2.05	0.99	1.02	0.44	1.26	1.46	NS
CD (5%)	NS	NS	NS	NS	NS	NS	NS	NS	10.12

CV (%)	7.07	7.39	6.26	11.21	10.47	5.13	12.28	13.27	19.02

Among the nutrient treatments, T5 (75% Night Soil + 25% Poultry Manure) was most effective in maximizing nutrient uptake with combined values of 46.10 kg/ha N, 14.00 kg/ha P, and 73.87 kg/ha K in straw as shown in Table 5, followed by T3 (75% Press Mud + 25% Poultry Manure) and T4 (100% Poultry Manure). The highest depressed nutrient uptake in straw in T1 (100% RDF) was 31.54 kg/ha N, 9.03 kg/ha P, and 60.41 kg/ha K. Interaction effects showed that the treatment combination M1T5 (puddled + night soil + poultry manure) had the maximum uptake for all parameters with 49.86 kg/ha N, 15.25 kg/ha P, and 78.77 kg/ha K. Minimum values of uptake were found in M2T1 (aerobic + 100% RDF). In general, as can be seen from Figure 1, 2, 3, 4, treatments that involved poultry manure and night soil in puddling conditions had consistently higher NPK content and uptake in both grain and straw. The uptake responses observed across treatments were within normal biological ranges for Basmati rice, and differences were mainly due to the varying nutrient release patterns and microbial activity of the organic inputs used under each water regime.

Table 5: Effect of Organic Nutrient Sources and Water Management Practices on NPK Uptake (kg/ha) in Straw of Basmati Rice under Puddled and Aerobic Conditions (Pooled over 2021–22 and 2022–23)

Treatment Details	NPK uptake in Straw								
	Nitrogen (N)			Phosphorous (P)			Potassium (K)		
	2021-22	2022-23	Pooled Mean	2021-22	2022-23	Pooled Mean	2021-22	2022-23	Pooled Mean
Main Plot – Irrigation Method (03)									
M_1: Puddled rice cultivation	44.84	45.70	45.27	12.81	14.14	13.48	71.73	74.43	73.08
M_2: Aerobic rice cultivation	36.50	37.48	36.99	10.30	11.41	10.86	62.81	63.90	63.35
Sem (±)	0.07	1.28	0.67	0.34	0.12	0.22	0.49	0.74	0.47
CD (5%)	0.41	7.76	4.06	2.06	0.73	1.34	3.00	4.48	2.86
Sub Plot – Nutrient Management									
T_1: 100 % RDF.	30.97	32.10	31.54	8.42	9.64	9.03	57.46	63.37	60.41
T_2: 75% FYM + 25% poultry manure.	39.21	40.19	39.70	11.07	12.10	11.58	65.29	66.45	65.87
T_3: 75% Press mud + 25% poultry manure.	44.22	45.02	44.62	12.78	14.22	13.50	71.34	72.68	72.01
T_4: 100% poultry manure.	42.84	43.67	43.25	12.12	13.44	12.78	69.25	70.10	69.67
T_5: 75% Night soil + 25% poultry manure.	45.66	46.54	46.10	13.47	14.54	14.00	73.31	74.43	73.87
T_6: 75% Urban compost + 25% poultry manure	41.11	42.03	41.57	11.50	12.73	12.11	66.97	67.99	67.48
Sem (±)	1.44	2.21	1.65	0.62	0.70	0.56	1.76	2.23	1.74
CD (5%)	4.25	6.52	4.85	1.82	2.06	1.65	5.20	6.57	5.12
Interaction									
M_1T_1	31.52	32.42	31.97	8.70	9.86	9.28	58.60	69.35	63.97
M_1T_2	44.78	45.63	45.21	12.76	13.75	13.25	70.21	71.42	70.81
M_1T_3	48.69	49.88	49.29	13.97	15.67	14.82	76.13	77.54	76.83

M_1T_4	47.82	48.37	48.10	13.60	15.24	14.42	74.79	75.26	75.02
M_1T_5	49.46	50.25	49.86	14.68	15.83	15.25	78.23	79.31	78.77
M_2T_6	46.74	47.64	47.19	13.17	14.53	13.85	72.45	73.72	73.08
M_2T_1	30.42	31.78	31.10	8.14	9.42	8.78	56.33	57.38	56.85
M_2T_2	33.63	34.75	34.19	9.37	10.46	9.91	60.38	61.47	60.92
M_2T_3	39.74	40.16	39.95	11.58	12.78	12.18	66.55	67.81	67.18
M_2T_4	37.85	38.97	38.41	10.64	11.65	11.14	63.72	64.93	64.32
M_2T_5	41.86	42.82	42.34	12.25	13.25	12.75	68.39	69.54	68.96
M_2T_6	35.47	36.41	35.94	9.83	10.93	10.38	61.50	62.25	61.87
Sem (±)	2.04	3.12	2.33	0.87	0.99	0.79	2.49	3.15	2.45
CD (5%)	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	8.27	13.01	9.57	13.00	12.81	10.96	6.20	7.64	6.01

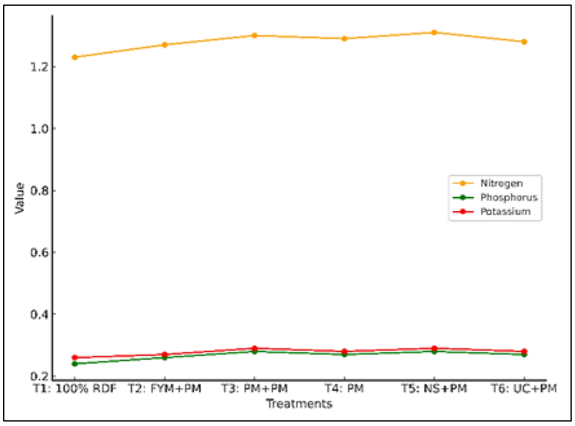

Figure 1: NPK Content in Grain (%)

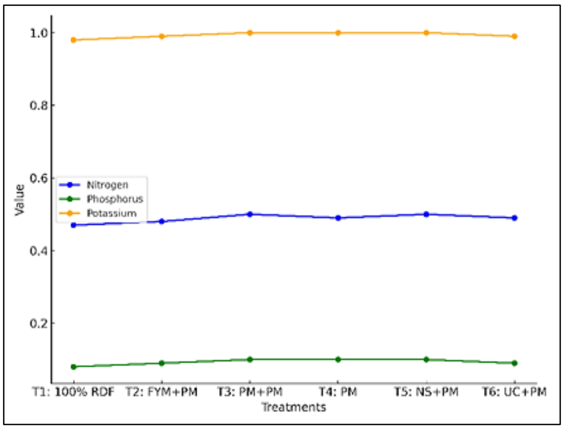

Figure 2: NPK Content in Straw (%)

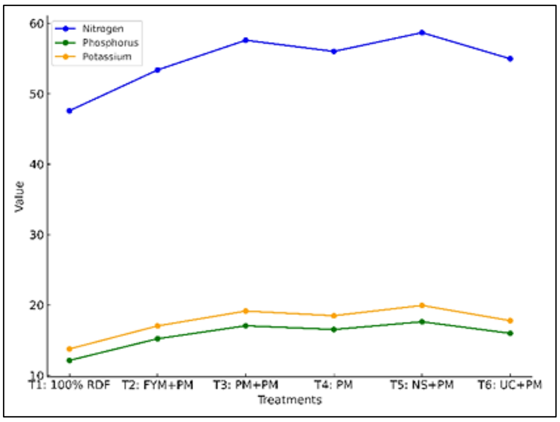

Figure 3: NPK Uptake in Grain (kg/ha**)**

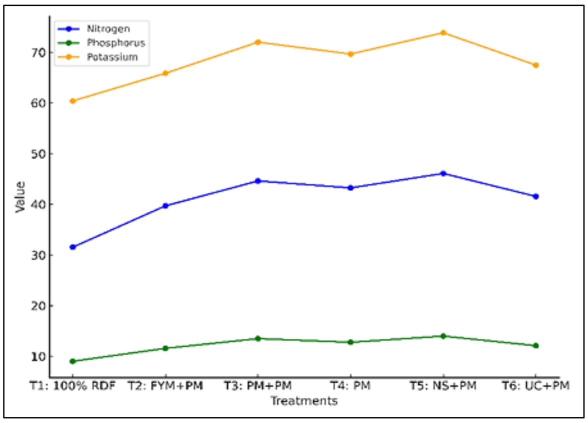

Figure 4: NPK Uptake in Straw (kg/ha)

Discussion

The marked rise in nitrogen concentration in Basmati grains under puddled rice production (1.30%) than aerobic production (1.25%) can be explained by greater retention of nitrogen and lesser volatilization losses under waterlogged conditions, which facilitate effective nitrogen uptake at key growth stages (30, 31). Phosphorus and potassium content in grains also followed a similar pattern, with puddled rice having pooled mean contents of 0.28% for both phosphorus and potassium, as opposed to 0.25% phosphorus and 0.27% potassium in the aerobic system. This is consistent with the findings of greater solubility of phosphorus in lowered soil conditions resulting in increased root uptake availability (32). The increased potassium uptake in puddled systems can be attributed to better retention of moisture, which favours increased potassium availability (33). Maximum NPK content in grains was found in the treatment 75% Night Soil + 25% Poultry Manure (T5), with 1.31% nitrogen, 0.28% phosphorus, and 0.29% potassium, followed closely by the treatment 75% Press Mud + 25% Poultry Manure (T3). This highlights the benefit of utilizing organic amendments with high readily mineralizable nitrogen and phosphorus (34). Lowest NPK levels in grains were observed in T1 (100% RDF), confirming that chemical fertilizers by themselves are not enough to maintain maximum nutrient content in grains (35). NPK composition in Basmati rice straw also varied considerably with different irrigation and nutrient management strategies, being higher in puddled situations (0.49% nitrogen, 0.10% phosphorus, and 1.00% potassium) than aerobic situations (0.48% nitrogen, 0.08% phosphorus, and 0.98% potassium). Such findings could be explained by the better moisture retention and enhanced microbial activities in puddled conditions that promote nutrient availability (36). of all the nutrient treatments, T5 (75% Night Soil + 25% Poultry Manure) exhibited maximum NPK content in straw, testifying to the efficiency of this organic blend in maintaining nutrient availability throughout the growing period (37). Nutrient uptake by Basmati rice grain revealed that puddled rice was consistently superior to aerobic rice, with pooled mean values of 57.68 kg/ha nitrogen, 17.08 kg/ha phosphorus, and 19.38 kg/ha potassium. The superior nutrient uptake capacity of puddled rice can be attributed to improved root-soil interaction, less volatilization, and better nutrient availability under anaerobic conditions (38). Among the nutrient amendments, T5 (75% Night Soil + 25% Poultry Manure) recorded the greatest NPK uptake by grains, followed by T3 (75% Press Mud + 25% Poultry Manure), showing that high mineralizable nutrient organic amendments greatly enhance nutrient uptake by crops (39). NPK uptake by straw also followed the same trend, with higher uptake in puddled conditions (45.27 kg/ha N, 13.48 kg/ha P, and 73.08 kg/ha K) than in aerobic conditions (36.99 kg/ha N, 10.86 kg/ha P, and 63.35 kg/ha K). Maximum nutrient absorption in straw was recorded in T5 (75% Night Soil + 25% Poultry Manure), reflecting the increased availability of nutrients and extended release of nutrients from this organic blend (40). Minimum values were recorded in T1 (100% RDF), which indicates the deficiency of chemical fertilizers in long-term nutrient absorption (41). The high interaction between irrigation practices and nutrient management further supports the synergistic advantage of organic nutrient mixtures, especially under puddled conditions. The greatest nutrient uptake was observed in the mixture of puddled rice with 75% Night Soil + 25% Poultry Manure (M1T5), which means that the integration of organic nutrients and effective water management can achieve maximum nutrient efficiency (42, 43). The findings of this research have practical implications for real world application, since they represent the combined effect of organic nutrient sources and water management practices under true field conditions. The conclusion of enhanced NPK uptake in both puddled and aerobic systems implies that nutrient–water synergy is a feasible solution for the improvement of input-use efficiency in rice production. This is particularly important for resource-limited areas like the Himalayan foothills, where climate instability and diminishing soil fertility require holistic management methods. These findings also emphasize the need for combining organic sources of nutrient with effective water management for sustainable and efficient nutrient utilization in Basmati rice, as enunciated in the principles of sustainable agriculture supported by the Sustainable Development Goals (SDGs) and the National Mission for Sustainable Agriculture (NMSA).

Implications and Contributions

The current research offers evidence of crucial significance that organic nutrient sources, in the form of mixtures of night soil and poultry manure, can very much increase NPK uptake by Basmati rice under aerobic as well as puddled conditions. The research provides practical insight for enhancing hill agriculture's sustainable nutrient practices and supports national efforts under the Sustainable Development Goals (SDGs) and National Mission for Sustainable Agriculture (NMSA) through aligning high-value crop cultivation with environmental responsibility and resource management.

Conclusion

The current research provides robust evidence supporting the role of organic nutrient management towards enhancing the recovery of nitrogen, phosphorus, and potassium in Basmati rice under variable water management regimes. While conventional systems prefer high-input, chemical-based systems to obtain maximum productivity, the current research reiterates that such systems are not always compatible with long-term soil health, environmental sustainability, or nutrient use efficiency, particularly in sensitive ecosystems like Uttarakhand's. The results clearly indicate that site-specific, organically augmented systems, especially when used with appropriate water management practices like puddling or aerobic methods, are not only capable of sustaining but also of improving nutrient uptake, thereby being part of a more sustainable and environmentally friendly rice cultivation system. Besides, this study closes an important knowledge gap by demonstrating that the nutrient acquisition response is extremely sensitive to the type of organic amendment and to the prevailing water regime. These inelegant soil-water-organic input interactions reinforce the need for more integrated agronomic practices that do not see nutrient and water management as discrete domains. The findings are that organic blends, particularly with high levels of mineralizable nutrients and microbial stimulants, are well accommodated in both traditional puddled and new aerobic systems, hence offering farmers an adaptable and sustainable tool box to meet the dual imperatives of productivity and conservation of the ecosystem. Significantly, this study affirms the general shift in consumer demand and agricultural policy towards residue-free, organically certified food systems. For high-value crops like Basmati rice, which are priced at a premium both domestically and in export markets, the ability to enhance nutrient uptake organically has implications that transcend yield, it crosses quality, market access, and global competitiveness. Furthermore, the applicability of the study to India's National Mission on Sustainable Agriculture and global frameworks like the Sustainable Development Goals contributes to its policy relevance and timeliness. Lastly, the integrated use of organic nutrient sources in different water regimes holds much promise to develop an agro ecosystem of rice production that is regenerative in nature, with a high value on soil health, optimal utilization of nutrients, and securing economic return at no cost to ecological integrity. In regions like the Himalayan foothills, where resource limitations and climate unpredictability prevail, this model of nutrient stewardship holds promise as a science-informed pathway to sustainable intensification and sustained agro ecosystem resilience. According to findings, farmers can benefit from the adoption of water-saving irrigation methods such as aerobic rice in conjunction with early application of well-decomposed organic manures prior to sowing or transplanting. The combined use enhances nutrient utilization and resource effectiveness under both puddled and aerobic systems also these findings have potential implications for improving national nutrient use efficiency goals by supporting the integration of organic inputs into extension advisories, especially in regions aiming to reduce dependence on chemical fertilizers while promoting climate-resilient practices.

Abbreviations

APEDA: Agricultural and Processed Food Products Export Development Authority, FAO: Food and Agriculture Organization of the United Nations, FYM: Farmyard Manure, IRRI: International Rice Research Institute, K: Potassium, N: Nitrogen, NMSA: National Mission for Sustainable Agriculture, P: Phosphorus, RDF: Recommended Dose of Fertilizers, SDGs: Sustainable Development Goals.

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Author Contributions

M. Nautiyal: designed the study, performed field experiments, gathered data, analysed data, wrote the manuscript, P. Bankoti: supervised the research, offered suggestions during the course of the research, critically reviewed the manuscript. Both authors have read and approved the final manuscript.

Conflict of Interest

The article's content is guaranteed and the authors bear responsibility for it. Each author works in collaboration without any conflict of interest.

Ethics Approval

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