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Integrated Nutrient Management Improves the Productivity and Nutrient Use Efficiency of *Lens culinaris* Medik.

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Abstract: Enhancing nutrient use efficiencies (NUEs) is an important factor in achieving the long-term sustainability of a production system. Our two-year experiment was aimed at accessing the NUEs of the integration of macro- and micronutrient fertilization responses of three lentil (*Lens culinaris*) cultivars. Three cultivars were planted in the main plots, and ten nutrient combinations were used in the sub-plots: N1, control; N2, 100% recommended dose of fertilizers (RDF) (20:40—N:P₂O₅); N3, vermicompost (VC) at 2 t ha^{−1}; N4, 50% recommended dose of nitrogen (RDN) + 100% recommended dose of phosphorus (RDP) + VC at 1 t ha^{−1}; N5, RDF + 0.5% ZnSO₄; N6, RDF + 0.5% FeSO₄; N7, RDF + 0.5% ZnSO₄ + 0.5% FeSO₄; N8, 50% RDN + 100% RDP + VC at 1 t ha^{−1} + 0.5% ZnSO₄; N9, 50% RDN + 100% RDP + VC at 1 t ha^{−1} + 0.5% FeSO₄; and N10, 50% RDN + 100% RDP + VC at 1 t ha^{−1} + 0.5% ZnSO₄ + 0.5% FeSO₄. The results show that the cultivar HM-1 (1.59–1.61 Mg ha^{−1}) recorded a significantly higher seed yield than cultivars Sapna (1.31–1.33 Mg ha^{−1}) and Garima (both 1.30 Mg ha^{−1}), while the cultivar Sapna had significantly more stover yield (1.86–1.90 Mg ha^{−1}) than cultivar HM-1 (1.68–1.73 Mg ha^{−1}). Cultivar HM-1 was more efficient in terms of partial factor productivity for N (77.5–78.5 kg kg^{−1}), P (48.2–48.7 kg kg^{−1}), K (143.6–145.5 kg kg^{−1}), Zn (1336–1352 kg kg^{−1}), and Fe (417–421 kg kg^{−1}) than Sapna and Garima. Application of 50% N + 100% P + VC at 1.0 t ha^{−1} + 0.5% ZnSO₄ + 0.5% FeSO₄ resulted in higher seed yield (1.63–1.65 Mg ha^{−1}) and agronomic efficiency for N (26.3–28.8 kg kg^{−1}), P (12.42–13.63 kg kg^{−1}), and K (52.3–57.4 kg kg^{−1}) over other tested practices in both years. Hence, it could be concluded that considering the integrated nutrient management paradigm including 10 kg N ha^{−1} coupled with 40 kg P₂O₅ ha^{−1} through synthetic fertilizers, vermicomposting 1.0 t ha^{−1} as an organic source and foliar spray of 0.5% each of ZnSO₄ and FeSO₄ (N10) produced a 56.8% higher seed yield than the control, in addition to improving nutrient dynamics and NUEs for N, P, K, Zn, and Fe. Therefore, integrated fertilization coupled with cultivar selection could help to achieve the long-term food and nutritional sustainability targeted by the Sustainable Development Goals (SDGs).

Keywords: nutrient use efficiency; pulses; lentil; sustainable development goals; integrated nutrient management

1. Introduction

In intensive cropping systems, the global consumption of the primary nutrients nitrogen (N), phosphorus (P), and potassium (K) recorded 109, 41, and 39 million tones (Mt), respectively, in 2020 [1]. Chemical fertilizers are the most common source of nutrients to enhance crop yields. There is an urgent need to enhance NUEs for sustainable development and to enhance the ecosystem services under eco-friendly management. Over the past 40 years, global crop production and productivity have increased at the cost of over four-fold nutrient removal from soil [2]. During these four decades, the amount of mineral fertilizers applied to field crops increased by 7.4-fold, along with a 2.4-fold increase in average productivity [3]. Furthermore, the recovery of applied fertilizers (N-P-K: 30-12-35%) was very low in arable lands, and was less than 5% for micronutrients [4,5] due to the incapability of crop cultivars in nutrient use [6]. Nutrient losses not only lead to yield reduction but also severely pollute natural resources. Farmers are continuously using heavy doses of chemical fertilizers without considering sustainable practices such as organic manures and create a nutrient imbalance in land-use systems, resulting in many negative effects on ecosystem services, biodiversity, environment, and human health [7]. It has also significantly reduced nutrient use efficiencies (NUEs) and long-term crop and soil productivity, and increased input costs (~30% of total agricultural production cost), which is a major concern for production economics. All these factors together act as obstacles to achieving production sustainability and the Sustainable Development Goals (SDGs) of the United Nations [8].

The declining NUEs due to overuse/unbalanced use of chemical fertilizers, particularly nitrogenous fertilizers, are a prime concern for the native soil fertility and sustainability of the agricultural system. The NUEs increase at higher levels of crop productivity when mineral fertilizers are used at a lower rate. Absorption efficiency (amount of absorbed nutrient/quantity of available nutrient) and utilization efficiency (yield/absorbed nutrient) are the two components of NUE [3]. Furthermore, agronomic efficiency (AE), partial nutrient balance (PNB), physiological efficiency (PE), partial factor productivity (PFP), and internal utilization efficiency (IUE) are important parameters for a better understanding of the absorption and utilization efficiency of crop plants under various management levels. AE determines both the agronomic and economic efficiency of fertilizer use. It is the cornerstone of NUE and answers the question of how much production can be improved by using nutritional input [9]. The PE measures the efficiency of capture of plant nutrients and conversion to seed yield, while the IUE reflects the fraction of applied nutrients converted to grain. The PNB is simply a nutrient removal to use ratio, which measures the nutrient output per unit of nutrient input. PFP provides critical information to farmers and researchers regarding the selection of a set of nutrient management practices. However, there is genetic diversity in both nutrient absorption efficiency and nutrient utilization efficiency for a vast range of crops. Within the crop, the selection of promising nutrient-efficient cultivars and nutrient management levels are two important factors governing the NUEs of the crop [10]. Crop cultivars respond differently to applied nutrients in terms of NUE due to the differences in nutrient absorption, translocation, shoot demands, and biomass production, owing to their diverse genetic and physiological mechanisms [6]. Organic manures, on the other hand, such as farmyard manure (FYM), vermicompost, and biochar, have been shown to improve the soil environment and nutrient supply in agroecosystems [11]. Co-applying organic manure with synthetic fertilizer decreases the amount of inputs needed, reduces soil bulk density, and enhances the soil's physical properties to boost the inorganic fertilizer retention, resulting in high NUEs [11,12].

Grain legumes have been recognized for their vital role in addressing global food security, human health, and nutritional security challenges as well as in tackling the challenges of soil and environmental health from the very beginning [13,14]. In this context, lentils (*Lens culinaris* Medick., Fabaceae) are a boon to restoring the inherent

physio-chemical and biological properties of soil for maintaining its fertility with biological nitrogen fixation (BNF) [15,16]. Hence, the selection of lentil varieties that take up more organic or inorganic fertilization from the soil and that use the absorbed nutrients more efficiently are two more ways of improving NUEs and helping to achieve SDGs.

Furthermore, interactions between lentil cultivars and nutrient availability enhance the performance under the integration of the nutrients. Hence, this experiment helps in the selection of lentil cultivars for higher productivity and NUEs, with a reduction of 50% N, and micronutrient management for soil and food quality.

2. Material and Methods

2.1. Experimental Site

The present field study was led during the winter seasons of 2016 and 2017 at the Agricultural Research Farm, Chaudhary Charan Singh Haryana Agricultural University (CCSHAU), Hisar, India. The experimental site is in the Hisar city of Haryana at a latitude of 29°10' N, longitude of 75°46' E, and an altitude of 215.2 m above mean sea level.

2.2. Climate and Weather

The monthly variations in weather conditions from June 2016 to May 2018 are presented in Table 1.

Table 1. Monthly variations in weather conditions from June 2016 to May 2018.

Months	Temperature Max. (°C)		Temperature Min. (°C)		Bright Sunshine (h)		Total Rainfall (mm)		Total Evaporation (mm)		Relative Humidity (Morning) (%)	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
June	39.6	37.2	27.7	25.6	7.8	7.3	91.0	283.8	212.6	197.0	71	77
July	35.0	35.1	26.2	27.0	5.9	6.8	244.8	83.0	132.1	151.7	90	88
August	34.0	34.7	25.7	26.3	6.0	6.3	80.4	95.5	130.8	131.2	90	90
September	35.2	34.9	24.2	23.5	8.8	6.8	2.8	56.6	142.6	124.7	87	87
October	34.6	35.0	18.5	17.2	7.8	6.6	12.0	0.0	121.1	111.6	85	85
November	29.3	27.2	10.6	10.8	5.8	3.4	0.0	0.0	59.0	85.4	92	90
December	24.4	21.7	7.4	6.1	6.3	5.2	0.0	3.8	38.9	39.0	97	91
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
January	18.6	20.3	6.9	4.8	4.1	5.4	41.2	10.9	35.3	38.5	99	96
February	24.3	24.5	7.8	7.9	7.7	6.7	0.0	1.2	57.5	56.8	92	91
March	29.0	30.9	11.3	12.2	8.6	6.9	2.9	0.0	110.2	113.0	90	82
April	38.6	36.6	19.1	19.6	8.7	7.3	3.1	14.0	218.1	192.1	57	60
May	36.0	36.8	17.5	17.2	8.1	7.2	2.3	4.5	232.2	221.3	52	54
Cropping cycle	27.4	26.9	10.5	10.2	6.9	5.8	47.2	29.9	519	524.8	92	90

The climate of this region is typically arid to semi-arid, tropical and sub-tropical, characterized by hot and dry summers and cold winters. The monsoon season begins in this region in the fourth week of June and lasts through the end of September, or occasionally until the first week of October. Between December and mid-February, winter showers are common. From March to May, however, there is a three-month dry season. In February, the temperature begins to climb and reaches its peak (42–45 °C) in May–June. Throughout the year, the relative humidity (morning) remains 51–95%; however, it begins to rise in the first week of June. Over the long-term average, the total annual mean pan evaporation of the experimental site is around 1910.2 mm. During the experiment, all-weather parameters were recorded at the meteorological observatory of CCSHAU in Hisar.

2.3. Treatment Details and Layout

The experiment was laid out in a split-plot design by replicating thrice, following all three principles of experimental design, i.e., replication, randomization, and lo-

cal control. Three cultivars, Sapna (LH 84-8), Garima (LH 84-6), and HM-1 (Haryana Massar-1) (LH89-48), were assigned to the main plots. In the sub-plots, ten nutrient management practices were adopted: N1, control; N2, recommended dose of fertilizers (RDF) ($\text{N-P}_2\text{O}_5$ —20–40 kg ha⁻¹); N3, vermicompost (VC) at 2 t ha⁻¹; N4, 50% recommended dose of nitrogen (RDN) + 100% recommended dose of phosphorus (RDP) + VC at 1 t ha⁻¹; N5, RDF + 0.5% ZnSO₄; N6, RDF + 0.5% FeSO₄; N7, RDF + 0.5% ZnSO₄ + 0.5% FeSO₄; N8, 50% RDN + 100% RDP + VC at 1 t ha⁻¹ + 0.5% ZnSO₄; N9, 50% RDN + 100% RDP + VC at 1 t ha⁻¹ + 0.5% FeSO₄; and N10, 50% RDN + 100% RDP + VC at 1 t ha⁻¹ + 0.5% ZnSO₄ + 0.5% FeSO₄. The foliar spray of ZnSO₄ and FeSO₄ was performed twice at the pre-flowering and pod formation stages.

According to the research methodology, the complete amounts of VC and chemical fertilizers were integrated into the soil at the time of seeding. The average concentrations of N, P, K, zinc (Zn), and iron (Fe) in vermicompost were found to be 1.15%, 0.55%, 1.08%, 0.06%, and 0.38%, respectively. Based on these concentrations, the amounts of nutrients supplied through different treatments of nutrient management are given in Table 2. All three cultivars were released from CCS HAU Hisar at different times (Sapna in 1991, Garima in 1996, and HM-1 in 2006).

Table 2. Amounts of nutrients (kg ha⁻¹) supplied through different nutrient management practices.

Treatment	N	P	K	Zn	Fe	NPK
N1	-	-	-	-	-	-
N2	20.0	40.0	-	-	-	60.0
N3	23.0	11.0	21.6	1.2	7.6	55.6
N4	21.5	45.5	10.8	0.6	3.8	77.8
N5	20.0	40.0	-	2.5	-	60.0
N6	20.0	40.0	-	-	2.5	60.0
N7	20.0	40.0	-	2.5	2.5	60.0
N8	21.5	45.5	10.8	3.1	3.8	77.8
N9	21.5	45.5	10.8	0.6	6.3	77.8
N10	21.5	45.5	10.8	3.1	6.3	77.8

N1: control, N2: RDF, N3: VC at 2 t ha⁻¹, N4: 50% RDN + 100% RDP + VC at 1 t ha⁻¹, N5: RDF + 0.5% ZnSO₄, N6: RDF + 0.5% FeSO₄, N7: RDF + 0.5% ZnSO₄ + 0.5% FeSO₄, N8: 50% RDN + 100% RDP + VC at 1 t ha⁻¹ + 0.5% ZnSO₄, N9: 50% RDN + 100% RDP + VC at 1 t ha⁻¹ + 0.5% FeSO₄, and N10: 50% RDN + 100% RDP + VC at 1 t ha⁻¹ + 0.5% ZnSO₄ + 0.5% FeSO₄.

2.4. Soil Sampling and Analysis

Before the start of the first year of the field trial, 15 soil samples were randomly collected from the 0–15 cm soil layer from different physiographic positions of the experimental field (2250 m²) in a zigzag manner. The collected soil samples were thoroughly mixed to form a composite sample of 0.5 kg. It was air-dried followed by oven-drying at 65 °C for 24–72 h to obtain a constant weight. The dried samples were gently crushed and sieved through a 2 mm sieve. Soil texture was determined by the United States Department of Agriculture (USDA) methods. The soil pH and electrical conductivity (EC) were determined in the saturation extract of 1:2 (soil: water suspension) [17]. Soil organic carbon (SOC) was quantified by Walkley and Black's method [18]. Soil available N was analyzed by the alkaline permanganate method of Subbiah and Asija [19]. The available soil P was extracted with 0.5 M NaHCO₃ [20], while the available soil Fe and Zn were extracted by DTPA (diethylene triamine penta acetic acid), as suggested by Lindsay and Norwell [21]. The exchangeable K in soil was extracted by 1M NH₄OAc and quantified with flame photometry [22]. The initial soil properties are summarized in Table A1.

2.5. Plant Sampling and Analysis

At crop harvesting, seed and plant samples representing field conditions were collected from all the experimental units. The plant sample encompasses stems, branches, leaves, etc. The collected samples were oven-dried at 65 °C for 24–72 h to obtain a constant weight.

The dried samples were grinded, sieved, and then used for further chemical analysis in the laboratory. These samples were analyzed for N, P, K, Zn, and Fe by following the standard procedure of analysis. The following formulas were used to calculate NUEs for different nutrients:

$$\text{Partial factor productivity (PFP) (kg seed/kg nutrient)} = Y/F \quad (1)$$

$$\text{Agronomic efficiency (AE) (kg seed/kg nutrient)} = Y - Y_0/F \quad (2)$$

$$\text{Partial nutrient balance (PNB) (kg nutrient/kg nutrient)} = U_H/F \quad (3)$$

$$\text{Internal utilization efficiency (IUE) (kg seed/kg nutrient)} = Y/U \quad (4)$$

$$\text{Physiological efficiency (PE) (kg seed/kg nutrient)} = Y - Y_0/U - U_0 \quad (5)$$

where Y = yield of a harvested portion of the crop with nutrients applied (treatment plot); Y_0 = yield with no nutrient applied (control plot); F = amount of nutrient applied; U = total nutrient uptake in aboveground crop biomass with nutrient applied; U_0 = nutrient uptake in aboveground crop biomass with no nutrient applied, and U_H = nutrient content of a harvested portion of the crop.

2.6. Crop Management

The experimental site was deeply ploughed in the summer by a tractor-drawn soil turning moldboard (MB) plough to expose weed rhizomes, incorporate and destroy already-grown weeds, and destroy damaging insect pests hiding in the soil. During the first week of November in both years, heavy pre-sowing irrigation was applied through the surface flooding method to aid effective ploughing and to ensure appropriate soil moisture for seed germination, establishment, and subsequent plant growth. Then, right before sowing, two harrowing events and a cross-ploughing event with a cultivator were completed. Following the cross-ploughing, the field was levelled with the use of a tractor-drawn planter and divided into distinct experimental units having a plot size of 20 m² (5 × 4 m) according to the layout plan and study protocol. The crop was sown at a row spacing of 22.5 cm with the help of an indigenous plough on 28–29 November 2016 and 1–2 December 2017 using a seed density of 35 kg ha^{−1}. To control existing weed flora in the field, manual weeding was performed twice, at 4 and 7–28 weeks after sowing, with the help of *kasola* [23]. Thinning was performed in conjunction with the first manual weeding by removing extra crop plants to maintain the desired plant population for better resource usage and crop yield. Coincidentally, in both years of experimentation, little rainfall occurred at the flowering and pod formation stages (Table 1), which fulfilled the water needs of the crop. Therefore, no additional irrigation was given during the entire crop cycle.

2.7. Statistical Analysis

The statistical analysis for the treatment means, critical difference, standard error mean, and variance was performed following the standard procedure of split-plot design in Microsoft Excel and SPSS by running post hoc analysis [24]. The significance of differences between treatment means was determined using least significance difference (LSD) values at $p \leq 0.05$ [25]. The standard level of significance used to justify a claim of a statistically significant effect is $p \leq 0.05$ [26,27]. A simple linear correlation was calculated between the amount of nutrients (N, P, K, Zn, Fe) supplied through chemical fertilizers and organic manure (i.e., vermicompost) and different use efficiencies (AE, PNB, PFP, PNB, PE) for both years. The amount of nutrients supplied in different treatments was calculated based on the concentration of nutrients in organic manure (Section 2.3), which is presented in Table 2.

3. Results

3.1. Crop Yield

The data on seed and stover yield of lentils (Table 3) revealed significant differences due to cultivar selection. Significantly higher seed yield was recorded for cultivar HM-1

(1.59 and 1.61 Mg ha⁻¹), followed by cultivars Sapna (1.33 and 1.31 Mg ha⁻¹) and Garima (both 1.30 Mg ha⁻¹) in both years. The latter two had statistically comparable ($p \leq 0.05$) seed yields. The stover yield of cultivar Sapna (1.86 and 1.82 Mg ha⁻¹) was statistically similar ($p \leq 0.05$) to Garima (1.83 and 1.87 Mg ha⁻¹) and significantly higher than cultivar HM-1 (1.68 and 1.73 Mg ha⁻¹) in both years of experimentation. However, the biological yield of lentils remained statistically unaffected; still, the cultivar HM-1 (3.27 and 3.34 Mg ha⁻¹) had numerically more biological yield than the cultivars Sapna (3.19 and 3.21 Mg ha⁻¹) and Garima (3.12 and 3.17 Mg ha⁻¹) in both years of study.

Table 3. The yield of lentil cultivars is influenced by different nutrient management levels.

Treatment	Seed Yield (Mg ha ⁻¹)		Stover Yield (Mg ha ⁻¹)		Biological Yield (Mg ha ⁻¹)	
	2016	2017	2016	2017	2016	2017
Cultivars						
Sapna	1.33 ^b	1.31 ^b	1.86 ^a	1.90 ^a	3.19	3.21
Garima	1.30 ^b	1.30 ^b	1.82 ^a	1.87 ^a	3.12	3.17
HM-1	1.59 ^a	1.61 ^a	1.68 ^b	1.73 ^b	3.27	3.34
SEm±	0.02	0.02	0.03	0.03	0.03	0.05
LSD ($p \leq 0.05$)	0.09	0.09	0.13	0.13	NS *	NS
Nutrient management practices						
N1	1.06 ^d	1.07 ^d	1.42 ^d	1.43 ^d	2.48 ^d	2.50 ^d
N2	1.32 ^b	1.35 ^b	1.75 ^b	1.80 ^b	3.07 ^b	3.15 ^b
N3	1.19 ^c	1.21 ^c	1.59 ^c	1.62 ^c	2.78 ^c	2.83 ^c
N4	1.54 ^a	1.56 ^a	1.94 ^a	2.00 ^a	3.48 ^a	3.56 ^a
N5	1.38 ^b	1.38 ^b	1.77 ^b	1.81 ^b	3.15 ^b	3.19 ^b
N6	1.35 ^b	1.36 ^b	1.76 ^b	1.81 ^b	3.11 ^b	3.17 ^b
N7	1.41 ^b	1.40 ^b	1.77 ^b	1.82 ^b	3.18 ^b	3.22 ^b
N8	1.60 ^a	1.62 ^a	1.95 ^a	2.01 ^a	3.55 ^a	3.63 ^a
N9	1.57 ^a	1.60 ^a	1.95 ^a	2.01 ^a	3.52 ^a	3.61 ^a
N10	1.63 ^a	1.65 ^a	1.96 ^a	2.02 ^a	3.59 ^a	3.67 ^a
SEm±	0.04	0.05	0.06	0.06	0.07	0.07
LSD ($p \leq 0.05$)	0.12	0.14	0.16	0.17	0.21	0.20

a–d: Different letters in the same column indicate significant difference at the 0.05 probability level, * NS—non-significant.

Among management practices, statistically, more seed (1.63 and 1.65 Mg ha⁻¹), stover (1.96 and 2.02 Mg ha⁻¹), and biological (3.59 and 3.67 Mg ha⁻¹) yields were recorded in N10 in both years (Table 3). This was significantly superior to RDF with or without application of ZnSO₄ and/or FeSO₄ (N2, N5, N6, N7), vermicomposting at 2 t ha⁻¹ (N3), and the control plot (N1). In both years, the plots with no nutrients added (control) had significantly lower seed (1.06 and 1.07 Mg ha⁻¹), stover (1.42 and 1.43 Mg ha⁻¹), and biological yields (2.48 and 2.50 Mg ha⁻¹). The magnitude of increase in yield in N10 was 53.3% and 60.4% for seed, 37.9% and 41.3% for stover, and 47.4% and 52.2% for biological yield, respectively, compared to the control during the experiment.

3.2. Nutrient Use Efficiencies

3.2.1. Agronomic Efficiency

AE determines the yield improvement with the addition of each unit of fertilizer input. Different genotypes respond to nutrient intake in different ways, which affect seed output and AE. In this study, the AE for N, P, K, Zn, and Fe did not change significantly ($p \leq 0.05$) in the two years of experimentation (Table 4), although numerically, cultivar superiority varied with experimental years. The cultivar Sapna was superior in the first year, while the cultivar Garima was superior in the second year in terms of AE for macro- (N, P, K) and

micronutrients (Zn, Fe). Cultivar HM-1 recorded the lowest values of all these parameters in both years.

Table 4. Agronomic efficiency (kg kg^{-1}) for macro- and micronutrients in lentils as influenced by cultivar selection and nutrient management levels.

Treatment	N		P		K		Zn		Fe	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Cultivars										
Sapna	18.9	20.1	10.25	10.82	41.1	44.5	350	378	106	112
Garima	17.5	20.4	9.41	10.97	38.5	44.5	328	381	97	113
HM-1	18.3	20.3	9.81	10.94	40.3	43.8	342	374	102	112
SEm $\pm$	2.55	2.78	1.57	1.31	6.89	4.81	65	44	14.6	14.1
LSD ($p \leq 0.05$)	NS *	NS	NS	NS	NS	NS	NS	NS	NS	NS
Nutrient management practices										
N1	-	-	-	-	-	-	-	-	-	-
N2	13.0 ^c	15.2 ^c	6.50 ^d	7.58 ^c	-	-	-	-	-	-
N3	5.7 ^d	6.3 ^d	11.91 ^a	13.26 ^a	6.1 ^b	6.8 ^b	109 ^b	122 ^b	17 ^e	140 ^b
N4	22.5 ^{ab}	24.8 ^a	10.62 ^{abc}	11.71 ^{abc}	44.7 ^a	49.4 ^a	805 ^a	888 ^a	126 ^c	131 ^b
N5	16.0 ^c	17.7 ^c	8.03 ^{bcd}	8.82 ^{bc}	-	-	128 ^b	141 ^b	-	-
N6	14.5 ^c	16.4 ^c	7.27 ^{cd}	8.20 ^c	-	-	-	-	116 ^c	150 ^a
N7	17.4 ^{bc}	18.8 ^{bc}	8.70 ^{bcd}	9.37 ^{bc}	-	-	139 ^b	150 ^b	139 ^a	157 ^a
N8	25.1 ^a	27.7 ^a	11.85 ^a	13.08 ^a	49.9 ^a	55.1 ^a	174 ^b	192 ^b	142 ^a	90 ^c
N9	23.5 ^a	26.5 ^a	11.12 ^{ab}	12.53 ^{ab}	46.8 ^a	52.8 ^a	843 ^a	950 ^a	80 ^d	98 ^c
N10	26.3 ^a	28.8 ^a	12.42 ^a	13.63 ^a	52.3 ^a	57.4 ^a	182 ^b	200 ^b	90 ^d	140 ^b
SEm $\pm$	1.97	2.22	1.20	1.34	3.43	4.59	48	51	3.7	4.3
LSD ($p \leq 0.05$)	5.6	6.3	3.41	3.81	10.1	13.5	139	147	12	15
Cultivar $\times$ Nutrient	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

a–d: Different letters in the same column indicate significant difference at the 0.05 probability level, * NS—non-significant.

With respect to nutrient management, the AE values for N (26.3 and 28.8 kg kg^{-1}), P (12.42 and 13.63 kg kg^{-1}), and K (52.3 and 57.4 kg kg^{-1}) were considerably higher for N10 than for other practices in both years (Table 4). However, the AE values for N in N10 were statistically comparable ($p \leq 0.05$) to those of N8 (25.1 and 27.7 kg kg^{-1}), N9 (23.5 and 26.5 kg kg^{-1}), and N4 (22.5 and 24.8 kg kg^{-1}) in both years. In the case of P, the figure of AE was statistically similar ($p \leq 0.05$) among N10, N3, N8, N9, and N4 in both years. For K, N10 had significantly higher AE than N3 (6.1–6.8 kg kg^{-1}) only. N9 was a significantly superior treatment in terms of AE values for Zn (843 and 950 kg kg^{-1}) over the rest of the treatments except N4 (805 and 888 kg kg^{-1}), to which it was statistically similar ($p \leq 0.05$) in both years. The lowest value of AE for Zn was found under N3 (109 and 122 kg kg^{-1}). The superiority of nutrient management treatments in terms of AE for Fe was controversial across the years, i.e., the N8 (142 kg kg^{-1}) had statistically higher values over remaining treatments except for N7 (139 kg kg^{-1}) in the first year, whereas in the second year, N7 (157 kg kg^{-1}) was statistically similar ($p \leq 0.05$) to N6 (150 kg kg^{-1}) and had significantly higher values over remaining practices. Across the years, the lowest values of AE for N (5.7, 6.3 kg kg^{-1}), K (6.1, 6.8 kg kg^{-1}), Zn (109, 122 kg kg^{-1}), and Fe (17 kg kg^{-1}) (in 2016) were retained by N3, while for P (6.50, 7.58 kg kg^{-1}), it was in N2.

The correlation of the amount of nutrients supplied through different nutrition management strategies with AE was uniform for NPK and Zn in both years but variable for Fe. In both years, this correlation was perfectly negative for K (−0.99, −0.99), Zn (−0.78, −0.78), and Fe (−0.88, −0.24); slightly negative for P (−0.12, −0.13); and no association was identified for N (−0.01, −0.03).

3.2.2. Partial Factor Productivity

Partial factor productivity (PFP) is a helpful NUE index that expresses the efficiency of a production system across varied nutrient management strategies. As a result, PFP helps farmers and researchers choose a fruitful set of nutrient management strategies. The PFP for macronutrients (N, P, K) and micronutrients (Zn, Fe) in lentil production varied significantly depending on cultivar selection and nutrient management levels (Table 5).

Table 5. Partial factor productivity (kg kg^{-1}) for macro- and micronutrients in lentils as influenced by cultivar selection and nutrient management levels.

Treatment	N		P		K		Zn		Fe	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Cultivars										
Sapna	65.2 ^b	65.1 ^b	40.3 ^b	40.1 ^b	121.9 ^b	123.1 ^b	1128 ^b	1134 ^b	352 ^b	351 ^b
Garima	62.8 ^b	64.0 ^b	38.6 ^b	39.3 ^b	119.5 ^b	120.7 ^b	1106 ^b	1114 ^b	343 ^b	345 ^b
HM-1	77.5 ^a	78.5 ^a	48.2 ^a	48.7 ^a	143.6 ^a	145.5 ^a	1336 ^a	1352 ^a	417 ^a	421 ^a
SEm $\pm$	0.86	1.45	0.63	0.66	1.74	1.13	18	14.7	7.66	8.1
LSD ($p \leq 0.05$)	3.48	5.85	2.5	2.7	7.02	4.6	73	59	31	33
Nutrient management practices										
N1	-	-	-	-	-	-	-	-	-	-
N2	65.5 ^c	66.5 ^d	32.7 ^b	33.2 ^b	-	-	-	-	-	-
N3	51.1 ^d	51.0 ^e	106.7 ^a	106.5 ^a	54.4 ^b	54.3 ^b	992 ^b	977 ^b	157 ^d	154 ^d
N4	71.7 ^{abc}	72.5 ^{abcd}	33.9 ^b	34.3 ^b	142.7 ^a	144.4 ^a	2572 ^a	2598 ^a	406 ^b	410 ^b
N5	68.8 ^{bc}	69.0 ^{bcd}	34.4 ^b	34.5 ^b	-	-	552 ^c	552 ^c	-	-
N6	66.2 ^c	67.7 ^{cd}	33.1 ^b	33.9 ^b	-	-	-	-	540 ^a	542 ^a
N7	70.0 ^{bc}	70.1 ^{abcd}	35.0 ^b	35.0 ^b	-	-	563 ^c	560 ^c	563 ^a	560 ^a
N8	73.9 ^{ab}	75.4 ^{ab}	34.9 ^b	35.6 ^b	147.0 ^a	150.1 ^a	516 ^c	523 ^c	421 ^b	427 ^b
N9	73.0 ^{ab}	74.2 ^{abc}	34.5 ^b	35.1 ^b	145.2 ^a	147.8 ^a	2610 ^a	2660 ^a	249 ^c	253 ^c
N10	76.5 ^a	76.6 ^a	36.2 ^b	36.2 ^b	152.3 ^a	152.4 ^a	524 ^c	531 ^c	258 ^c	261 ^c
SEm $\pm$	1.99	2.21	1.46	1.56	3.18	4.46	34	45.5	12.7	13.9
LSD ($p \leq 0.05$)	5.70	6.32	4.2	4.5	9.3	13.1	98	131	37	40
Cultivar $\times$ Nutrient	NS [*]	NS	NS	NS	NS	NS	NS	NS	NS	NS

^{a–e}: Different letters in the same column indicate significant difference at the 0.05 probability level, * NS—non-significant.

The PFP for N (62.8–78.5 kg kg^{-1}), P (38.6–48.7 kg kg^{-1}), K (119.5–145.5 kg kg^{-1}), Zn (1106–1352 kg kg^{-1}), and Fe (417–421 kg kg^{-1}) significantly varied among lentil cultivars over the experimental years. A significant increase in PFP for N was reported in cultivar HM-1 (77.5–78.5 kg kg^{-1}) compared to cultivars Sapna (65.2–65.1 kg kg^{-1}) and Garima (62.8–64.0 kg kg^{-1}). The increase in PFP for N in cultivar HM-1 was 23.4% and 22.7% over Garima, and 18.8% and 20.6% over Sapna in the respective years. This shows that cultivar HM-1 requires less investment in N to produce a greater seed yield than remaining cultivars. Likewise, cultivar HM-1 had higher PFP for P (48.2–48.7 kg kg^{-1}), K (143.6–145.5 kg kg^{-1}), Zn (1336–1352 kg kg^{-1}), and Fe (417–421 kg kg^{-1}) compared to Sapna and Garima. The extent of improvement in PFP in cultivar HM-1 for all these macro- and micronutrients was 20.2–24.9%, being the lowest for K (20.2–20.5%) and the highest for P (24.9–23.9%) over cultivar Garima across the growing years.

Regardless of the growing year, among various nutrient management levels, the values of PFP for N, P, K, Zn, and Fe were 51.0–76.6, 32.2–106.7, 54.3–152.4, 516–2660, and 154–563 kg kg^{-1} , respectively (Table 5). It was found that N10 recorded the highest PFP values for N (76.5–76.6 kg ha^{-1}) and K (152.3–152.4 kg kg^{-1}), being statistically similar ($p \leq 0.05$) to N8, N9, and N4, while N3 had the lowest values for both N (51.0–51.1 kg kg^{-1}) and K (54.3–54.4 kg kg^{-1}). The magnitude of improvement in PFP was 49.7–50.2% for N and 180.0–180.7% for K in N10 concerning N3 (lowest). The maximum PFP of 106.7

and 106.5 kg kg⁻¹ for P was noticed in N3, which was 226.3% and 220.8% higher than N2 (lowest, 32.7–33.2 kg kg⁻¹) in the two years. Likewise, the PFP for Zn was also significantly varied, the highest value being for N9 (2610 and 2660 kg kg⁻¹), closely followed by N4 (2572 and 2598 kg kg⁻¹). The N8 had the lowest values (516, 523 kg kg⁻¹), which was ~4 times less than N9. The treatment N7 had significantly higher values of PFP for Fe (563 and 560 kg kg⁻¹), which was 27.9% and 27.5% higher than N3 (lowest, 157 and 154 kg kg⁻¹) in both years, respectively.

3.2.3. Partial Nutrient Balance

Partial nutrient balance (PNB) is the simplest form of nutrient recovery efficiency, which is measured as nutrient output per unit of nutrient input (a “removal to use” ratio). It is also known as “output minus input” on rare occasions. It is useful to know how many nutrients are being removed from the system compared to how many nutrients are being applied. In the present study, the PNB values for N were significantly higher in cultivar HM-1 (4.25–4.32 kg kg⁻¹) compared to cultivars Sapna (3.93–3.98 kg kg⁻¹) and Garima (3.80–3.84 kg kg⁻¹, lowest values) (Table 6).

Table 6. Partial nutrient balance (kg kg⁻¹) for macro- and micronutrients in lentils as influenced by cultivar selection and nutrient management levels.

Treatment	N		P		K		Zn		Fe	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Cultivars										
Sapna	3.93 ^b	3.98 ^b	0.29	0.30	3.39	3.69	0.069	0.084	0.143	0.149
Garima	3.80 ^b	3.84 ^b	0.30	0.32	3.42	3.58	0.068	0.083	0.140	0.148
HM-1	4.25 ^a	4.32 ^a	0.33	0.35	3.50	3.52	0.066	0.089	0.138	0.144
SEm±	0.07	0.10	0.008	0.006	0.09	0.12	0.002	0.002	0.004	0.004
LSD ($p \leq 0.05$)	0.28	0.32	NS *	NS	NS	NS	NS	NS	NS	NS
Nutrient management practices										
N1	-	-	-	-	-	-	-	-	-	-
N2	3.49 ^{cd}	3.53 ^d	0.22 ^c	0.23 ^b	-	-	-	-	-	-
N3	2.84 ^e	2.89 ^e	0.79 ^a	0.82 ^a	1.67 ^c	1.73 ^c	0.064 ^b	0.071 ^b	0.059 ^d	0.062 ^d
N4	4.10 ^{bc}	4.18 ^{bc}	0.24 ^{bc}	0.24 ^b	3.62 ^b	3.77 ^b	0.141 ^a	0.182 ^a	0.139 ^b	0.150 ^b
N5	3.89 ^{cd}	3.92 ^{cd}	0.25 ^{bc}	0.26 ^b	-	-	0.034 ^c	0.041 ^c	-	-
N6	3.85 ^{cd}	3.86 ^{cd}	0.24 ^{bc}	0.25 ^b	-	-	-	-	0.218 ^a	0.227 ^a
N7	4.20 ^{abc}	4.33 ^{abc}	0.27 ^b	0.28 ^b	-	-	0.034 ^c	0.042 ^c	0.223 ^a	0.230 ^a
N8	4.52 ^{ab}	4.61 ^a	0.26 ^{bc}	0.27 ^b	3.96 ^a	4.15 ^a	0.029 ^c	0.038 ^c	0.147 ^b	0.153 ^b
N9	4.45 ^{ab}	4.55 ^{ab}	0.25 ^{bc}	0.27 ^b	3.95 ^a	4.13 ^a	0.142 ^a	0.184 ^a	0.099 ^c	0.103 ^c
N10	4.61 ^a	4.69 ^a	0.26 ^{bc}	0.28 ^b	3.99 ^a	4.19 ^a	0.030 ^c	0.039 ^c	0.100 ^c	0.102 ^c
SEm±	0.16	0.13	0.013	0.015	0.10	0.14	0.002	0.002	0.006	0.007
LSD ($p \leq 0.05$)	0.45	0.37	0.038	0.04	0.31	0.40	0.006	0.007	0.018	0.020
Cultivar × Nutrient	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

a–e: Different letters in the same column indicate significant difference at the 0.05 probability level, * NS—non-significant.

Irrespective of the growing year, the average extent of this increment in HM-1 for N was 12.2% over Garima and 8.3% over Sapna. The statistical variations concerning the PNB values for PKZn and Fe remained non-significant among cultivars. Still, cultivars Sapna and HM-1 outperformed in PNB values for Fe and P, respectively. When it comes to K and Zn, the cultivars’ superiority differed between HM-1 and Sapna in both the productive years.

Irrespective of the production year, the PNB values greatly varied across the nutrient management practices, ranging from 2.84 to 4.69 for N, 0.22 to 0.82 for P, 1.67 to 4.19 for K, 0.030 to 0.184 for Zn, and 0.059 to 0.230 kg kg⁻¹ for Fe. N10 recorded the greatest values of

PNB for N ($4.61\text{--}4.69\text{ kg kg}^{-1}$) and K ($3.99\text{--}4.19\text{ kg kg}^{-1}$), which were 62.3% and 140.6% higher than N3 (lowest, $2.84\text{--}2.89\text{ kg ha}^{-1}$ N and $1.67\text{--}1.73\text{ kg kg}^{-1}$ K), respectively, as an average of both years. The PNB values for N in N10 were statistically comparable ($p \leq 0.05$) with those of N8 ($4.52\text{--}4.61\text{ kg kg}^{-1}$), N9 ($4.45\text{--}4.55\text{ kg kg}^{-1}$), and N7 ($4.20\text{--}4.43\text{ kg kg}^{-1}$) in both years. Moreover, the PNB value for K in N10 was found to be statistically similar ($p \leq 0.05$) to that of N9 ($3.95\text{--}4.13\text{ kg kg}^{-1}$) and N8 ($3.96\text{--}4.15\text{ kg kg}^{-1}$). In contrast, the PNB value for P was significantly highest in N3 ($0.79\text{--}0.82\text{ kg kg}^{-1}$), which was around 2.5 times (average of both years) more than N2 (lowest, $0.22\text{--}0.23\text{ kg kg}^{-1}$). In the case of Zn, the significantly highest PNB was found in N9 ($0.142\text{--}0.184\text{ kg kg}^{-1}$), closely followed by N4 ($0.141\text{--}0.182\text{ kg kg}^{-1}$). It continuously declined with an increase in the amount of Zn application, and thus, the lowest values were reported from N7 ($0.029\text{--}0.038\text{ kg kg}^{-1}$; 3.9 times less). The PNB value for cumulative Fe was significantly higher in N7 ($0.223\text{--}0.230\text{ kg kg}^{-1}$) and N6 ($0.218\text{--}0.227\text{ kg kg}^{-1}$) over the remaining practices, while the significantly lowest value was retained by N3 ($0.059\text{--}0.062\text{ kg kg}^{-1}$).

The linear correlation coefficient between the amount of nutrients applied through nutrient management practices and PNB was negative. Irrespective of year, for P (-0.96), K (-0.99), Zn (-0.92), and Fe (-0.96), it was a perfect negative correlation, while for N (-0.17), it was a partial negative correlation. Hence, like PFP, the values of PNB declined with an increasing amount of nutrients.

3.2.4. Internal Utilization Efficiency

Internal utilization efficiency (IUE) is a useful metric for determining how efficiently nutrients are used. It is defined as the yield per unit of total nutrient absorption [28]. In other words, it refers to a plant's inherent ability to produce yield per unit of nutrient in its tissues [29]. An extremely high IUE indicates a nutritional deficit. It is concerned with the plant's ability to convert nutrients obtained from various sources into economic yields (seed, etc.). This formula depicts the instantaneous yield of biomass per unit of nutrient and includes the concept of "productivity" previously suggested by Ingestad [30] and Ingestad and Agren [31]. In the present experiment, the varietal differences in IUE of K, Zn, and Fe were found to be significant (Table 7). The IUE for K ($41.0\text{--}41.01\text{ kg g}^{-1}$), Zn ($15.01\text{--}20.14\text{ kg g}^{-1}$), and Fe ($2.98\text{--}3.06\text{ kg g}^{-1}$) was significantly greater in cultivar HM-1 than in Sapna and Garima, while the latter two cultivars have more or less similar values for all these elements. Though the value of IUE for N and P remained non-significant among the cultivars, the highest values were retained in cultivar HM-1, i.e., $18.42\text{--}18.81$ and $143.0\text{--}146.1\text{ kg kg}^{-1}$, respectively, over cultivars Sapna and Garima. The use of organic and inorganic fertilizers improved nutrient availability, soil organic matter (SOM), microbial and enzymatic activities, and various soil physical properties, resulting in increased biomass output, nutrient uptake, and utilization efficiency [32]. In our study, the IUE for macro- and micronutrients remained almost uniform over the experimental period (Table 7).

Across the years, the IUE values ranged from 16.39 to 20.41 kg kg^{-1} for N, 126.4 to 151.6 kg kg^{-1} for P, 31.5 to 40.4 kg kg^{-1} for K, 13.40 to 18.61 kg g^{-1} for Zn, and 2.42 to 2.96 kg g^{-1} for Fe. The IUE for N was significantly more in N2 (18.99 , 20.41 kg kg^{-1}) than in the remaining treatments, although it was statistically comparable ($p \leq 0.05$) with N3 (18.38 kg kg^{-1}), N4 (17.58 kg kg^{-1}), N5 (17.77 kg kg^{-1}), and N6 (17.70 kg kg^{-1}) in the first year and with N3 (18.82 kg kg^{-1}) in the second year of the experiment.

The IUE for P was also found higher in N2 (148.3 , 151.6 kg kg^{-1}); still, it was non-significant with other treatments in the first year, but in the second year, it was significantly superior only to N9 (134.6 kg kg^{-1}), N10 (131.8 kg kg^{-1}), N4 (130.0 kg kg^{-1}), N6 (131.0 kg kg^{-1}), and N8 (126.4 kg kg^{-1}). In case of K, N4 ($38.5\text{--}40.4\text{ kg kg}^{-1}$) produced significantly higher IUE than only N3 ($31.5\text{--}33.9\text{ kg kg}^{-1}$), while it was statistically comparable with the remaining practices, i.e., N8, N9, and N10, in both years. Moreover, the highest values of IUE for Zn were observed from N9 ($14.44\text{--}18.61\text{ kg g}^{-1}$), which was statistically superior only to N3 (lowest, 15.62 kg g^{-1}) in the first year and N5 (lowest, 13.40 kg g^{-1}) in the second year. The IUE for Fe was significantly greater under N4 ($2.80\text{--}2.96\text{ kg g}^{-1}$);

however, it was statistically similar to N3 (2.67 kg g⁻¹) and N8 (2.88 kg g⁻¹) in the first year. Likewise, in the second year, the statistical superiority of N4 was only to N6 (lowest, 2.42 kg g⁻¹), while there was a statistical similarity with the remaining treatments.

The correlation between the amount of nutrients added and IUE for NPKZn and Fe greatly varied in both years. Therefore, an average of them was taken. The correlation for N (−0.16), P (−0.21), and Zn (−0.47) was partially negative; for K (−0.87), this was a perfect negative correlation; and Fe (0.08) did not correlate. The complete negative correlation for K might be due to the luxury consumption of K without contributing much to crop yield production.

Table 7. Internal utilization efficiency for macro- and micronutrients in lentils as influenced by cultivar selection and nutrient management levels.

Treatment	N (kg kg ⁻¹)		P (kg kg ⁻¹)		K (kg kg ⁻¹)		Zn (kg g ⁻¹)		Fe (kg g ⁻¹)	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Cultivars										
Sapna	16.82	16.99	140.0	136.7	35.8 ^b	33.2 ^b	15.95 ^b	13.32 ^b	2.49 ^b	2.42 ^b
Garima	17.00	17.21	131.8	128.1	35.1 ^b	33.4 ^b	15.84 ^b	13.18 ^b	2.47 ^b	2.41 ^b
HM-1	18.42	18.81	146.1	143.0	41.0 ^a	41.1 ^a	20.14 ^a	15.01 ^a	3.06 ^a	2.98 ^a
SEm±	0.38	0.59	2.84	3.8	1.08	1.07	0.28	0.24	0.06	0.06
LSD ($p \leq 0.05$)	NS *	NS	NS	NS	4.5	4.3	1.12	0.91	0.23	0.24
Nutrient management practices										
N1	-	-	-	-	-	-	-	-	-	-
N2	18.99 ^a	20.41 ^a	148.3	151.6 ^a	-	-	-	-	-	-
N3	18.38 ^{ab}	18.82 ^{ab}	137.8	143.2 ^{ab}	33.9 ^b	31.5 ^b	15.62 ^b	13.72 ^{ab}	2.67 ^{abc}	2.60 ^{ab}
N4	17.58 ^{ab}	17.63 ^{bc}	143.4	130.0 ^b	40.4 ^a	38.5 ^a	18.30 ^a	14.36 ^a	2.96 ^a	2.80 ^a
N5	17.77 ^{ab}	17.32 ^{bc}	142.2	139.7 ^{ab}	-	-	16.26 ^{ab}	13.40 ^b	-	-
N6	17.70 ^{ab}	17.80 ^{bc}	139.6	131.0 ^b	-	-	-	-	2.47 ^c	2.42 ^b
N7	16.89 ^b	17.57 ^{bc}	131.6	135.2 ^{ab}	-	-	16.51 ^{ab}	13.48 ^{ab}	2.55 ^c	2.47 ^{ab}
N8	16.55 ^b	16.78 ^{bc}	137.4	126.4 ^b	37.4 ^{ab}	36.5 ^{ab}	17.82 ^{ab}	13.78 ^{ab}	2.88 ^{ab}	2.77 ^{ab}
N9	16.39 ^b	16.41 ^c	137.2	134.6 ^b	36.8 ^{ab}	36.2 ^{ab}	18.61 ^a	14.44 ^a	2.56 ^c	2.55 ^{ab}
N10	16.41 ^b	16.31 ^c	135.8	131.8 ^b	37.8 ^{ab}	36.7 ^{ab}	18.05 ^{ab}	13.71 ^{ab}	2.62 ^{bc}	2.60 ^{ab}
SEm±	0.68	0.70	6.02	5.5	1.8	1.8	0.78	0.60	0.12	0.15
LSD ($p \leq 0.05$)	1.94	1.99	NS	16.9	5.6	5.5	2.50	0.98	0.31	0.36
Cultivar × Nutrient	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

^{a-c}: Different letters in the same column indicate significant difference at the 0.05 probability level, * NS—non-significant.

3.2.5. Physiological Efficiency

The increase in yield in response to the increase in crop uptake of the nutrients in above-ground sections of the plant is known as physiological efficiency (PE). The PE, like the IUE, focuses on the plants' ability to turn nutrients obtained from a source into economic yield. It is a significant indicator of NUE that aids in determining the source (organic/inorganic) and adoption of management strategies, including their optimal combination, as well as determining the feasibility of nutrient requirements of a production system. In the present experiment, the PE for P was significantly affected by varietal selection in lentils, in which the cultivar Sapna (116.5 and 113.7 kg kg⁻¹) was statistically similar to Garima (112.7 and 106.4 kg kg⁻¹) and was more efficient than HM-1 (97.5 and 104.0 kg kg⁻¹) in the respective years (Table 8). In contrast, the PE for NKZn and Fe was not significantly affected by the varietal selection in lentils. Despite the lack of statistical significance, there was a general trend indicating that cultivar Sapna has relatively higher PE for N (12.47 and 13.69 kg kg⁻¹) and Fe (3.03 and 3.67 kg g⁻¹) than Garima and HM-1. Similarly, there was also a general trend of relatively more PE for K (57.6 and 45.0 kg kg⁻¹) and Zn (38.8 and

16.5 kg g⁻¹) under HM-1 than under Sapna and Garima across the years, but without any significant differences.

Table 8. Physiological efficiency for macro- and micronutrients in lentils as influenced by cultivar selection and nutrient management levels.

Treatment	N (kg kg ⁻¹)		P (kg kg ⁻¹)		K (kg kg ⁻¹)		Zn (kg g ⁻¹)		Fe (kg g ⁻¹)	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Cultivars										
Sapna	12.47	13.69	116.5 ^a	113.7 ^a	50.6	44.5	35.4	14.4	3.03	3.67
Garima	11.55	13.64	112.7 ^a	106.4 ^a	48.2	40.8	37.5	15.1	2.52	2.86
HM-1	11.33	11.69	97.5 ^b	104.0 ^b	57.6	45.0	38.8	16.5	2.90	3.48
SEm±	0.38	0.46	2.8	2.9	2.1	1.9	1.6	1.0	0.91	1.03
LSD ($p \leq 0.05$)	NS *	NS	7.3	7.7	NS	NS	NS	NS	NS	NS
Nutrient management practices										
N1	-	-	-	-	-	-	-	-	-	-
N2	14.43 ^a	16.33 ^a	142.2 ^a	134.8 ^a	-	-	-	-	-	-
N3	9.40 ^f	9.14 ^f	72.7 ^f	84.0 ^e	21.6 ^d	24.9 ^d	36.0 ^c	15.4 ^{ab}	3.27 ^c	2.69 ^d
N4	13.23 ^b	13.54 ^{bc}	119.5 ^b	123.4 ^b	66.1 ^a	57.2 ^a	41.8 ^b	15.7 ^{ab}	5.15 ^a	4.19 ^a
N5	12.39 ^{bc}	14.03 ^b	106.0 ^d	93.3 ^d	-	-	24.5 ^e	14.0 ^c	-	-
N6	10.89 ^e	12.44 ^{de}	114.4 ^{bc}	111.2 ^c	-	-	-	-	2.17 ^f	2.40 ^e
N7	10.77 ^e	11.46 ^e	91.7 ^e	90.2 ^{de}	-	-	31.8 ^d	16.3 ^a	2.49 ^e	2.36 ^e
N8	12.02 ^c	12.39 ^{de}	118.0 ^b	113.0 ^c	61.0 ^{ab}	48.3 ^b	34.4 ^{cd}	14.9 ^{bc}	3.77 ^b	3.99 ^a
N9	11.10 ^{de}	12.05 ^{de}	106.3 ^{cd}	111.3 ^c	57.9 ^{bc}	45.0 ^{bc}	55.6 ^a	16.6 ^a	2.47 ^e	3.55 ^c
N10	11.82 ^{cd}	12.67 ^{cd}	109.2 ^{cd}	110.8 ^c	53.4 ^c	41.7 ^c	36.6 ^c	14.2 ^c	2.72 ^d	3.47 ^c
SEm±	0.34	0.41	3.7	4.1	2.2	1.9	1.2	0.5	0.09	0.10
LSD ($p \leq 0.05$)	0.87	1.07	8.2	8.9	6.7	5.3	3.9	1.2	0.20	0.23
Cultivar × Nutrient	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

a–f: Different letters in the same column indicate significant difference at the 0.05 probability level, * NS—non-significant.

Table 8 shows a significantly higher value of PE for N (14.43–16.33 kg kg⁻¹) and P (134.8–142.2 kg kg⁻¹) in N2. Significantly lower values were obtained in N3 (9.14–9.40 and 72.7–84.0 kg kg⁻¹ for N and P, respectively). The improvement in PE for N in N2 was 53.5% and 78.7% in the first and second years, respectively, while for P, it was 95.6% and 60.5% over N3, respectively. On the contrary, the PE for K was significantly higher with N4 (57.2–66.1 kg kg⁻¹) compared to the remaining treatments, except for N8 (61.0 kg kg⁻¹) in the first year. Significantly lower values for K were gained from N2, which was 206.0% and 129.7% less than N4 in both years, respectively. In both years, there was a significant difference in the PE value for Zn. This falls between 24.5 and 55.6 kg g⁻¹ in the first year and between 14.0 and 16.6 kg g⁻¹ in the second year under various nutrient management levels. In this line, N9 (55.6, 16.6 kg g⁻¹) had 126.9% and 18.6% higher values of PE for Zn than N5 (24.5, 14.9 kg g⁻¹), which had the lowest PE in the respective years of the experiment. Compared with N9, N3, N4, and N7 had no significant effect on PE for Zn in the second year of study. The PE of Fe (2.17–5.15 kg g⁻¹) was also significantly varied due to fertilization treatments across the years. The greatest value for Fe was recorded in N4 (5.15, 4.19 kg g⁻¹), although it was statistically similar to N8 (3.99 kg g⁻¹) in the second year. Moreover, significantly higher values of Zn and Fe were found in N4, while the lowest values were obtained in N5 (2016) and N6 (2017) for Fe in both years.

4. Discussion

4.1. Cultivars

4.1.1. Crop Yield

The lentil cultivar HM-1 produced significantly higher seed yield ($1.59, 1.61 \text{ Mg ha}^{-1}$) than Sapna ($1.33, 1.31 \text{ Mg ha}^{-1}$) and Garima (both 1.30 Mg ha^{-1}) in both years, respectively (Table 3). The proper mobilization of dry matter production towards the sink (seed yield) is an important factor for economic yield. The superiority of cultivar HM-1 might be because it may have more ability to transfer assimilates into economic yield because of its differential gene expression and response to applied inputs. Along with this, the Harvest Index of HM-1 was much higher as compared to Sapna and Garima, which also gave it a higher yield. Additionally, cultivar HM-1 produced a high number of primary and secondary branches ($12.22\text{--}12.25$ vs. $9.54\text{--}9.64 \text{ plant}^{-1}$), and thereafter pods per plant ($106\text{--}108$ vs. $69\text{--}73$) [33], which directly contributed to the seed yield and, thus, its superiority over Sapna and Garima. The variation in seed yield of different lentil cultivars has been reported by various researchers [34–36]. The stover yield of cultivar Sapna ($1.86\text{--}1.90 \text{ Mg ha}^{-1}$) closely followed by Garima ($1.82\text{--}1.87 \text{ Mg ha}^{-1}$) was significantly greater than HM-1 ($1.68\text{--}1.73 \text{ Mg ha}^{-1}$) (Table 1). This was due to the vigorous vegetative growth of Sapna and Garima and consequently higher biomass production of leaves. These two cultivars are bold-seeded and have vigorous growth habits that might have spent more photosynthetic energy on augmenting their vegetative growth rather than accumulation in seeds. On the other hand, the assimilates in the cultivar HM-1 may have been translocated more into the sink portion of the plant (i.e., seed) rather than in vegetative growth. Similar findings were reported by Biswas and co-workers [36]. The biological yield of lentils remained statistically comparable with all the cultivars in both years. This was because of the higher seed yield production by cultivar HM-1, and greater stover yield in cultivars Sapna and Garima (Table 3).

4.1.2. Nutrient Use Efficiencies

The quantity of supplemental seed yield collected per kg of nutrient provided to a crop is agronomic efficiency (AE). It denotes the increment in seed yield with each unit addition of nutrients to the crop, thereby driving the gain in productivity improvement by the usage of nutrient input. It is critical to increase nutrient intake and reduce losses in soil, water, and the environment to improve the AE of a production system for environmental security while also increasing productivity and economic efficiency [37]. In the present two-year experiment, the lentil cultivars Sapna, Garima, and HM-1 had no significant ($p \leq 0.05$) differences in AE for NPKZn and Fe (Table 4), although the superiority of cultivars differed with experimental years. In the first year, the cultivar Sapna was superior while in the second year, cultivar Garima was superior in terms of AE for macro- (N, P, K) and micronutrients (Zn, Fe). The PFP is a simple indicator for assessing NUE, which typically expresses the efficiency of a production system across nutrient management practices. The lentil cultivar HM-1 was more efficient in terms of conversion of applied NPKZn and Fe into the seed yield (PFP) (Table 5) as compared to Garima and Sapna. The PNB simply measures the nutrient output per unit of nutrient input, which is just a ratio of removal to the use of nutrients. The lentil cultivar HM-1 took more N (Table 6) from the soils to which these nutrients were added through synthetic fertilizers or organically (i.e., through vermicomposting), measured in terms of PNB. Cultivar HM-1 has more ability to transform NPKZn and Fe acquired from the soil into economic yield (Table 7), measured in terms of IUE. The superiority of IUE values in cultivar HM-1 was significant for K, Zn, and Fe, but it was statistically comparable for N and P with cultivars Sapna and Garima. In contrast, the increase in yield in response to the increased crop uptake of organically/inorganically applied P in above-ground plant parts (i.e., PE) was significantly higher in cultivar Sapna, which was statistically ($p \leq 0.05$) comparable to Garima (Table 8). This could be attributed to variations in the cultivars' P allocation to their seeds and stover, as well as their absorption. Fageria and co-workers [38] found differences in P-use efficiency

among crop species and genotypes within species, including dry bean. Plants differ widely in their ability to grow in low-P soils [39], and this has been related to numerous plant features, including the root system, architecture, and root hair density. Lentil cultivars respond to nutrients from the soil, fertilizers, and organic manure in diverse ways. Genetic differences in central physiological and morphological features such as nutrient intake, metabolism, distribution, and remobilization underpin varietal differences in nutrient usage [40,41]. Individual morphological, anatomical, and biophysical traits, such as larger canopies with thicker leaves, larger leaf phloem transactional area, rapid solubilization and remobilization of nutrients from older to younger leaves, and lower dark respiration rates, may be linked to cultivar Sapna and Garima's lower nutrient efficiency. Nutrient transport within the plant system has a significant impact on the amount of nutrients provided to seeds and eventual economic produce [42–44]. These cultivars (Sapna and Garima) extracted many nutrients from the soil, but they could not cause them to seed or convert them to an economical yield, lowering the NUE. The ability of cultivar HM-1 to maintain a higher N inflow (N intake rate per unit root) than other cultivars may be the cause/mechanism of its superior nutritional efficiency. Thinner roots with higher surface areas in cultivar HM-1 investigate the soil more thoroughly, which increases nutrient availability, especially micronutrients [45]. Differences in biochemical consumption and re-translocation of Zn and Fe from older to younger tissues in shoots could explain the unexplained variance in Zn and Fe efficiency among genotypes [46].

4.2. Nutrient Management

4.2.1. Crop Yield

Among nutrient management practices, statistically more seed ($1.63, 1.65 \text{ Mg ha}^{-1}$), stover ($1.96, 2.02 \text{ Mg ha}^{-1}$), and biological ($3.59, 3.67 \text{ Mg ha}^{-1}$) yields were recorded in N10 in both years of experimentation, respectively (Table 3). Although the improvement in all these traits remained non-significant with foliar fertilization, it was more pronounced with Zn compared to Fe foliar fertilization. Therefore, N10 was statistically comparable with N4, N8, and N9 in terms of seed, stover, and biological yield. This numerical increment in crop yield with Zn and Fe application could be attributed to increased total dry matter production because of better uptake of Zn and Fe (Tables 7 and 8) and their translocation to reproductive parts. In the respective years, the magnitude of the increase in seed yield with this treatment (N10) was 53.3% and 60.4% over the control. The improvement in growth-attributing parameters followed by yield attributes, including pods per plant and seeds per pod, was the major reason behind the advanced crop yield with N10. The higher seed yield achieved in this promising vermicompost and inorganic nutrient application (N10) was a combined effect of the applied major nutrients. This improved the availability of plant nutrients by continuously releasing nutrients in the soil solution, which promotes crop growth parameters. The favorable growth parameters directly influenced yield attributes and consequently increased crop yield. Earlier, Aggarwal and Ram [47] also proved the significance of the integrated use of organic and inorganic fertilizers towards improvements in the crop yield of lentils. The study of Apori et al. [11] also showed that the combined application of biochar with FYM and/or NPK improved soil quality indicators such as soil pH, total organic carbon, available P, and total N compared to solely applied manure and NPK, which in turn improved crop yield. Comparable findings were reported by Niri et al. [48] and Singh and Singh [49].

4.2.2. Agronomic Efficiency

Sustainable nutrient management is the key to exploring the full potential of lentil crops in terms of improved AE. The data for AE (Table 4) revealed that the maximum AE for N, P, and K were recorded in N10 compared to other nutrient management paradigms, although N10 was statistically similar to N4, N8, and N9 in the case of N. Moreover, the improvement in AE for P in N10 was non-significant to N3, N4, N8, and N9, while the AE for K in N10 was significantly superior only to that of N3. The increased AE in N10 for

different nutrients could be due to the yield increment per unit of nutrient applied. The higher production was linked to the beneficial effect of combining organic manures and inorganic fertilizers on soil health, including a higher nutritional level, which influenced the crop's growth and yield-attributing characteristics [50]. The improved AE of the crop was directly attributed to the enhanced seed yields. Fageria and Baligar [51] also reported that high AE is obtained if the yield increment per unit nutrient applied is high because of reduced losses and increased uptake of nutrients. The results corroborate the findings of several authors [52–57]. The superiority of treatments in terms of AE for micronutrients (Zn, Fe) differed in comparison with macronutrients. The AE for Zn (Table 4) was found to be significantly higher in N9, closely followed by N4 over the remaining treatments. This increased AE for Zn in N9 followed by N4 was associated with higher seed yield (Table 3) at the cost of less Zn application (0.60 kg ha^{-1}) (Table 2), although seed yield was also greater in N8 and N10, but in these, the rate of Zn application was much higher (3.6 kg ha^{-1}) than in N9 and N4 (Table 2). This resulted in reduced AE in N8 and N10 and higher in N9 and N4. The AE for Fe was controversial across crop growing years, where N8, being statistically similar to N7, was superior to other treatments in the first year, while in the second year, N7 was superior only to N8 and N9. The controversial results of AE for Fe might be due to it having the lowest solubility (10^{-6} – 10^{-20} M) among cations, which further decreases in calcareous conditions (Table 1). This is the only micronutrient whose deficiency correction is most difficult even after fertilization due to its rapid precipitation into unavailable $\text{Fe}(\text{OH})_3$. As a result, even after a sufficient amount of Fe is applied to the soil, it quickly becomes adsorbed on clay minerals, and plants do not respond to it.

4.2.3. Partial Factor Productivity

The data for PFP presented in Table 5 reveal a negative correlation between the value of PFP and the amount of nutrients added. Irrespective of the growing year, N10 recorded maximum PFP for N and K, which was statistically similar to N4, N8, and N9. This could be due to a prolonged period of coordinated nutrient supply [58], as well as the synergistic influence of NP and K on plant growth. The judicious use of organic and inorganic fertilizers, as well as micronutrient foliar spray, improved nutrient balance and indigenous soil N supply that thus contributed to the rise in PFP for N and K. This improved nutrient supply, uptake, and efficiency and collectively enhanced seed yield and PFP in N10 [59]. In case of P, the plot supplied with the lowest amount of P (N3) (Table 2) recorded the maximum PFP. This was associated with a significant improvement in seed yield over the control plot with a slight addition of P through VC, which was about one-fourth of the amount of P added from other treatments (Table 2). The decreased PFP for P in other treatments, including practices of organic plus inorganic management, was mainly allied to a considerably higher P supply (i.e., 40 – 45 kg ha^{-1}) (Table 2). The PFP for Zn and Fe also significantly varied among the nutrient management practices. In this regard, treatment N9, closely followed by N4, was superior in PFP for Zn, and treatment N7, being statistically similar to N6, had a greater value of PFP for Fe. The PFP for Zn obtained from N9 was linked to its higher seed production, coupled with a very low supply of Zn from organic sources.

4.2.4. Partial Nutrient Balance

Like the PFP value, the PNB value dropped with each unit addition of mineral fertilizers to the crop by various practices. In this experiment, the nutrient intake from BNF, precipitation, and atmosphere was not included in the balance calculations. In our research, we found that under various nutrient management practices, there are generally positive N and K partial balances. This indicates that N and K levels are not limiting factors in lentil production, and in the long run, these nutrient management practices have the potential to sustain crop yields. In this study, the PNB values for N and K were higher in treatments encompassing organic manures (i.e., VC at 1.0 t ha^{-1}) in conjunction with a lower dose of N (i.e., 10 kg ha^{-1}) and the full quantity of RDP (i.e., 40 kg ha^{-1}) (Table 6). N10 has the

highest values for both N and K, though N was statistically equivalent with N7, N8, and N9. A PNB value <1 means nutrient inputs vastly outnumber nutrient removal, indicating avoidable nutrient losses and therefore the need for improvement in NUE [60]. Hence, the near zero or negative P, Zn, and Fe balances in the different approaches indicate that these systems continue to deplete nutrient stocks. This gives rise to concerns about the sustainability of lentil production. In this regard, the PNB values for P, Zn, and Fe were significantly higher in N3, N7, N9, and N7, respectively, than the rest of the treatments during both growing seasons. However, for P, the PNB values are near 1 (0.79 and 0.82) in N3, suggesting that in this treatment, soil fertility will be sustained at a steady state. Additionally, over the short-term experiment and on individual farms, PNB can show substantial fluctuations, especially for P and K. Therefore, to assess the PNB more accurately, a long-term experiment over several years is more useful [61].

4.2.5. Internal Utilization Efficiency

The IUE is an effective indicator to be used to determine the relationships between seed yield and whole-plant nutrient accumulation. In the present experiment, the IUE for N was significantly higher in N2 (Table 7), which indicates more pronounced effects of N accumulation on seed yield in N2-treated plots compared with the remaining plots. The IUE values for P (2017), K, Zn, and Fe were significantly higher in treatments N2, N4, N9, and N4, respectively. The IUE of nutrients depends on the quantity of seed produced per unit of nutrient uptake. The treatment N2 produced a sufficient amount of yield with less N uptake ($50.7\text{--}50.9\text{ kg ha}^{-1}$) compared to the treatments having a higher yield, i.e., N4, N8, N9, and N10 ($64.2\text{--}75.7\text{ kg ha}^{-1}$), which resulted in improved IUE of N under N2. These findings show that by reducing fertilizer input, optimal nutrient management was able to sustain plant nutrition of macro- and micronutrients for maximum yield, seed nutrient concentrations, and NUEs.

4.2.6. Physiological Efficiency

The physiological efficiency of lentil significantly responded to the nutrient management paradigm. The improved PE for N and P (Table 8) was noted from N2 (RDF), which was 53.5% and 78.7% for N, and 95.6% and 60.5% higher for P over N3 (RDF, lowest PE) in the respective years. This is probably due to greater improvement in seed yield with the increase in crop uptake of the N and K under N2 in above-ground parts of the plant. The findings are consistent with those of several other researchers [62–65], who found that increasing the nutrient dose reduced PE. On the contrary, the PE for K was significantly higher with N4 compared to the remaining fertilization treatments, but still, in the case of K, it was statistically similar to N8. Similarly, the N4 was superior in PE for Fe in both years, but the treatment of N4 was statistically similar to N8 in the second year. This might be associated with the ability of plants under N4 to efficiently convert acquired K and Fe in the source to economically productive yield. For Zn, the PE values calculated were significantly higher in N9 than in the remaining practices, although they were statistically similar with N3, N4, and N7 in the second year of experimentation. The treatment N9 had a considerably higher seed yield (Table 3), and while the Zn was supplied in very small quantities (through VC) (Table 2), plants were also much more affirmed in the transformation of attained Zn into seed yield.

5. Conclusions

Improving NUEs in grain legumes has become the priority of researchers to achieve the United Nations' Sustainable Development Goals (SDGs). In this direction, the present study was carried out to explore and maximize the potential of lentil cultivars for continual and improved nutrient delivery from organic sources combined with synthetic fertilizers to improve crop yield, NUEs, and protection of soil, environment, and human health. From this field study, it is concluded that organic manure (i.e., vermicompost) can be integrated with a reduced dose of nitrogenous fertilizers and foliar fertilization of Zn and

Fe to improve NUEs for macro- and micronutrients while enhancing crop yield at the same time. Among the lentil cultivars under diverse nutrient management practices, HM-1 was found to be more productive ($1.59\text{--}1.61\text{ Mg ha}^{-1}$), remunerative, economically viable, and resource-conserving than cultivars Sapna and Garima. Considering the integrated nutrient management paradigm including 10 kg N ha^{-1} coupled with $40\text{ kg P}_2\text{O}_5\text{ ha}^{-1}$ through synthetic fertilizers, vermicomposting 1.0 t ha^{-1} as an organic source and foliar spray of 0.5% each of ZnSO_4 and FeSO_4 (N10) produced 56.8% higher seed yield ($1.63\text{--}1.65\text{ Mg ha}^{-1}$) than the control ($1.06\text{--}1.07\text{ Mg ha}^{-1}$), in addition to improved nutrient dynamics and NUEs for N, PKZn, and Fe. Finally, it may be concluded that 50% of the RDN can be substituted with organic manures (i.e., vermicompost) without compromising crop productivity and soil fertility while improving NUEs and, thus, soil, human, and environmental health.

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Appendix A

Table A1. Initial properties of soil (0–15 cm) at the experimental site.

Particulars	Mean Value
A. Mechanical composition	
Sand (%)	72.5
Silt (%)	22.0
Clay (%)	5.5
Soil texture	Sandy loam
B. Chemical properties	
pH (1:2 soil: water)	8.20
Electrical conductivity (dS m^{-1}) (1:2 soil: water)	0.52
Organic carbon (%)	0.42
Available N (kg ha^{-1})	137
Available P_2O_5 (kg ha^{-1})	14.6
Available K_2O (kg ha^{-1})	416
DTPA-extractable Zn (mg kg^{-1})	0.70
DTPA-extractable Fe (mg kg^{-1})	6.81

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