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# Nutrient Management Influences Root Characteristics and Nitrogen Use Efficiency in the Vegetable-Based Agroecosystem in the Northwestern Himalayas

**Archana Sharma [1], Jagjeet Chand Sharma [1], Yog Raj Shukla [2], Manohar Lal Verma [1], Upender Singh [1], Ranjit Singh Spehia [3], Deeksha Sharma [4], Krishan Lal Gautam [5,*], Rushal Dogra [5], Huseyin Baris Tecimen [6,7], Munesh Kumar [8] and Amit Kumar [9]**

[1] Department of Soil Science and Water Management, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan 173230, Himachal Pradesh, India; archanasharma201213@gmail.com (A.S.)
[2] Department of Vegetable Science, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan 173230, Himachal Pradesh, India
[3] Krishi Vigyan Kendra, Tabo, Lahaul and Spiti, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan 173230, Himachal Pradesh, India
[4] Department of Entomology, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan 173230, Himachal Pradesh, India
[5] Deparment of Silviculture and Agroforestry, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan 173230, Himachal Pradesh, India
[6] Soil Science and Ecology Department, Faculty of Forestry, Istanbul University-Cerrahpasa, 34473 Istanbul, Turkey
[7] Indian River Research and Education Center, Institute of Food and Agricultural Sciences, University of Florida, Fort Pierce, FL 34945, USA
[8] Department of Forestry and Natural Resources, HNB Garhwal University, Srinagar 249161, Uttarakhand, India
[9] School of Hydrology and Water Resources, Nanjing University of Information Science and Technology, Nanjing 210044, China
* Correspondence: krishanlalgautam99@gmail.com

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**Abstract:** Imbalanced nutrient fertilization adversely affects root growth and alters the nutrient use efficiency of a crop. This study aimed to understand the influence of integrated nutrient management on root characteristics and nitrogen use efficiency in the vegetable-based agroecosystem. The field trial was conducted at the Department of Soil Science and Water Management of Dr. Y S Parmar University of Horticulture and Forestry Nauni, Solan (HP) India in 2019 and 2020. There were nine treatments *viz.* $T_1$- control, $T_2$-100% farmyard manure (FYM; N equivalent basis), $T_3$-100% N, $T_4$-100% NP, $T_5$-100% NK, $T_6$-100% PK, $T_7$-100% NPK, $T_8$-100% NPK + FYM (recommended practice), and $T_9$-150% NPK + FYM on root densities (mass, volume, and length) and N use efficiency of cauliflower and capsicum. The results observed that different treatments exert significant effects on measured as well as derivative parameters. In detail, the application of 150% NPK + FYM recorded significantly higher root-mass density (0.72 and 1.71 g $m^{-3} \times 10^{-3}$), root-volume density (4.49 and 2.52 $m^3$ $m^{-3} \times 10^{-3}$), and root-length density (1.21 and 0.81 cm $m^{-3} \times 10^{-4}$) in cauliflower and capsicum, respectively, which was statistically at par with treatment $T_9$ (100% NPK + FYM). Similarly, this treatment (150% NPK + FYM) resulted in a maximum positive N (774.6 kg $ha^{-1}$), P (650.4 kg $ha^{-1}$), and K (334.9 kg $ha^{-1}$) balance of soil after the complete harvest of two cropping-sequence cycles. However, maximum agronomic N use efficiency (59.9 and 67.9 kg $kg^{-1}$) and apparent recovery of N (39.3 and 59.7%) were recorded under 100% FYM (N equivalence) in cauliflower and capsicum, respectively, but this treatment produced the negative N balance (−91.7 kg $ha^{-1}$) and K (−340.3 kg $ha^{-1}$) in soil, whereas significant improvement in agronomic use efficiency, apparent recovery of applied N, as well as in soil, and the NPK balance was recorded under 100% NPK + FYM over the other treatment. This study recommended an integrated nutrient module that is the application of 100% NPK + FYM to ensure better root growth and positive nutrient balance in the soil.

**Keywords:** NPK balance; nitrogen-use efficiency; root-length density; root-mass density; root-volume density

## 1. Introduction

Soil is an important natural resource for plant nutrition and the quality of soil for production depends on its sustainable supply of plant nutrients. Land use systems effectively influence the fertility and stability of an ecosystem [1]. The rapid increase in global food demand certainly increased the requirement for crop nutrient management and optimisation but the over usage of soil nutrients alters the nutrient use efficiency (NUE) of a crop. The indiscriminate use of inorganic nitrogenous fertilizers either excessively or imbalanced by farmers became a concern in the research community due to the potential threat to global water, soil acidification, and water eutrophication [2,3]. However, insufficient or unnecessary application of fertilizers does not guarantee consistently growing yield, which can result in low efficiency of nutrient usage [4]. Under an intensive cropping system, continuous application of imbalanced inorganic fertilization cannot maintain the desired level of crop production, whereas coapplication of chemical fertilizer and organic manures provides for the upholding and sustaining of crop production and also improves root growth which enhances the water and nutrient-use efficiency [5,6]. Nitrogen (N) is the main limiting nutrient for the growth and development of plants and is added to the agricultural field to boost crop yields [7,8]. Optimal N fertilization is vital to meeting the need for N for plants and increasing crop yields. Application of N beyond plant need is the major factor contributing to reduced NUE, higher crop production, and large N losses to the environment via leaching and emitting greenhouse gas (GHG; NO and $N_2O$) [9]. Optimizing N fertilization is a vital task to increase crop yields and is helpful in mitigating environmental issues [10]. Unreasonable fertilization management not only decreases the NUE but also enhances the production cost and environmental risk [11]. The literature reveals that numerous studies have been made in the global scientistic fraternity on breeding N-efficient cultivars to optimize the N application strategies and perform precision agriculture techniques [12–14]. Organic manure added to the soil provides carbon (C) and other essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) to the soil, which are indispensable for crop growth and further complete their life cycle [14–16]. Thus, a nutrient (NPK) management scheme through efficient fertilization can play an important role in crop production and provides the gateway for increasing crop productivity [4–17].

Root morphological characteristics and physiological activities are greatly affected by the excessive use of nitrogen [18]. Root nutrient-absorption capacity depends upon the root characteristic *viz.* total length, volume, and effective root-absorption area, which are highly influenced and improved with N application [19]. Carbohydrate and starch synthesis in the leaves and stems are greatly influenced by phosphorus, thereby improving the grain weight and quality by increasing nutrient transportation to the grains [20]. Adequate P and K supply promote dry matter accumulation and root development [21,22]. Adequate application of nutrients, particularly N and P, improves the root-mass density by increasing the number as well as the length of the root hair [6]. The addition of organic manure improves the profuse growth of secondary roots as well as root hair. Root-length density (RLD) is a central parameter to study water and nutrient movement in the vadose zone and soil–plant–atmosphere continuum [23]. The lack of understanding of the effect of different fertilizers' applications ultimately results in either yield gaps, economic losses, or negative NPK soil balance that could be recovered through optimized conditions. The role of balanced and imbalanced fertilization with farmyard manure (FYM) on root parameters and NPK balance has been well established in cereal crops but such studies are very meagerly available in vegetable crops.

Phosphorus (P) or potassium(K) status is influenced by the application of P and K fertilizers to the soil which are further responsive to the crop nutrient uptake and N utilization [24]. The nutrient and water uptake capability of plants from the soil merely depends upon an essential absorption system [25,26] functioned by the root morphology viz. root depth, root branching, number of root hairs and root tips [27]. The anchoring plants in the soil, and the absorption and translocation of nutrients and water for the synthesis of phytochromes and other organic compounds functions, make root studies prominently significant [28]. Above-ground growth and biomass yield of a crop are greatly influenced by root systems [29]. The knowledge of factors that influence root development is important for improving nutrient cycling in soil–plant systems [30]. Leaf quantity and the nutrient release pattern determine the nutrient budget and their impact on the ecosystem [31]. Dry-matter accumulation and yield provide the physiological basis for nutrient absorption and translocation and influence crop growth and development [26–32]. Continuous cultivation accelerates the loss of organic matter and microbial activities significantly in the soil. Therefore, nutrient uptake must be maintained by nutrient replacement [33]. Former studies have suggested that NUE and grain yield largely depends on the total root length, root biomass and root number owing to the NPK interaction [34–36]. The literature reveals that previous studies were mainly focused on reducing chemical fertilizers and use, particularly of N fertilizers on crop productivity, and predicting qualitative properties [26,29,32]. However, most of the studies failed to consider the comparative assessment of NPK and FYM on root characteristics, particularly root densities and nutrient–soil balance, especially in the vegetable-based cropping sequence. Agricultural trends in the last five decades have intensified production with the increased exercise of commercial seeds, pesticides, fertilizers, etc. [37,38]. The unscientific practices have adversely affected soil health [39]. In the highly dissected landscapes of the Himalayan belt, bioclimatic conditions change rapidly and may vary within short distances resulting in a pronounced heterogeneity of soil types and their chemical and physical properties [31,40], hence influencing crop production sharply [37]. Therefore, this study aimed to explore the effects of chemical fertilizers with FYM on the root characteristics, NUE and NPK status of soil under the cauliflower and capsicum cropping sequence. This study is novel in this field since there is no scientific report available yet on the Indian Northwestern Himalayas comparing the response to integrated nutrient management (INM) on root characteristics and nitrogen use efficiency. Thus, to clarify the hypothesis, the objectives of the study were to access the root characteristics of cauliflower and capsicum under balanced and imbalanced fertilization and to analyze the NPK balance of soil under the cauliflower–capsicum cropping sequence.

## 2. Materials and Methods

### *2.1. Experimental Site*

The field campaign was conducted over two successive years at an experimental farm at the Department of Soil Science and Water Management of Dr. Y S Parmar University of Horticulture and Forestry, Solan at the vegetable-based agroecosystem (cauliflower–capsicum cropping sequence) from October 2019 to August 2021. The experimental farm was located at 30°51′ N latitude and 76°11′ E longitude with an elevation of 1200 m above mean sea level (m asl) and a slope of 7–8%, which falls into the subtropical, subhumid temperate agro-climatic zone of Himachal Pradesh [41]. Annual rainfall of the area is 1100 mm, 75% of which is received from mid-June to mid-September (monsoon) (Figure 1).

According to the soil taxonomy of the United States Department of Agriculture, the soils in the study area belong to typic-eutrochrept and sandy loam in texture. At the initiation of the trial, the values of soil physical properties (at 0–15 cm depth) such as bulk density, saturated hydraulic conductivity ($K_s$), and moisture retention were 1.32 Mg $m^{-3}$, 7.92 cm $h^{-1}$, 25.0 (at 0.33 bar s), and 7.32 (0.15 bar s) percent, respectively. Similarly, the soil chemical properties of the experimental site were given in Table 1 (Table S1).

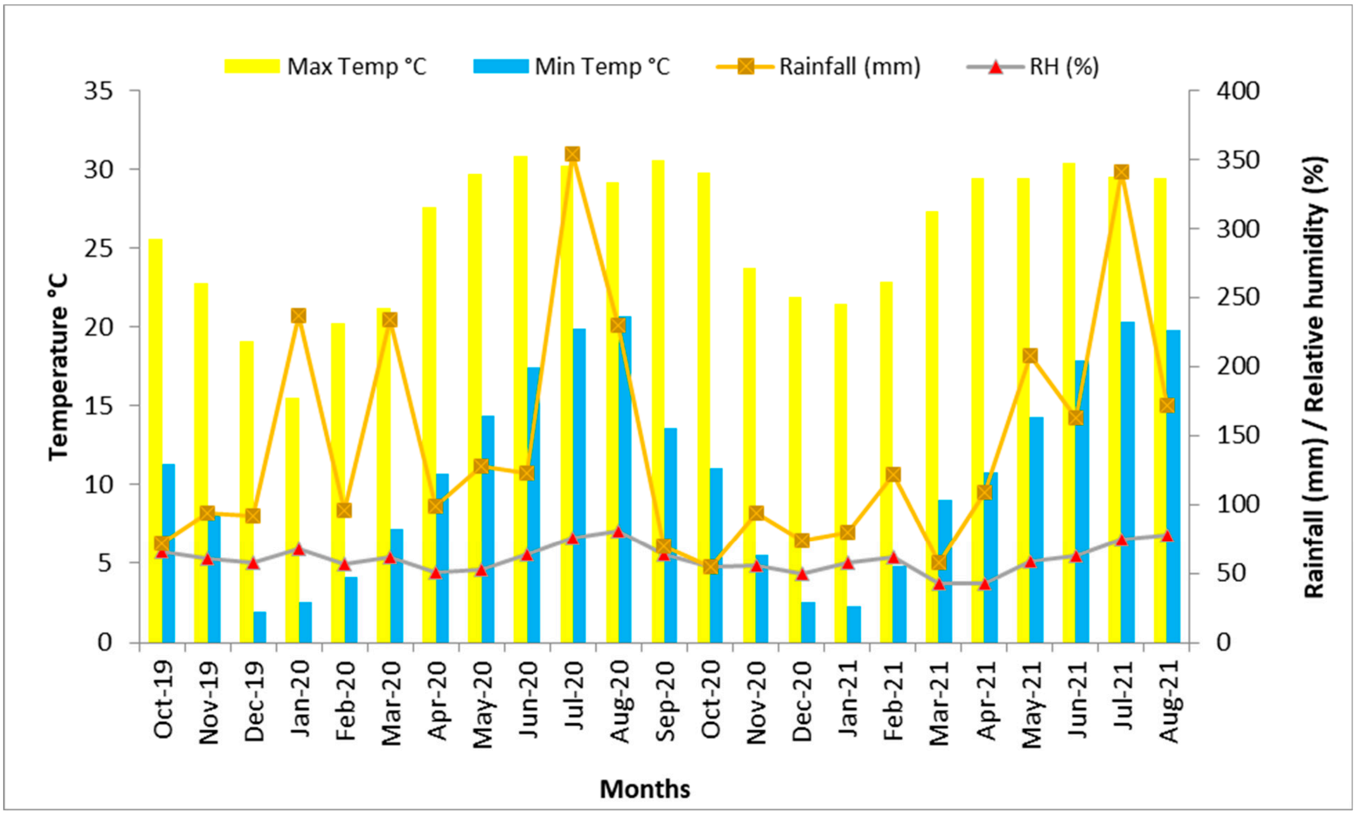



**Figure 1.** Mean monthly temperature (°C), rainfall (mm) and relative humidity (%) during cropping season (Source: Meteorological Observatory, Department of Environment Science, Dr Y S Parmar University of Horticulture and Forestry, Nauni, Solan, HP 173230).

**Table 1.** Physicochemical properties of the experimental site.

| Soil Parameter | Unit | Estimated Value |
|---|---|---|
| pH | Unitless | 6.60 |
| EC | dS $m^{-1}$ | 0.25 |
| OC | g $kg^{-1}$ | 13.10 |
| Available N | kg $ha^{-1}$ | 350.8 |
| Available P | kg $ha^{-1}$ | 98.4 |
| Available K | kg $ha^{-1}$ | 489.4 |
| Available Ca | cmol ($p^+$) $kg^{-1}$ | 12.8 |
| Available Mg | cmol ($p^+$) $kg^{-1}$ | 3.53 |
| Available $SO_4^{2-}$S | kg $ha^{-1}$ | 38.80 |
| Available Fe | Ppm | 15.84 |
| Available Zn | Ppm | 3.05 |
| Available Cu | Ppm | 2.24 |
| Available Mn | Ppm | 14.33 |

### *2.2. Experimental Design and Treatments*

The study was conducted with 9 treatments viz., $T_1$-control (no fertilization), $T_2$-100% FYM (quantity of FYM was calculated on N equivalent basis, i.e., the total recommended dose of N was supplied through FYM), $T_3$-100% N (only 100% recommended dose of N was supplied through chemical fertilizers, i.e., Urea), $T_4$-NP (100% N and P requirements of crops were supplied through chemical fertilizers i.e., urea and single super phosphate, respectively), $T_5$-NK (100% N and K requirements of crops were provided through chemical fertilizers, i.e., urea and muraite of potash, respectively), $T_6$-PK (100% P and K requirements of crops were supplied through inorganic fertilizers, i.e., single supper phosphate and muraite of potash, respectively), $T_7$-NPK (100% recommended dose of NPK was met through inorganic fertilizers), $T_8$-100% NPK + FYM (recommended practice), and $T_9$-150% NPK + FYM replicated thrice in a complete randomized block design in a plot size of 3 m × 2.7 m. A recommended fertilizer dose of 150:100:54 and 100:76:54 kg of N, $P_2O_5$, and $K_2O$ ha$^{-1}$ represented NPK in cauliflower and capsicum, respectively. Application rates for chemical fertilizers and FYM for each treatment have been described in Table 2. The cauliflower (variety: PSBK-1)-capsicum (variety: Kaveri 254- F1) cropping sequence was followed for two years (2019–2021).

**Table 2.** The amount of farmyard manure, urea, single super phosphate, and muriate of potash fertilizers used in different treatments.

| Treatments | Cauliflower (Per Plot) | | | | Capsicum (Per Plot) | | | |
|---|---|---|---|---|---|---|---|---|
| | Farm Yard Manure (kg) | Urea (g) | Single Super Phosphate (g) | Muraite of Potash (g) | Farm Yard Manure (kg) | Urea (g) | Single Super Phosphate (g) | Muraite of Potash (g) |
| $T_1$ (Control) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $T_2$ (100% FYM) | 24.3 | 0 | 0 | 0 | 24.3 | 0 | 0 | 0 |
| $T_3$(100% N) | 0 | 264 | 0 | 0 | 0 | 176 | 0 | 0 |
| $T_4$ (100% NP) | 0 | 264 | 506.3 | 0 | 0 | 176 | 384.8 | 0 |
| $T_5$ (100% NK) | 0 | 264 | 0 | 73 | 0 | 176 | 0 | 73 |
| $T_6$ (100% PK) | 0 | 0 | 506.3 | 73 | 0 | 0 | 384.8 | 73 |
| $T_7$ (100% NPK) | 0 | 264 | 506.3 | 73 | 0 | 176 | 384.8 | 73 |
| $T_8$ (100% NPK + FYM) | 20.3 | 264 | 506.3 | 73 | 20.3 | 176 | 384.8 | 73 |
| $T_9$ (150% NPK + FYM) | 30.4 | 396 | 759.4 | 109.5 | 30.4 | 264 | 577.1 | 109.5 |

### *2.3. Crop Management*

The field was prepared during 2019 by ploughing and then manual tillage operations were done for subsequent trials (cauliflower–capsicum cropping sequence for 2 years), to avoid the soil mixing of different plots. The nine treatments were laid in a randomized block design (RBD) with three replications. Well-decomposed FYM (250 q ha$^{-1}$ recommended dose) was used and had a carbon: nitrogen (C: N) ratio of 58. Chemical fertilizers containing high amounts of NPK were applied as urea, single super phosphate (SSP), and muriate of potash (MOP), respectively. The fertilizers were through broadcasting and mixed in the soil before transplanting. Urea was applied in split doses to avoid N losses.

### *2.4. Sampling and Measurements*

Sampling for root growth parameters, viz. root volume density (RVD), root mass density (RMD), and root length density (RLD), was done at the harvesting stage of the crops. To collect root samples, a sharp-edged iron rod was inserted into the soil profile [42]. Each core was 5.5 cm wide, 15 cm long, and 15 cm deep, which yielded soil cores of those dimensions. The sampling depth was determined by the actual growth of crop roots; the minimum was 30 cm and the maximum was 60 cm. To collect the roots, all the cores were soaked in water overnight, then stirred vigorously and the soil was removed from the roots by washing them with a fine jet of water. The soil suspension was passed through a fine 0.2 mm mesh having a 25 cm diameter and 8 cm depth. RVD was measured by using the displacement method [43], which was calculated using the formula:

$$\text{Root-volume density (RVD; m}^3\ \text{m}^{-3} \times 10^{-3}) = \frac{\text{Volume of roots by displacement method}}{\text{Volume of the core}}$$

After the measurement of root-volume density through the displacement method as described above, the same root samples were then placed, folded, and pressed gently to remove imbibed water. After that roots were cut into pieces and placed in an oven for drying at 60 ± 5 °C until a constant weight. Finally, the dried weight of the roots was taken for the estimation of root-mass density [43].

$$\text{Root-mass density (RMD; g m}^{-3} \times 10^{-3}) = \frac{\text{Dry weight of roots}}{\text{Volume of the core}}$$

Root length (RL) was determined by using a glass-bottom shallow dish of 40 cm × 20 cm dimensions with the help of graph paper ruled in mm placed just below the dish. The wet roots were separated at the root–shoot joint and spread randomly on a disk containing water provide there was no overlapping between the cut pieces. The long-branched roots were cut into smaller pieces. The vertical and horizontal lines of a 1 cm grid were used to count the intersections of roots (Ri) on the graph paper. Care was taken to avoid more than 400 counts in one instance. Root length was computed using the modified version of Newman [44] formula as proposed by Marsh [45] and Tenant [46], as Root length $= \frac{11}{14} \times$ number of intersections (Ri) $\times$ grid unit

$$\text{Root-length density (RLD; cm m}^{-3} \times 10^{-4}) = \frac{\text{Root length}}{\text{Volume of the core}}$$

The agronomic use efficiency of nitrogen ($AE_N$) was calculated by using the Dobermann formula [47]:

$$AE_N\ (\text{kg kg}^{-1}) = \frac{\text{Yield in fertilized plot} - \text{Yield in control plot}}{\text{Amount of Napplied}}$$

The apparent nitrogen recovery ($AR_N$) was calculated by using the following formula:

$$AR_N\ (\%) = \frac{N_f - N_{uf}}{N_a} \times 100$$

where, $N_f$ and $N_{uf}$ were nitrogen accumulation in fertilized and unfertilized plots (kg ha$^{-1}$) and $N_a$ is the amount of N fertilizer applied (kg ha$^{-1}$).

### *2.5. NPK Balance*

The nutrient balance (NPK) in each plot under each treatment was determined by separating the inputs (inorganic fertilizer and FYM) and outputs (nutrient uptakes (NPK) by crops) of the plot. Nutrient balance for NPK was calculated by subtracting nutrient uptakes and nutrient status at the time of harvest from the total nutrients added (initial status of soil nutrients plus added nutrients) to the plots [48]. Nutrient uptake was determined by using the following formula:

$$\text{Nutrient uptake (kg ha}^{-1}) = \{\text{Nutrient content (\%)} \times \text{Dry matter yield (kg ha}^{-1})\}/100$$

$$\text{Nutrient balance} = [\text{Initial Status of soil nutrients (a)} + \text{Nutrient added (b)}] - [\text{Nutrient uptake by crop(c)} + \text{Nutrient status at the time of harvest (d)}]$$

### *2.6. Statistical Analysis*

Data were analyzed as a randomized block design and one-way analysis of variance (ANOVA), as described by Panse and Sukhatme [49] and graphs were prepared by using Microsoft Office (version 2010). For comparing treatment means, the critical difference (CD) was calculated at a 5% level of significance.

## **3. Results**

### *3.1. Root-Mass Density (RMD) of Cauliflower and Capsicum*

The root mass density of cauliflower and capsicum under different treatments has been shown in Figure 2a. Two-year experimental data showed that the root-mass density was significantly influenced only for the second year under cauliflower, whereas under capsicum, it was effectively influenced under both years of study. Root-mass density was gradually improved under the integrated application of inorganic fertilizers (NPK) along with FYM under both crops. During the first year of the study, root-mass density was higher than the control but was statistically found nonsignificant. After one year of study on the complete cropping sequence (cauliflower–capsicum), root-mass density under the second year of cauliflower crop was found to be statistically significant under different treatments and the highest RMD (0.72 g $m^{-3} \times 10^{-3}$) in $T_8$ (100% NPK + FYM) and $T_9$ (150% NPK + FYM), which was statistically at par with $T_2$ i.e., 100 FYM on N equivalence basis (0.68 g $m^{-3} \times 10^{-3}$), $T_5$ i.e., 100% NK (0.69 g $m^{-3} \times 10^{-3}$), and $T_7$ i.e., 100% NPK (0.67 g $m^{-3} \times 10^{-3}$), whereas the lowest RMD was under $T_4$ i.e., 100% NP (0.58 g $m^{-3} \times 10^{-3}$), which was significantly at par with $T_1$, i.e., control (0.63 g $m^{-3} \times 10^{-3}$), $T_3$, i.e., 100% N (0.60 g $m^{-3} \times 10^{-3}$), and $T_6$, i.e., 100% PK (0.62 g $m^{-3} \times 10^{-3}$). Based on pooled data, treatment $T_9$ was recorded with the highest RMD (1.71 g $m^{-3} \times 10^{-3}$), which was significantly at par with $T_6$ (1.62 g $m^{-3} \times 10^{-3}$), $T_7$ (1.63 g $m^{-3} \times 10^{-3}$), and $T_8$ (1.70 g $m^{-3} \times 10^{-3}$), while lowest under the control (1.16 g $m^{-3} \times 10^{-3}$). Year and interaction between treatment and year were insignificant concerning RMD. In general, balanced fertilization could effectively improve the number of roots and further efficient utilization of nutrients to enhance the proliferation of roots.

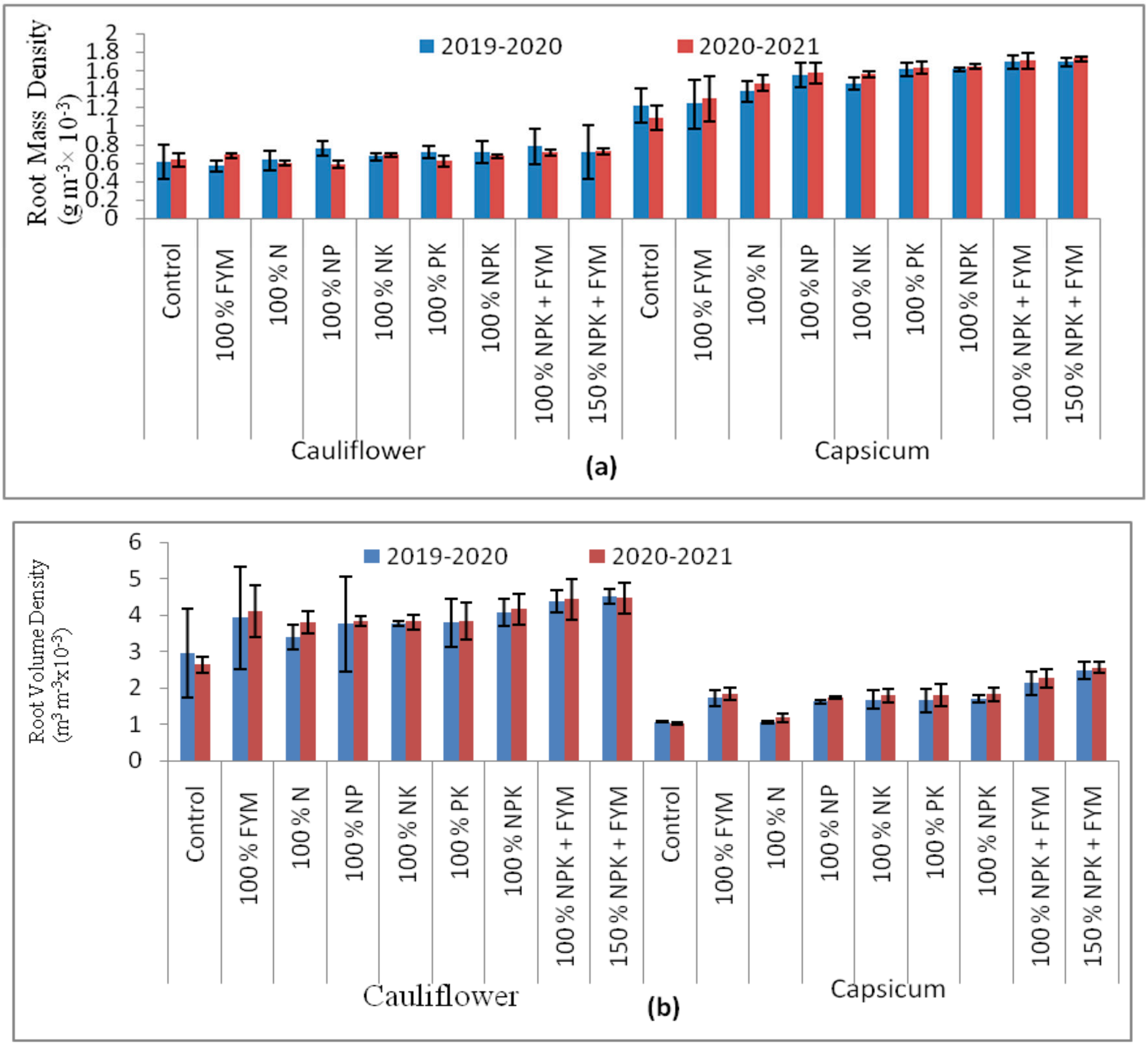



**Figure 2.** *Cont.*

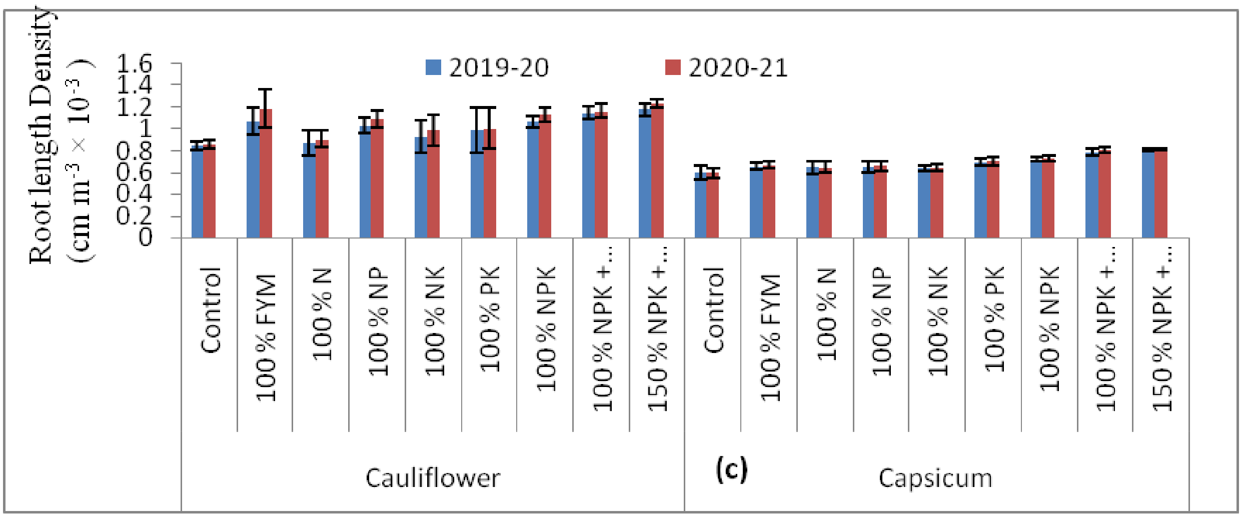



**Figure 2.** Effect of nutrient management on (**a**) Root-mass density (**b**) Root-volume density (**c**) Root-length density of cauliflower and capsicum; error bar indicates the $SE_d$ ± of the treatments.

### 3.2. Root-Volume Density of Cauliflower and Capsicum

Different treatments influenced the root-volume density of cauliflower and capsicum (Figure 2b). The root-volume density of cauliflower was statistically influenced only after one year of fertilization. On pooling of data, it was found that the highest RVD (4.49 $m^3$ $m^{-3}$ × $10^{-3}$ and 2.52 $m^3$ $m^{-3}$ × $10^{-3}$) was noted under treatment $T_9$ (150% NPK + FYM), while the lowest was under $T_1$, i.e., the control (2.79 $m^3$ $m^{-3}$ × $10^{-3}$ and 1.04 $m^3$ $m^{-3}$ × $10^{-3}$) for cauliflower and capsicum, respectively. Treatment $T_9$ was statistically at par with all the treatments except control and 100% N ($T_3$).

### 3.3. Root-Length Density (RLD) of Capsicum and Cauliflower

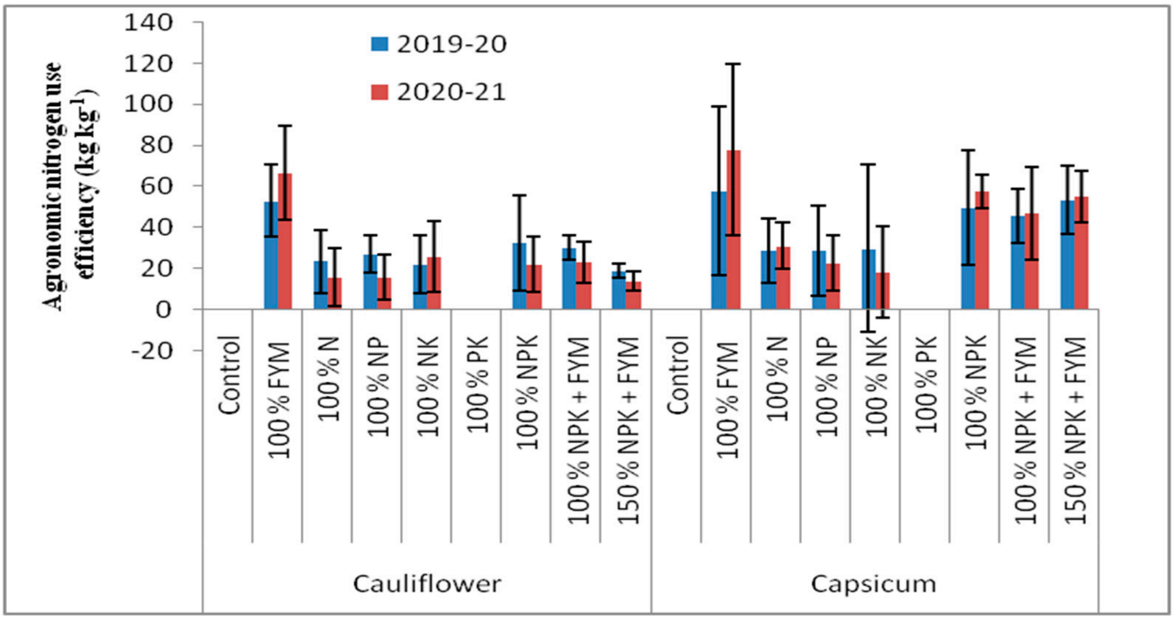
Different treatments significantly influenced the root-length density of cauliflower and capsicum during both the years of study (Figure 2c). The root-length density of both the crops under balanced and imbalanced fertilization was markedly improved over $T_1$ (absolute control). Pooled data analysis showed that the highest RLD was recorded in treatment $T_9$, i.e., 150% NPK + FYM (1.21 cm $m^{-3}$ × $10^{-4}$ in cauliflower and 0.81 cm $m^{-3}$ × $10^{-3}$ in capsicum), while the lowest was under the control (0.85 and 0.60 cm $m^{-3}$ × $10^{-4}$) for cauliflower and capsicum respectively. All the treatments significantly increased the root length density over the control. After two years of fertilization, balanced fertilization increased the RLD by 42.0% and 35% in cauliflower and capsicum respectively, over the control (absolute). In general, the replacement of inorganic fertilization along with the integration of inorganic and organic fertilization could effectively improve the growth of absorbing roots which proliferate more under porous soils with the addition of organic manure. As the addition of organic manure improves, the physical properties of soil, i.e., water holding capacity, soil aggregation, porosity, etc., which are responsible for the growth of absorbing roots; otherwise poor physical status of soil promoted the growth of conducting roots, which became more under deep soil (nonporous).

### 3.4. Agronomic Nitrogen-Use Efficiency ($AE_N$) and Apparent Recovery of Nitrogen ($AR_N$) in Cauliflower and Capsicum

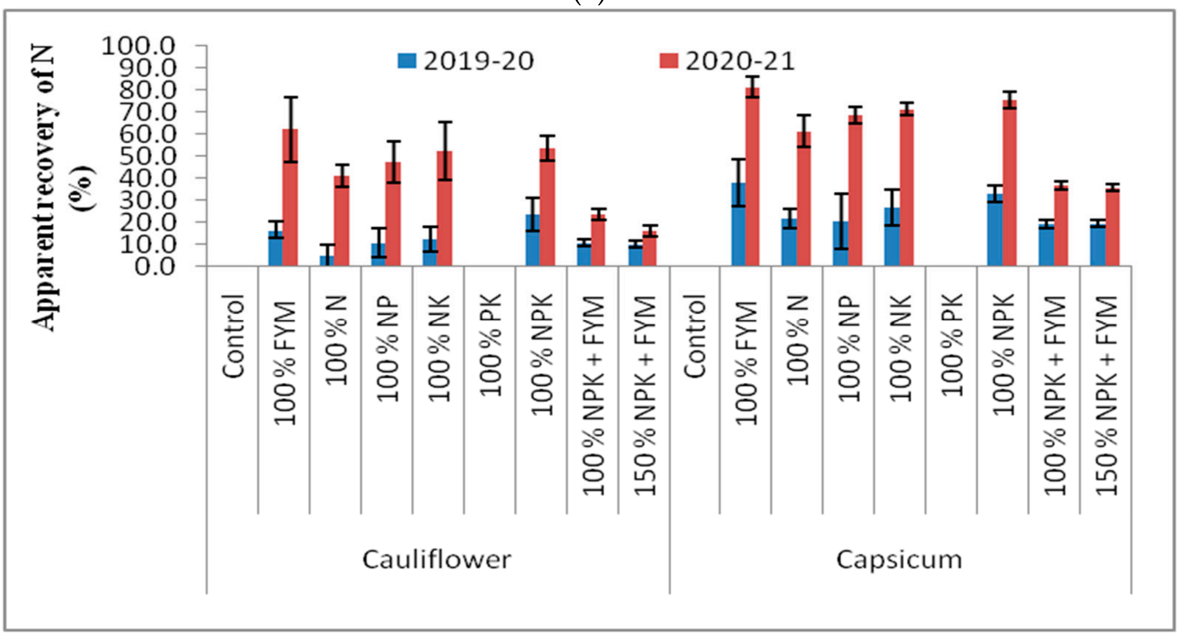
Agronomic nitrogen use efficiency ($AE_N$) was significantly affected under different treatments during both years of study in cauliflower and capsicum (Figure 3a). Treatment $T_2$, i.e., 100 FYM N equivalent basis, was recorded with the highest $AE_N$ (59.9 kg $kg^{-1}$) and the lowest $AE_N$ (16.6 kg $kg^{-1}$) in cauliflower was recorded under $T_9$, i.e., 150% NPK + FYM. Under the capsicum crop, the same treatment ($T_2$) showed significantly higher $AE_N$ (67.9 kg $kg^{-1}$) and the lowest was under $T_5$ i.e., 100% NK (24.2 kg $kg^{-1}$) which was found to be at par with all treatments except 100% FYM N equivalent basis (67.9 kg $kg^{-1}$), 100%

NPK (53.7 kg kg$^{-1}$), and 150% NPK + FYM (54.2 kg kg$^{-1}$). The year and the interaction effect were found to be nonsignificant for both crops.

Different treatments had significant effects on the apparent recovery of nitrogen in cauliflower and capsicum during both the years of study (Figure 3b). Application of sole 100% FYM on N equivalent basis was recorded with the highest apparent recovery of nitrogen in cauliflower (39.3%) and capsicum (59.7%) which was statistically at par with 100% NPK, whereas the lowest apparent recovery of nitrogen (13.0 and 27.6%) was observed under 150% NPK + FYM in cauliflower and capsicum, respectively. The year and the interaction effect between treatment and year were significant for both crops.




(**a**)




(**b**)

**Figure 3.** Effect of nutrient management on (**a**) agronomic nitrogen-use efficiency (**b**) apparent recovery of nitrogen of cauliflower and capsicum. The error bar indicates the $SE_d$ $\pm$ of the treatments.

### 3.5. NPK Balance

Higher NPK was removed from the soil with the application of inorganic fertilizer or no fertilizer application and both resulted in a negative soil–NPK balance (Tables 3–5). A positive NPK balance was found under the coapplication of NPK and FYM. Treatment $T_9$, i.e., 150% NPK + FYM recorded with the highest positive N balance (774.6 kg $ha^{-1}$). There was a negative N balance in all the treatments except 100% N, 100% NPK + FYM, and −150% NPK + FYM. Soil–P balance ranged from −102.2 to 650.4 kg $ha^{-1}$. Treatment T9 was recorded with a maximum positive P balance (650.4 kg $ha^{-1}$). Except for the control, 100% N, and 100% NK, all other treatments were recorded with a positive P balance. Positive P balance might be due to the inactivation of iron, aluminium, and hydroxyl Al ions, thereby reducing the P fixation in soil and building up the P balance. In the case of K balance, all the treatments registered with a negative K balance except $T_8$ 100% NPK + FYM and $T_9$ 150% NPK + FYM, which was ascribed to the imbalanced fertilization.

**Table 3.** Effect of different treatments on N balance (kg $ha^{-1}$) under cauliflower and capsicum (2 cycles).

| Treatments | Initial N Status (a) | N Added | | Total N Added (b) | N Uptake | | Total N Uptake (c) | Soil N Status after Harvest (d) | Actual Gain/ Loss over the Initial (a–d) | N Balance (a + b)–(c + d) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Cauliflower | Capsicum | | Cauliflower | Capsicum | | | | |
| $T_1$ (control) | 350.9 | 0.0 | 0.0 | 0.0 | 230.3 | 116.2 | 346.5 | 298.5 | 52.34 | −294.1 |
| $T_2$ (100% FYM N equivalent basis) | 350.9 | 300.0 | 200.0 | 500.0 | 344.2 | 218.4 | 562.6 | 379.9 | −29.02 | −91.7 |
| $T_3$ (100% N) | 350.9 | 300.0 | 200.0 | 500.0 | 311.3 | 156.5 | 467.8 | 359.7 | −8.79 | 23.4 |
| $T_4$ (100% NP) | 350.9 | 300.0 | 200.0 | 500.0 | 326.3 | 196.0 | 522.2 | 367.3 | −16.42 | −38.7 |
| $T_5$ (100% NK) | 350.9 | 300.0 | 200.0 | 500.0 | 325.3 | 180.3 | 505.6 | 369.9 | −18.99 | −24.6 |
| $T_6$ (100% PK) | 350.9 | 0.0 | 0.0 | 0.0 | 269.2 | 151.0 | 420.3 | 333.6 | 17.31 | −403.0 |
| $T_7$ (100% NPK) | 350.9 | 300.0 | 200.0 | 500.0 | 334.5 | 218.5 | 553.0 | 374.0 | −23.09 | −76.1 |
| $T_8$ (100% NPK + FYM) | 350.9 | 550.0 | 450.0 | 1000.0 | 408.2 | 249.6 | 657.9 | 381.0 | −30.08 | 312.1 |
| $T_9$ 150% NPK + FYM) | 350.9 | 825.0 | 675.0 | 1500.0 | 414.4 | 278.2 | 692.6 | 383.7 | −32.79 | 774.6 |

**Table 4.** Effect of different treatments on P balance (kg $ha^{-1}$) under cauliflower and capsicum (2 cycles).

| Treatments | Initial P Status (a) | P Added | | Total P Added (b) | P Uptake | | Total P Uptake (c) | Soil P Status after Harvest (d) | Actual Gain/Loss over the Initial (a–d) | P Balance (a + b)–(c + d) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Cauliflower | Capsicum | | Cauliflower | Capsicum | | | | |
| $T_1$ (control) | 98.4 | 0.0 | 0.0 | 0.0 | 39.3 | 20.8 | 60.1 | 77.6 | 20.80 | −39.3 |
| $T_2$ (100% FYM N equivalent basis) | 98.4 | 120.0 | 80.0 | 200.0 | 63.4 | 42.4 | 105.9 | 135 | −36.60 | 57.6 |
| $T_3$ (100% N) | 98.4 | 0.0 | 0.0 | 0.0 | 49.6 | 30.6 | 80.3 | 107.4 | −9.00 | −89.3 |
| $T_4$ (100% NP) | 98.4 | 200.0 | 152.0 | 352.0 | 51.0 | 38.8 | 89.8 | 117.3 | −18.90 | 243.3 |
| $T_5$ (100% NK) | 98.4 | 0.0 | 0.0 | 0.0 | 50.4 | 36.8 | 87.1 | 113.5 | −15.10 | −102.2 |
| $T_6$ (100% PK) | 98.4 | 200.0 | 152.0 | 352.0 | 55.4 | 40.3 | 95.7 | 123.9 | −25.50 | 230.8 |
| $T_7$ (100% NPK) | 98.4 | 200.0 | 152.0 | 352.0 | 60.0 | 45.4 | 105.3 | 134.4 | −36.00 | 210.7 |
| $T_8$ (100% NPK + FYM) | 98.4 | 300.0 | 252.0 | 552.0 | 73.3 | 52.5 | 125.8 | 140.2 | −41.80 | 384.4 |
| $T_9$ 150% NPK + FYM) | 98.4 | 450.0 | 378.0 | 828.0 | 75.1 | 57.6 | 132.7 | 143.3 | −44.90 | 650.4 |

**Table 5.** Effect of nutrient management on K balance (kg $ha^{-1}$) under cauliflower and capsicum (2 cycles).

| Treatments | Initial K Status (a) | K Added | | Total K Added (b) | K Uptake | | Total K Uptake (c) | Soil K Status after Harvest (d) | Actual Gain/Loss over the Initial (a–d) | K Balance (a + b)–(c + d) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Cauliflower | Capsicum | | Cauliflower | Capsicum | | | | |
| $T_1$ (control) | 489.4 | 0.0 | 0.0 | 0.0 | 161.5 | 157.9 | 319.4 | 442.8 | 46.60 | −272.8 |
| $T_2$ (100% FYM N equivalent basis) | 489.4 | 150.0 | 100.0 | 250.0 | 263.0 | 252.3 | 515.3 | 564.4 | −75.00 | −340.3 |
| $T_3$ (100% N) | 489.4 | 0.0 | 0.0 | 0.0 | 202.7 | 195.0 | 397.7 | 453.8 | 35.60 | −362.1 |
| $T_4$ (100% NP) | 489.4 | 0.0 | 0.0 | 0.0 | 229.0 | 232.8 | 461.8 | 466.1 | 23.30 | −438.5 |
| $T_5$ (100% NK) | 489.4 | 108.0 | 108.0 | 216.0 | 210.0 | 218.1 | 428.1 | 542.3 | −52.90 | −265.0 |
| $T_6$ (100% PK) | 489.4 | 108.0 | 108.0 | 216.0 | 229.8 | 244.3 | 474.2 | 550 | −60.60 | −318.8 |
| $T_7$ (100% NPK) | 489.4 | 108.0 | 108.0 | 216.0 | 238.8 | 268.6 | 507.4 | 554.8 | −65.40 | −356.8 |
| $T_8$ (100% NPK + FYM) | 489.4 | 358.0 | 358.0 | 716.0 | 316.0 | 311.1 | 627.0 | 560.6 | −71.20 | 17.8 |
| $T_9$ 150% NPK + FYM) | 489.4 | 537.0 | 537.0 | 1074.0 | 327.2 | 334.6 | 661.7 | 565.8 | −76.40 | 335.9 |

### *3.6. Correlation between RMD, RVD, RLD, Soil Chemical Properties, and NPK Uptake*

The relationship among root-mass density (RMD), root-volume density (RVD), and root-length density (RLD) available N, available P, available K, available Ca, available Mg, available sulphate-S, total N uptake, total P uptake, and total K uptake in cauliflower and capsicum were analyzed using regression correlation coefficient (Figures 4 and 5). The correlation matrix showed that the studied parameters were highly correlated to each other at various levels of significance, where the level of significance for different parameters are shown with * at 5%, ** at 0.1%, and *** at 0.01% level of significance. However, root-mass density (RMD) of cauliflower and capsicum was found to be nonsignificantly correlated with available N and available Mg. This might be due to nitrogen and Mg contents enhancing photosynthesis and increasing the accumulation of carbohydrates in the fruits [44]. Higher P availability significantly improves the root-mass density (Figures 4 and 5) which could be ascribed to the increased number, as well as the length of, root hairs [5].

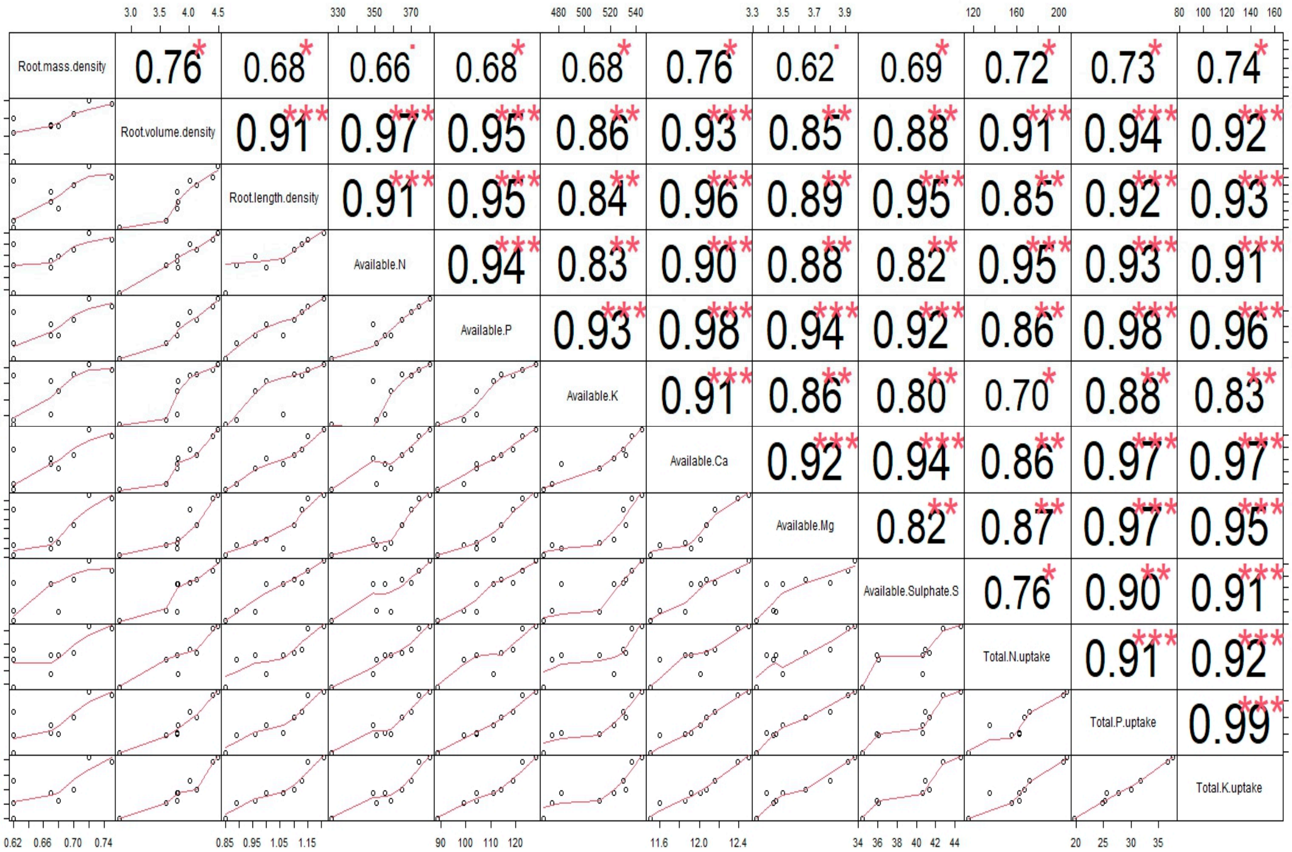



**Figure 4.** Correlation of root-mass density (RMD), root-volume density (RVD), root-length density (RLD), available N, available P, available K, available Ca, available Mg, available sulphate-S, total N uptake, total P uptake, and total K uptake in cauliflower; *, **, and *** represent significant levels of correlation coefficients of $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

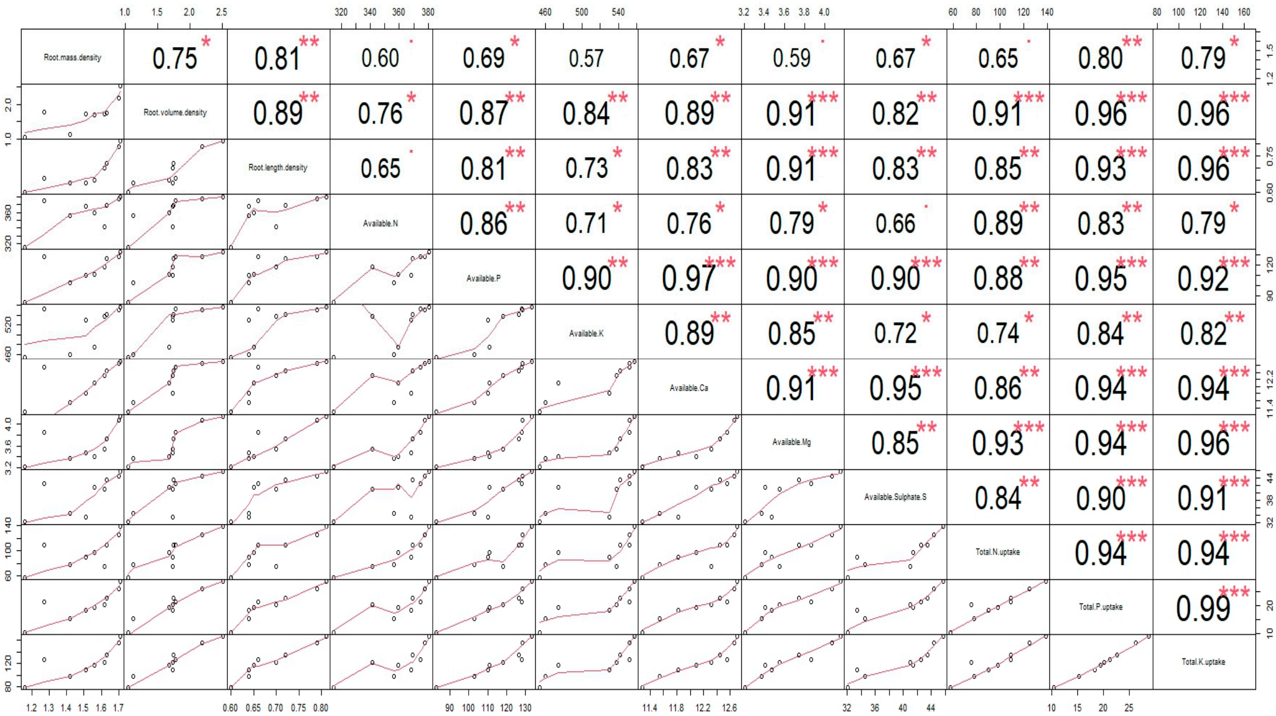



**Figure 5.** Correlation of root-mass density (RMD), root-volume density (RVD), root-length density (RLD), available N, available P, available K, available Ca, available Mg, available sulphate-S, total N uptake, total P uptake, and total K uptake in capsicum. *, **, and *** represent significant levels of correlation coefficients of $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

## 4. Discussion

### *4.1. Effect of Nutrient Management on Root Characteristics of Cauliflower and Capsicum*

The application of NPK fertilizers with FYM improves root growth and development [23]. An increase in root surface area improves the absorption of nutrients which resulted in an increase in root-mass weight [50]. Root-mass density increased with 150% NPK + FYM, which could be due to enhanced nutrition and nutrient availability. Improved RMD with higher P availability (Figures 4 and 5) might be due to the enhanced number, as well as the length of, root hairs. Integrated use of inorganic and organic fertilizers promotes root proliferation and improves the nutrient-use efficiency of crops [6,51]. Du et al., [24] reported that the coapplication of NPK increased the size of the root which was caused mainly by greater root proliferation, branching, and dry-matter accumulation. It is evident that the addition of FYM improves the soil's physical condition, which exhibited low soil resistance to root penetration and enhances the extension, as well as the proliferation, of roots. In addition, improved soil physical properties, viz., temperature, moisture, and aeration under organic-matter addition are essential for root distribution possibly due to the high buffering capacity of organic matter that results in enhanced root-mass, as well as root-volume, densities [51]. Profuse growth of minor roots and root hairs could be another important reason for the upgrading of root volume upon the addition of organic amendments (FYM) [6].

Root-length density (RLD) is a significant parameter for water and nutrient movement in the vadose zone and to study SPAC [23]. Lower RLD under control and 100 percent N might be due to lower available P content, lower organic matter, and high soil strength [6]. Similar results were also reported by Bandopadhyay et al. [51] and Shenggang et al. [52]. Our study showed that positive correlation among root characteristics, soil-nutrient availability, and their uptake (Figures 4 and 5). The lower availability of nitrogen and phosphorus negatively affects the aboveground parts, i.e., leaf area and photosynthetic capacity per unit leaf area, ultimately reducing carbohydrate accumulation for root growth [53].

### *4.2. Effect of Nutrient Management on Agronomic Nitrogen-Use Efficiency and Apparent Recovery of Nitrogen in Cauliflower and Capsicum*

Organic manures such as FYM have been traditionally important inputs for maintaining soil fertility and ensuring yield stability. Organic sources of nutrients are a slow release of fertilizers as these synchronize the plant nutrient demand with respect to time and space with the nutrients supplied from the labile pool and could serve as alternate nutrient sources [54]. Coapplication of NPK had higher NAE chiefly due to enhanced N uptake rather than higher use of the absorbed nitrogen [24]. N uptake potentially influences crop yield and NUE and is a key component of apparent recovery. The results are in agreement with the findings of researchers who worked on various cropping systems [55] in radish, [56] in sweet pepper, and [57] in tomatoes and reported that NUE decreases with increasing rates of N fertilizer. Higher N recovery under NPK along with manure indicates that the manure amendment may promote N absorption from the chemical fertilizer [58]. Our study further demonstrates that the conjoint is a satisfactory choice to improve NUE in the Western Himalayas.

### *4.3. Effect of Nutrient Management on NPK Balance under Cauliflower–Capsicum Cropping Sequence (2 Cycles)*

The combined application of NPK and FYM resulted in a positive NPK balance. The negative balance is due to larger uptake by the crops than in addition [59]. With the judicious application of organic matter, the losses of nutrients through leaching could be reduced, and the united application of organic and inorganic sources can sustain soil fertility and yield [60]. Similar results were also reported by other researchers [48,61–63]. Application of both organic and inorganic sources of nutrients in balance to the crop of sequence, which accumulated higher NPK in soil than consumption [64]; jointly they perform better for higher fertility balance.

## 5. Conclusions

In an extensive cropping system, the integration of inorganic fertilizers with organic manure will not only sustain crop production but also would be effective in promoting root growth and facilitate enhanced water and nutrient-use efficiency. This could significantly improve root growth and efficiency of N, which potentially decreases the fertilizer inputs. Comparing all the treatments, the combined application of NPK and FYM resulted in a positive balance of NPK. Luxury consumption is associated with potassium and results indicated that imbalanced fertilization negatively impacted the K balance. Maximum agronomic N-use efficiency and apparent recovery of N were recorded under 100% FYM (N equivalence) but this resulted in a negative balance of NPK in soil, whereas application of 100% NPK + FYM improved the agronomic use efficiency and apparent recovery of application N, as well as soil NPK balance over the other treatment. Therefore, this integrated nutrient module, i.e., application of 100% NPK + FYM, is recommended to ensure better root growth and positive nutrient balance. It is crucial to optimise the efficiency of nitrogen utilisation by decreasing nitrogen fertiliser input and boosting crop N absorption. This study will assist policymakers in taking into account organic manure in addition to NPK under integrated nutrient management for vegetable production that can be scaled up and widely used by smallholder farmers. This work could further provide a scientific basis for the usage of imbalanced chemical fertilization and recognize the optimum nutrient module, i.e., the combined application of inorganic fertilizers and organic manure for sustainable crop production and soil-health improvement.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151310593/s1, Table S1: Methods followed by the analysis of soil physicochemical properties [65–71].

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and original draft preparation, A.S., D.S. and K.L.G.; Writing-review and editing, A.S., J.C.S., Y.R.S., M.L.V., U.S., R.S.S., D.S. and K.L.G. and H.B.T.; Funding acquisition, M.K. and A.K. All authors have read and agreed to the published version of the manuscript.

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