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Research article

Can site-specific nutrient management improve the productivity and resource use efficiency of climate-resilient finger millet in calcareous soils in India?

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ABSTRACT

Finger millet, an important 'Nutri-Cereal' and climate-resilient crop, is cultivated as a marginal crop in calcareous soils. Calcareous soils have low organic carbon content, high pH levels, and poor structure. Such a situation leads to poor productivity of the crop. Site-specific nutrient management (SSNM), which focuses on supplying optimum nutrients when a crop is needed, can ensure optimum production and improve the nutrient and energy use efficiency of crops. Moreover, developing an appropriate SSNM technique for this crop could offer new insights into nutrient management practices, particularly for calcareous soils. A field experiment was conducted during the rainy seasons of 2020 and 2021 in calcareous soil at Dr. Rajendra Prasad Central Agricultural University, Pusa, India. The experiment consisted of 8 treatments, *viz*. control, nitrogen (N)/phosphorus (P)/potassium (K)-omission, 75 %, 100 %, and 125 % recommended fertilizer dose (RFD), and 100 % recommended P and K + 30 kg ha^{-1} N as basal + rest N as per GreenSeeker readings. From this study, it was observed that the GreenSeeker-based SSNM resulted in the maximum grain yield (2873 kg ha^{-1}), net output energy (96.3 GJ ha^{-1}), and agronomic efficiency of N (30.6 kg kg^{-1}), P (68.9 kg kg^{-1}), and K (68.9 kg kg^{-1}). The application of 125 % RFD resulted in ~7 % lower yield than that under GreenSeeker-based nutrient management. Approximately 12 % greater energy use efficiency and 21–36 % greater nutrient use efficiency were recorded under GreenSeeker-based nutrient management than under 125 % RDF. The indigenous supplies of N, P, and K were found to be 14.31, 3.00, and 18.51 kg ha^{-1}, respectively. Thus, 100 % of the recommended P and K + 30 kg ha^{-1} N as basal + rest N according to GreenSeeker readings can improve the yield, nutrient use efficiency, and energy balance of finger millet in calcareous soils.

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1. Introduction

India is considered the largest producer of different types of millet crops. Finger millet [*Eleusine coracana* (L.) Gaertn.] accounts for approximately 85 % of all minor millets produced in India [1]. The area and production of this crop stand just after those of rice, wheat, maize, sorghum, and pearl millet [2]. Approximately 1.98 million tons (Mt) of finger millet are produced in 1.19 million hectares (Mha) of the area, with a productivity of 1661 kg per hectare (kg ha^{-1}) [3]. The productivity of the crop in the calcareous soils of Bihar is much lower (~994 kg ha^{-1}). The low productivity of this crop in calcareous soils is primarily due to imbalanced nutrient management. Growers often concentrate on applying nitrogenous fertilizers while neglecting the balanced application of other essential nutrients [4]. Hence, a suitable nutrient management approach must be developed to increase the productivity and efficiency of the inputs used for this crop in calcareous soils. The primary aim of this study was to create customized nutrient management strategies tailored to SSNM to enhance productivity and optimize nutrient and energy utilization for finger millet cultivation. Additionally, this study sought to validate nitrogen scheduling for finger millet crops by utilizing normalized difference vegetation index (NDVI) measurements obtained from GreenSeeker readings.

Finger millet is a nutrient-rich crop that is also known as Nutri-Cereal. It contains approximately 7.3 % protein, a low-fat content of approximately 1.3 %, and 3.6 % crude fibre [5]. It also holds an exceptionally high amount of calcium (344 mg 100 g^{-1}) and a considerable amount of iron (3.9 mg 100 g^{-1}) in its grain [6]. In dairy and cattle feedings, finger millet straw is one of the most common feedstuffs [7]. Moreover, crops can grow in a broad range of soils and climates, and crops are generally less affected by different pests and diseases [8]. Its ability to adapt to a wide range of climates makes this crop a certain crop under uncertain climates. All of these factors make this crop a potential substitute for climate-resilient crops under natural disaster conditions such as drought. In addition, finger millet is a C_4 plant that sequesters carbon more efficiently, thereby allowing CO_2 abatement, which is also beneficial to the environment [9]. Therefore, this crop has become an automatic choice in dry farming systems [10].

Despite having many benefits, this crop is cultivated with the least amount of care as a marginal crop in India. Maitra et al. [11] stated that crops are generally considered low-fertilizer input crops for small farmers who live on subsistence farms, and these crops exhibit low yields under poor nutrient management. As a result, the actual potential of the crop has yet to be explored by Indian farmers. This situation necessitates the development of appropriate nutrient management practices for this crop. The low nutrient use efficiency and environmental pollution associated with imbalanced nutrient management practices are major concerns about present-day nutrient management practices [12,13]. The recovery efficiencies for nitrogen (N), phosphorus (P), and potassium (K) are roughly 20–30 %, 15–20 %, and 30–40 %, respectively. In contrast, the recovery efficiencies for secondary nutrients and micronutrients are much lower, ranging from 3 to 8% [14]. Moreover, most current farmer fertilization approaches do not focus on available soil nutrients or target crop yields [15–17]. As a result, a substantial yield gap for most crops is frequently observed in Indian agriculture [4,18]. In this context, the site-specific nutrient management (SSNM) method might be a plausible way to reduce the present wide yield gap [19]. The SSNM approach emphasizes supplying crop nutrition exactly when the crop needs that nutrient. This approach focuses on balanced nutrient application based on crop needs considering the indigenous nutrient supply from the soil [20]. Moreover, several previous studies on the nutrient management of finger millet reported that the adoption of proper nutrient management practices can improve the yield of this crop. Dass et al. [21] reported that integrated nutrient management (INM) increased the grain yield of finger millet plants by 25 %. Hatti et al. [22] reported that the application of a 100 % recommended dose of NPK combined with FYM markedly boosted the grain and straw yields of finger millet. All of these previously published reports indicate the importance of nutrient management for this crop to achieve better yields. The calcareous soils of Bihar contain a relatively high amount of calcium carbonate ($CaCO_3$), a low amount of soil organic matter, high electrical conductivity (EC), and alkaline soil reactions, resulting in a significant impact on N loss as well as a reduction in the solubility and availability of both K and P [23–25]. Under such conditions, nutrient management using SSNM is beneficial because it facilitates nutrient supply to the crop when needed considering the indigenous soil nutrient supply. Pramanick et al. [4] reported that, compared with chemical practices, SSNM can improve the system yield of maize-based cropping systems by 10–12 %. They also reported that SSNM can improve overall soil health and nutrient use efficiency compared to those under farmers' practices. SSNM can be achieved using modern tools such as GreenSeeker and leaf colour charts (LCCs) [4]. There is no such literature available on SSNM for finger millet, especially in calcareous soils. This study was carried out to narrow this existing research gap.

Energy-efficient crop cultivation is also currently a primary concern [26,27]. Crop production strategies must be designed in such a way that they can be more energy efficient. A better energy use efficiency in crop production leads to environmental and economic sustainability [28]. Increased input energy in crop production through increased chemical fertilization without considering the soil nutrient supply further augments the cost of cultivation, making this a major concern for policymakers. Implementing balanced fertilizer applications for effective nutrient management can reduce the energy input necessary for crop production. This method not only guarantees crop yield but also boosts the energy efficiency of the entire process. Finger millet, which is inherently energy efficient, generates more output energy (in the form of biomass production) per unit of input energy. Additionally, enhancing crop cultivation energetics through appropriate nutrient management practices would offer further advantages.

With these considerations in mind, the present study hypothesized that SSNM using GreenSeeker-based NDVI readings could improve the yield, nutrient use efficiency, and overall energetics of finger millet cultivation in calcareous soils. Therefore, this research aimed to create an optimal SSNM tailored for finger millet plants, aiming to boost both the production and efficiency of input use, specifically in calcareous soils.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted at the Crop Research Center, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar, India (25°59'N, 85°40'E, 52.9 m above MSL), during two consecutive rainy seasons, 2020 and 2021. The soil at the experimental site was sandy and loose in texture and was within the soil taxonomical class and typic calciorthent. The initial nutrient status of the soil (0–15 cm depth) is presented in Table 1. The study area has a subtropical humid climate with a mean annual rainfall of 1400 mm. The mean monthly temperature ranged from 33.8 °C in August to 26.7 °C in November 2020, while in 2021, the mean monthly temperature ranged from 33.9 °C in August to 26.2 °C in November. During the experimental period, 1035 and 1144 mm of rainfall occurred in 2020 and 2021, respectively. The rainfall was the highest in July and the lowest in October. The relative humidity varied from 96 % to 58 % during the study period.

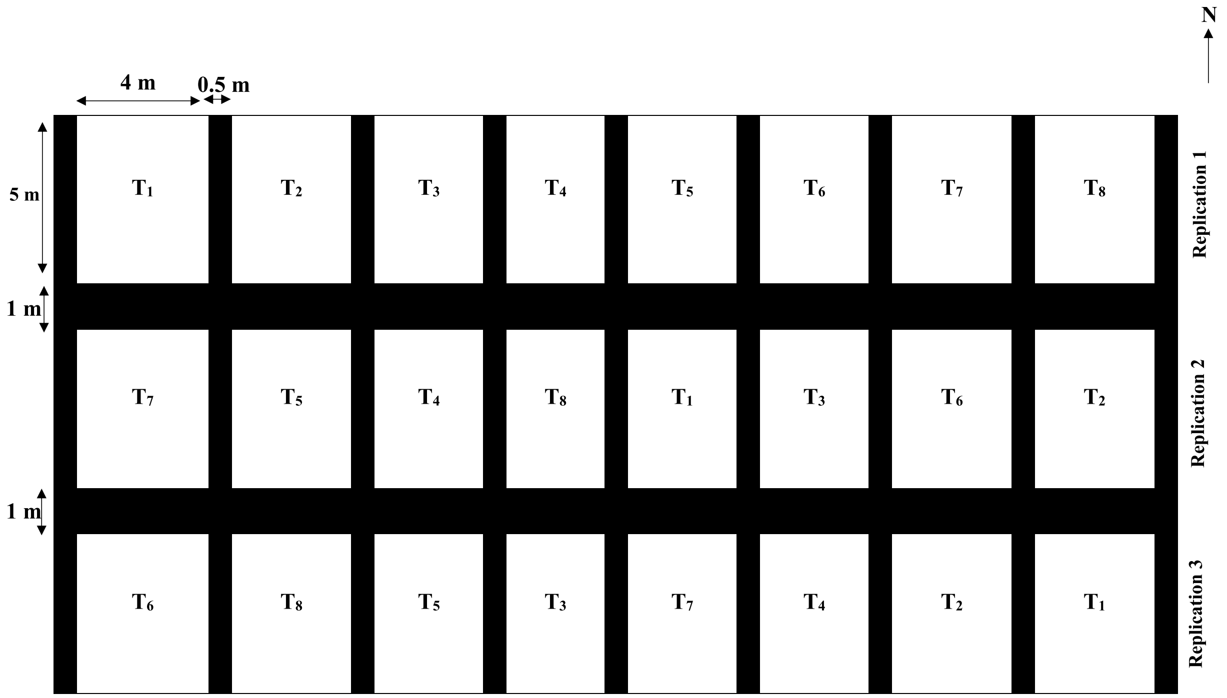
2.2. Treatment details

The experiment was conducted with 8 treatments replicated three times under a randomized complete block design during both years of the study, *viz*. 2020 and 2021. The layout of the study is presented in Fig. 1. The treatment details are as follows: T_1 – Control (no application of fertilizers); T_2 – N-omission (application of recommended P and K fertilizers); T_3 – P-omission (application of recommended N and K fertilizers); T_4 – K-omission (application of recommended N and P fertilizers); T_5 – 75 % recommended fertilizer dose (RFD); T_6 – 100 % RFD; T_7 – 125 % RFD; T_8 – 100 % recommended P and K (RD_{PK}) + 30 kg ha^{-1} N as basal + rest N as per GreenSeeker-reading. Table 2 provides a brief description of the treatments. A control treatment (no application of fertilizers) was included to determine the nutrient use efficiencies. N, P, and K omission treatments were taken in this study to determine the indigenous supply of these nutrients to the crop for producing biomass and yield. The RFD varied from 75 % to 125 % to assess the response of the crop in different fertilizer levels. In this experiment, GreenSeeker-based nitrogen management was employed to evaluate whether this site-specific nutrient management (SSNM) technique could effectively enhance nitrogen management, thereby improving crop growth and yield. The RFD of finger millet is 60 kg ha^{-1} N, 30 kg ha^{-1} P, and 30 kg ha^{-1} K [29]. Full amounts of P and K fertilizers were applied at the time of sowing. Then, 50 % of the N fertilizer was applied as basal fertilizer, and the remaining 50 % of the N fertilizers were top dressed in two equal splits during the active tillering and flowering stages of the crop. The sources of the N, P, and K nutrients were urea, single superphosphate, and muriate potash, respectively. In the case of T_8, 30 kg ha^{-1} N fertilizer was applied as basal fertilizer, and the remaining N fertilizers were applied as per the GreenSeeker reading. GreenSeeker (Trimble, Inc.) is an optical sensor that measures two wavelengths of reflected light. The first is in the visible region (660 nm), and the second is in the near-infrared region (770 nm). Spectral reflectance is measured with spectral vegetation indices such as the normalized difference vegetation index (NDVI). The sensor angle was adjusted such that it was 70 cm above the height and parallel to the sensing area. The green seeker's trigger was pressed consistently when moving in the crop rows and released after finishing one plot (nonreference area). The calculation of the NDVI involved assessing the intensity of the reflected light from the target using the photodiode detector located within the sensor. The same process was followed for the high-N reference area (sufficiency plot with 200 % RFD). The sufficiency plot was constructed separately from the data used in this study to validate the GreenSeeker reading and to estimate the precision of the N requirement for the crop. The process was performed from 25 days after sowing to the reproductive stage of the crop. GreenSeeker readings (normalized difference vegetation index [NDVI]) were taken at 3-day intervals for the T_8 and sufficiency plots to monitor frequently whether the crop was facing any stresses due to lack of nitrogen. Afterward, these values, which included the days from sowing when the NDVIs were taken, the NDVIs from the sufficiency plot, and the treated plot (T_8), were fitted to the Oklahoma State University Sensor-based Nitrogen Rate Calculator (https://nue.okstate.edu/SBNRC/mesonet.php; accessed on 03 August 2023). Based on the sensor-based N rate calculation, 37.5 kg ha^{-1} of N was needed for finger millet in addition to the basal application of 30 kg ha^{-1} N. An additional 37.5 kg of N was applied as follows: 14.5 kg at 28 DAS, 15 kg at 55 DAS, and 8 kg at 70 DAS. Thus, a total of 67.5 kg ha^{-1} N was applied in the T_8 treatment. The area of each plot was 20 m^2 (5 m length × 4 m width). Omission plots were used to determine the indigenous nutrient supply and yield response of the fertilizers applied to the study soil to determine the fertilizer dose for the crop.

The indigenous nutrient supply was estimated according to the formula given by Witt and Dobmann [30]:

Table 1
Initial physical and chemical status of the experimental soil at 0–15 cm depth.

Parameters	Value	Interpretation	Analytical method
Bulk density (Mg m^{-3})	1.42	–	Core sampler [35]
pH (1:2-soil:water)	8.20	Alkaline	Beckman's pH meter [32]
Organic carbon (g kg^{-1})	4.2	Low	Walkley and Black method [33]
Available N (kg ha^{-1})	241	Medium	Alkaline permanganate method [34]
Available P (kg ha^{-1})	13.8	Medium	Olsen's method [32]
Available K (kg ha^{-1})	128	Low	Neutral normal ammonium acetate method [32]
Free $CaCO_3$ (%)	32.3	Calcareous	Chromic acid wet oxidation method [33]



T_1 – Control (no application of fertilizers); T_2 – N-omission (application of recommended P and K fertilizers); T_3 – P-omission (application of recommended N and K fertilizers); T_4 – K-omission (application of recommended N and P fertilizers); T_5 – 75% recommended fertilizer dose (RFD); T_6 – 100% RFD; T_7 – 125% RFD; T_8 – 100% recommended P and K (RD_{PK}) + 30 kg ha^{-1} N as basal + rest N as per GreenSeeker-reading

Fig. 1. Layout of the experiment.

Table 2
Brief description of the treatments.

Treatments	Brief description
T_1: Control	No nutrients were applied
T_2: N omission	30 kg ha^{-1} of P and K were applied
T_3: P omission	60 kg ha^{-1} of N, and 30 kg ha^{-1} of K were applied
T_4: K omission	60 kg ha^{-1} of N and 30 kg ha^{-1} of P were applied
T_5: 75 % Recommended fertilizer dose (RFD)	45 kg ha^{-1} of N 22.5 kg ha^{-1} of P and K were applied
T_6: 100 % RFD	60 kg ha^{-1} of N, 30 kg ha^{-1} of P and K were applied
T_7: 125 % RFD	75 kg ha^{-1} of N, 37.5 kg ha^{-1} of P and K were applied
T_8: 100 % RD_{PK} + 30 kg ha^{-1} N + GS	30 kg ha^{-1} of N, P, and K were applied as basal; the rest N (37.5 kg ha^{-1}) was applied as per the GreenSeeker-reading

$$INS = NU_{N\text{- omission}};\ IPS = NU_{P\text{- omission}};\ IKS = NU_{K\text{- omission}} \ldots \qquad \text{(Eq. 1)}$$

where INS denotes the indigenous nitrogen supply; $NU_{N\text{-omission}}$ denotes N uptake by crops with N omission; IPS is the indigenous phosphorus supply; $NU_{P\text{-omission}}$ is P uptake by crops with P omission; IKS is the indigenous potassium supply; and $NU_{K\text{-omission}}$ is K uptake by crops with K omission.

The yield response to fertilizer (YRF) was computed by the following formula by Xu et al. [31]:

$$YRF = GY_{RFD} - GY_{OT} \ldots \qquad \text{(Eq. 2)}$$

where GY_{RFD} = Grain yield with 100 % RFD; GY_{OT} = Grain yield with N, P or K-omission plots.

2.3. Soil sampling and analysis

Soil samples were collected randomly from four locations within each plot of the experiment, following a zig-zag pattern after the completion of the study. After thorough mixing, a quarter of the combined samples from each plot were retained for further processing.

Bulk samples from all plots were processed according to specified parameters. Soil chemical properties were analyzed based on samples collected at a depth of 0–15 cm. After 30 min of equilibrium, the soil pH was measured using a microprocessor-based pH meter in a 1:2.5 soil-to-water ratio [32]. Following the Walkley and Black [33] rapid-titration method with orthophosphoric acid, potassium dichromate, sulfuric acid, and sodium fluoride, the soil organic carbon was evaluated and recorded. Available (mineralisable) nitrogen in the soil was determined by using the alkaline permanganate ($KMnO_4$–N) method [34]. Phosphorus estimation was done by using sodium bicarbonate as an extractant [32]. Colour development was measured using a UV-VIS double beam spectrophotometer (Systronics India Pvt. Ltd., Ahmedabad, India) at 720 nm wavelength with known standards. Available potassium (exchangeable + water-soluble K) in soil was determined by using a neutral normal ammonium acetate solution using a Flame photometer (Systronics India Pvt. Ltd., Ahmedabad, India [32].

2.4. Crop management

The crop, finger millet, was sown on 15 July for both years of the study. The variety of finger millet used was RAU-8. This variety is well accepted by the farmers in the study area. The certified seeds of RAU-8 were procured from the Directorate of Seed, RPCAU, Pusa. The spacing was 25 cm from row to row and 10 cm from plant to plant. The seed rate of the crop was 12 kg ha^{-1}. The crop was harvested on 8 November 2020 and 10 November 2021. Finger millet is a hardy crop that is affected by insects and diseases. Therefore, no plant protection measures were needed during either year of study. To control weeds within the study area, two manual hand-weeding sessions were conducted: the first at 15 days after sowing (DAS) and the second at 35 DAS. The crop received sufficient rainfall during both years. Thus, no irrigation was provided. Rather, a proper drainage operation was performed to remove the excess water during July and August for successful crop establishment.

2.5. Growth, yield, and yield attributing characters

Growth parameters, *viz*. The plant height, dry matter accumulation, and crop growth rate (CGR) were recorded in this study. Plant height (cm) and dry matter accumulation (g m^{-2}) were recorded at the time of harvesting. The height of the plant was measured from the base of the plant to the topmost part of the plant using a ruler. To measure dry matter accumulation, aboveground plant parts were collected from a 1 m^{-2} area and subsequently air-dried at 70 °C in an oven. Afterward, the dried plant samples were weighed, and the data were recorded. The CGR was measured from 60 to 90 DAS. Dry matter accumulation at 60 DAS and 90 DAS was recorded, and the CGR was estimated using Eq. (3):

$$CGR = \frac{Dry\ matter\ accumulation\ at\ 90\ DAS - Dry\ matter\ accumulation\ at\ 60\ DAS}{30} \qquad \text{(Eq. 3)}$$

The yield-attributing characteristics, *viz*. The number of productive tillers m^{-2}, number of ear heads $plant^{-1}$, number of fingers per ear $head^{-1}$, finger length, weight of grains per ear $head^{-1}$ (g), and test weight (g) were recorded at the time of harvest. The crop was harvested from the net plot area of each treatment. After harvesting, the crop was sundried for 3 days, after which the plants were threshed and manuallywn. The yield of the crop was recorded at a 14 % moisture level.

2.6. Nutrient uptake and use efficiencies

Plant samples were collected from each plot at the time of harvesting and these samples were dried at 70 ± 2 °C for 24 h. The dried plant samples were ground for analysis of nitrogen (N), phosphorus (P), and potassium (K) following the standard methods. The total nitrogen content (%) in the tuber was determined by modified Macro Kjeldahl's method [32]. For P and K content (%) analysis, plant samples were digested using a tri-acid mixture (HNO_3:H_2SO_4:$HClO_4$, 9:1:4) for 2 h. Determination of P content was done spectrophotometrically as the yellow phospho-vanado-molybdate complex [32]. Ammonium molybdate–ammonium metavanadate reagent, 5 M HCl, P stock standard solution (100 ppm of P), and P working standard solution (0, 10, 20, 30, 40, and 50 ppm of P) were used to determine P content. 5 ml of both 5 M HCl and ammonium molybdate–ammonium metavanadate reagent was mixed with 10 ml of each P working standard solution followed by dilution to 50 ml to prepare standard graph of P. Then P absorbance was recorded at 470 nm wavelengths with the help of the UV-VIS spectrophotometer. P absorbance in the plant sample was determined by comparing it with the previously made standard P curve. The filtrate aliquot after wet digestion was taken and the K content (%) was determined using a Flame photometer [32]. Nutrient uptake was estimated by multiplying the nutrient content of grain or straw by the respective yield. Nutrient use efficiencies were measured in terms of agronomic efficiency (AE), partial factor of productivity (PFP), internal efficiency (IE), partial nutrient budget (PNB), and recovery efficiency (RE) according to the following formula [36]:

$$\text{Agronomic efficiency } (kg\ kg^{-1}) = \frac{\text{Grain yield in treated plot} - \text{Grain yield in control plot}}{\text{Applied NPK}} \qquad \text{(Eq. 4)}$$

$$\text{Recovery efficiency } (kg\ kg^{-1}) = \frac{\text{Nutrient uptake in treated plot} - \text{Nutrient uptake in control plot}}{\text{Applied NPK}} \qquad \text{(Eq. 5)}$$

$$\text{Internal efficiency } (kg\ kg^{-1}) = \frac{\text{Grain yield in treated plot}}{\text{Nutrient uptake in treated plot}} \qquad \text{(Eq. 6)}$$

$$\text{Partial factor productivity } \left(\text{kg kg}^{-1}\right) = \frac{\text{Grain yield in treated plot}}{\text{Applied NPK}} \quad \text{(Eq. 7)}$$

$$\text{Partial nutrient budget } \left(\text{kg kg}^{-1}\right) = \frac{\text{Nutrient uptake in treated plot}}{\text{Applied NPK}} \quad \text{(Eq. 8)}$$

Agronomic efficiency indicates the efficiency of applied nutrients in increasing the yield of a crop, while recovery efficiency indicates nutrient recovery by the crop over nutrient uptake per unit of nutrient applied. To estimate agronomic efficiency and recovery efficiency, the control plot, which received no external crop nutrients, was considered. The enhancement in yield or nutrient uptake due to the applied nutrients was then assessed. Such metrics clearly indicate the benefits of applied nutrients. Internal efficiency signifies the inherent capacity of a crop to produce biomass per unit of nutrient intake. The partial factor productivity denotes the yield per unit nutrient applied, while the particle nutrient budget accounts for the gains and losses of nutrients in an agricultural system. All these efficiency metrics are widely used for the agronomic study on nutrient management to find out the efficiency of applied nutrients to produce crop biomass and yield. One of the focal objectives of this study was to evaluate the nutrient use efficiency of various nutrient management strategies for finger millet. Therefore, these metrics were carefully considered.

2.7. *Energy utilization, balance, and productivity*

Table 3 represents the energy equivalents to all the inputs used in this study for both the years as well as the energy equivalents of the output of the study, i.e., grain and straw yield. The input energy was estimated by using these energy equivalents, as suggested by several researchers. The gross output energy was calculated by adding the output energy of the grain and straw. Other energy indices, *viz*. Net output energy, energy use efficiency, and energy productivity were estimated according to the following formulae [22]: energy use efficiency denotes the magnitude of efficient use of input energy, while energy productivity indicates biomass production per unit of energy used.

$$\text{Net output energy (GJ ha}^{-1}) = \text{Gross output energy (GJ ha}^{-1}) - \text{Input energy (GJ ha}^{-1}). \quad \text{(Eq. 9)}$$

$$\text{Energy use efficiency } (\%) = \frac{\text{Gross output energy } \left(\text{GJ ha}^{-1}\right)}{\text{Input energy } \left(\text{GJ ha}^{-1}\right)} \quad \text{(Eq. 10)}$$

$$\text{Energy productivity } \left(\text{kg GJ}^{-1}\right) = \frac{\text{Grain yield} + \text{straw yield } \left(\text{kg ha}^{-1}\right)}{\text{Input energy } \left(\text{GJ ha}^{-1}\right)} \quad \text{(Eq. 11)}$$

2.8. *Statistical analysis*

The data on different growth parameters, yield attributing characters, and yield of finger millet were collected at the time of harvest in each year of the study. Data on nutrient uptake were estimated in the laboratory after analyzing the nutrient content. Data on soil parameters were recorded after the completion of the two years of the study. All the data were statistically analyzed using analysis of variance (ANOVA) for RCBD as described by Gomez and Gomez [42]. The statistical software SAS v9.4 (SAS, Inc., North Carolina, USA) was used to analyze all the data. Pooled analysis was performed after performing Bartlett's chi-square test. Bartlett's chi-square test was performed to analyze the homogeneity of the variance. Then, pooled analysis was performed because the error variance was homogeneous. The least significant difference (LSD) test at the 5 % probability level was used for pairwise comparisons of the mean data. SigmaPlot v13.0 software (Systat Software, Inc.) was used to construct all the graphs presented in this research paper.

Table 3
Energy equivalents for various inputs and output products in the study.

Particulars	Unit	Energy equivalents (MJ h^{-1})	References
Adult male	Manpower h^{-1}	1.96	Soni et al. [36]
Adult female	Womanpower h^{-1}	1.60	Soni et al. (2013) [36]
Cultivator	h	3.135	Nassiri and Singh (2009) [37]
Tractor	h	64.80	Devasenapathy et al. (2009) [38]
Sprayer	h	0.502	Nassiri and Singh (2009) [37]
Diesel	L	56.30	Nassiri and Singh (2009) [37]
N fertilizer	kg	60.60	Kuswardhani et al. (2013) [39]
P fertilizer	kg	11.10	Chaudhary et al. (2009) [40]
K fertilizer	kg	6.70	Chaudhary et al. (2009) [40]
Finger millet grain	kg	14.7	Tuti et al. (2012) [41]
Finger millet straw	kg	12.5	Tuti et al. (2012) [41]

3. Results

3.1. Growth

The different nutrient management practices influenced the growth parameters of the finger millet plants (Table 4). The highest values of plant height, dry matter accumulation, and crop growth rate (CGR) were recorded with 100 % RD_{PK} + 30 kg ha^{-1} N + GreenSeeker (T_8). Plant height, the accumulation of dry matter, and the CGR were enhanced significantly through the application of nitrogen, as per the GreenSeeker readings, along with 100 % P and K (T_8) over the application of 100 % RFD. The application of 125 % RFD and 100 % RD_{PK} + 30 kg ha^{-1} N + GreenSeeker (T_8) had similar effects on all the growth parameters. However, in the T8 treatment, approximately 2–3% more growth occurred in terms of plant height, and dry matter accumulation exceeded 125 % of the RFD. In the T_8 treatment, approximately 6 % more dry matter accumulated than in the 100 % RDF treatment for finger millet. The greatest reductions in plant height, dry matter accumulation, and CGR were also observed in the N-omission treatment group compared to the P or K-omission treatment group.

3.2. Yield and yield-attributing characters

The yield-related characteristics and finger millet yields varied significantly with the application of the different nutrient management treatments (Table 5). The highest numbers of productive tillers $plant^{-1}$ (95), ear head $plant^{-1}$ (5.16), finger ear $head^{-1}$ (4.13), finger length (6.87), grain weight ear $head^{-1}$ (1.74), test weight (2.28), economic yield (2873 kg ha^{-1}) and byproduct yield (4933 kg ha^{-1}) were found under the T_8 treatment (100 % RD_{PK}+30 kg ha^{-1} N + GreenSeerker). Among the treatments, T_8 and T_7 (125 % RFD) were found to have similar yield-related characteristics and yields. Among the different yield-attributing characteristics of the crop, the numbers of productive tillers $plant^{-1}$ and ear hears $plant^{-1}$ were influenced most by the application of different nutrient management practices. The application of N through GreenSeeker reading (T_8) resulted in approximately 8, 7, 10, 6, 9, and 3 % more productive $tillers^{-1}$, ear head $plant^{-1}$, finger $head^{-1}$, finger length, grain weight ear $head^{-1}$, and test weight, respectively than those under the application of 100 % RFD. Concerning the grain yield and straw yield of the crop, the application of 25 % more RFD did not significantly increase the yield of finger millet compared to the yield under 100 % RFD. However, the smart application of N according to the GreenSeeker reading (T_8) resulted in a significant improvement in yield of more than 100 % of the RFD, with approximately 12 and 21 % greater grain and straw yields, respectively, than 100 % of the RFD. Both the grain and straw yields drastically decreased in the control plot, where no nutrients were added. A comparison of the omission plots revealed that the yield reduction was greatest for N-omission, followed by P-omission and K-omission.

3.3. Nutrient uptake

Different nutrient management practices influenced the total N, P, and K uptake by finger millet (Fig. 2a–c). The application of 100 % RD_{PK}+30 kg ha^{-1} N + GreenSeeker (T_8) resulted in N uptake by the crop that was on par with the application of 125 % RFD (T_7) (Fig. 2a). However, the maximum uptakes of P and K by the crop were estimated at 125 % RFD, which was on par with the T_8 treatment and 100 % RFD (T_6) (Fig. 2b and c). The total N, P, and K uptake increased by 17 %, 12 %, and 5 %, respectively, in response to the application of GreenSeeker-based N (T_8) compared to that in response to 100 % RFD. The lowest amount of nutrient uptake was estimated for the control plot. The N-omission, P-omission, and K-omission treatments resulted in the minimum uptake of N, P, and K, respectively, compared with the other treatments except for the control.

3.4. Nutrient use efficiency and indigenous nutrient supply

Different nutrient management practices significantly influenced the different efficiencies of nutrient use by finger millet (Table 6). The maximum values of agronomic efficiency (AE) and recovery efficiency (RE) for N (30.6 and 0.82 kg kg^{-1}, respectively), P (68.9 and 0.73 kg kg^{-1}, respectively), and K (68.9 and 1.63 kg kg^{-1}, respectively) were obtained with the application of 100 % RD_{PK} + 30 kg ha^{-1}

Table 4
Growth parameters of finger millet as influenced by different treatments (pooled over two years).

Treatments	Plant height (cm)	Dry matter accumulation (g m^{-2} d^{-1})	CGR during 60–90 days after sowing
T_1: Control	58.7 ± 3.3^{e}	490 ± 31^{f}	9.27 ± 1.21^{g}
T_2: N omission	61.1 ± 4.5^{de}	521 ± 33^{ef}	9.83 ± 0.91^{f}
T_3: P omission	62.3 ± 2.9^{d}	550 ± 25^{de}	10.73 ± 1.11^{e}
T_4: K omission	63.0 ± 3.8^{d}	580 ± 18^{d}	11.50 ± 1.15^{d}
T_5: 75 % Recommended fertilizer dose (RFD)	95.1 ± 5.7^{c}	670 ± 23^{c}	12.47 ± 2.22^{c}
T_6: 100 % RFD	100.9 ± 6.8^{b}	757 ± 45^{b}	14.03 ± 3.05^{b}
T_7: 125 % RFD	102.0 ± 7.1^{ab}	780 ± 50^{ab}	14.13 ± 2.37^{ab}
T_8: 100 % RD_{PK} + 30 kg ha^{-1} N + GS	104.1 ± 5.1^{a}	802 ± 37^{a}	14.27 ± 3.11^{a}

RFD for finger millet is 60, 30, 30 kg ha^{-1} N, P, and K, respectively; RD_{PK} denotes the application of recommended doses of P and K; GS denotes GreenSeeker-based N management; Values followed by the standard deviation (n = 6); different letters followed by mean values show statistical significant at P = 0.05, otherwise at par.

Table 5
Yield attributes and yield of finger millet as influenced by different treatments (pooled over two years).

Treatments	Productive tillers m^{-2}	Ear head $plant^{-1}$	Fingers ears $head^{-1}$	Finger length (cm)	Weight of grains ear $head^{-1}$ (g)	Test weight (g)	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})
T_1: Control	55 ± 3.3^{e}	2.33 ± 0.2^{g}	3.03 ± 0.7^{d}	5.50 ± 1.1^{c}	1.18 ± 0.15^{c}	2.04 ± 0.10^{b}	805 ± 21^{f}	2012 ± 115^{e}
T_2: N omission	63 ± 5.5^{d}	2.90 ± 0.7^{f}	3.20 ± 0.1^{cd}	5.77 ± 0.5^{bc}	1.25 ± 0.17^{bc}	2.15 ± 0.25^{ab}	1067 ± 37^{e}	2455 ± 77^{d}
T_3: P omission	67 ± 2.6^{d}	3.33 ± 0.5^{e}	3.30 ± 0.4^{bcd}	5.88 ± 1.2^{bc}	1.30 ± 0.09^{bc}	2.17 ± 0.13^{ab}	1288 ± 33^{d}	2905 ± 109^{c}
T_4: K omission	68 ± 1.9^{d}	3.67 ± 0.8^{d}	3.45 ± 0.5^{bcd}	6.04 ± 1.6^{abc}	1.29 ± 0.22^{abc}	2.12 ± 0.11^{ab}	1426 ± 67^{d}	3123 ± 99^{c}
T_5: 75 % RFD	80 ± 4.5^{c}	4.34 ± 0.5^{c}	3.55 ± 0.6^{abcd}	6.20 ± 1.2^{abc}	1.50 ± 0.33^{abc}	2.19 ± 0.09^{ab}	2079 ± 55^{c}	4294 ± 141^{b}
T_6: 100 % RFD	88 ± 8.8^{b}	4.84 ± 0.4^{b}	3.75 ± 0.7^{abc}	6.50 ± 1.3^{ab}	1.59 ± 0.47^{ab}	2.22 ± 0.21^{ab}	2563 ± 75^{b}	4833 ± 105^{a}
T_7: 125 % RFD	93 ± 11.1^{ab}	5.00 ± 0.9^{ab}	3.88 ± 1.1^{ab}	6.60 ± 1.8^{ab}	1.62 ± 0.21^{ab}	2.26 ± 0.44^{a}	2692 ± 101^{ab}	4890 ± 133^{a}
T_8: 100 % RD_{PK} + 30 kg ha^{-1} N + GS	95 ± 5.1^{a}	5.16 ± 1.1^{a}	4.13 ± 0.9^{a}	6.87 ± 0.9^{a}	1.74 ± 0.17^{a}	2.28 ± 0.05^{a}	2873 ± 88^{a}	4933 ± 111^{a}

RFD (recommended fertilizer dose) for finger millet is 60, 30, 30 kg ha^{-1} N, P, and K, respectively; RD_{PK} denotes the application of recommended doses of P and K; GS denotes GreenSeeker-based N management; Values followed by the standard deviation ($n = 6$); different letters followed by mean values show statistical significant at $P = 0.05$, otherwise at par.

N + GreenSeeker, and these treatments were closely followed by 100 % RFD. Notably, both the AE and RE were lower when the RFD increased from 100 % to 125 %. The minimum values of AE and RE for N (8.1 and 0.22 kg kg^{-1}, respectively) were found in the P-omission plot, while the minimum values of AE and RE for P (8.7 and 0.06 kg kg^{-1}, respectively) and K (8.7 and 0.27 kg kg^{-1}, respectively) were found in the N-omission plot. Concerning the internal efficiency (IE) of N, P, and K, the maximum IE values for N (74.6 kg kg^{-1}), P (429 kg kg^{-1}), and K (78.4 kg kg^{-1}) were found in the N-omission, P-omission, and K-omission plots, respectively. The minimum IE value of N was estimated with the application of 100 % RD_{PK} + 30 kg ha^{-1} N + GS, while the minimum IE values of P and K were found with the application of 125 % RFD. The maximum value of the partial factor of productivity (PFP) of N (49.5 kg kg^{-1}) was estimated under the 75 % RFD plot, while the maximum values of PFP of P (95.8 kg kg^{-1}) and K (95.8 kg kg^{-1}) were found with the application of 100 % RD_{PK}+30 kg ha^{-1} N + GreenSeeker. Similar trends to those found for the PFP of N, P, and K nutrients were also found for the PNB. In general, the application of 125 % RFD resulted in lower nutrient use efficiency than did the application of 100 % or 75 % RFD. The yield response to fertilizer (YRF) in the calcareous soil in this study over two years was evaluated and is shown in Fig. 3. The present study showed that the yield of N fertilizer in the YRF treatment was greater (1496 kg ha^{-1}) than that in the P fertilizer (1275 kg ha^{-1}) and K fertilizer (1137 kg ha^{-1}) treatments. The indigenous nutrient supply (INS) of N, P, and K was also estimated from the respective omitted plots and is presented in Fig. 4. Among the three major nutrients, the indigenous supply of K was the highest (18.51 kg ha^{-1}). The INSs of N and P were 14.31 and 3.00 kg ha^{-1}, respectively.

3.5. Energy utilization, balance, and productivity

Gross output energy, net energy, energy use efficiency, and energy productivity were significantly influenced by the application of the different types of nutrients in this study. The highest quantity of input energy was estimated with the application of 125 % RFD (T_7), followed by T_8 and T_6. Input energy was greater in the 75 % RFD treatment (T_5) than in the P-omission and K-omission treatments. The lowest amount of input energy was estimated under the control plot. Compared with those of all the other treatments, significantly greater amounts of gross output energy and net output energy were estimated with the application of 100 % RD_{PK}+30 kg ha^{-1} N + GreenSeeker (T_8) (Table 7). Approximately 3 % and 6 % more net output energy was generated under treatment T_8 than under 125 % RFD (T_7) and 100 % RFD (T_6), respectively. A comparison of the energy use efficiency under the different treatments revealed that the energy use efficiencies under the 75 % RFD (T_5), 100 % RFD (T_6), and 100 % RD_{PK} + 30 kg ha^{-1} N + GreenSeeker (T_8) treatments were similar and significantly greater than those under all the other treatments. The energy use efficiencies under the P and K omission treatments were much lower than those under all the other treatments. Concerning energy productivity (kg GJ^{-1}) under different treatments, the maximum value of energy productivity was found under 75 % RFD (T_5), which was on par with 100 % RFD (T_6) and 100 % RD_{PK} + 30 kg ha^{-1} N + GreenSeeker (T_8). The energy productivity under 125 % RFD (T_7) was approximately 10 % less than the energy productivity under 100 % RFD and 100 % RD_{PK} + 30 kg ha^{-1} N + GreenSeeker. Interestingly, the energy productivity in the control plot was approximately 45–55 % greater than that in the P or K-omission plots.

4. Discussion

4.1. Growth and yield

The maximum increases in growth parameters were found under the application of 100 % RD_{PK}+30 kg ha^{-1} N + GreenSeeker (T_8), and this treatment was on par with the application of 125 % RFD. This increase in the growth of finger millet might be attributed to the

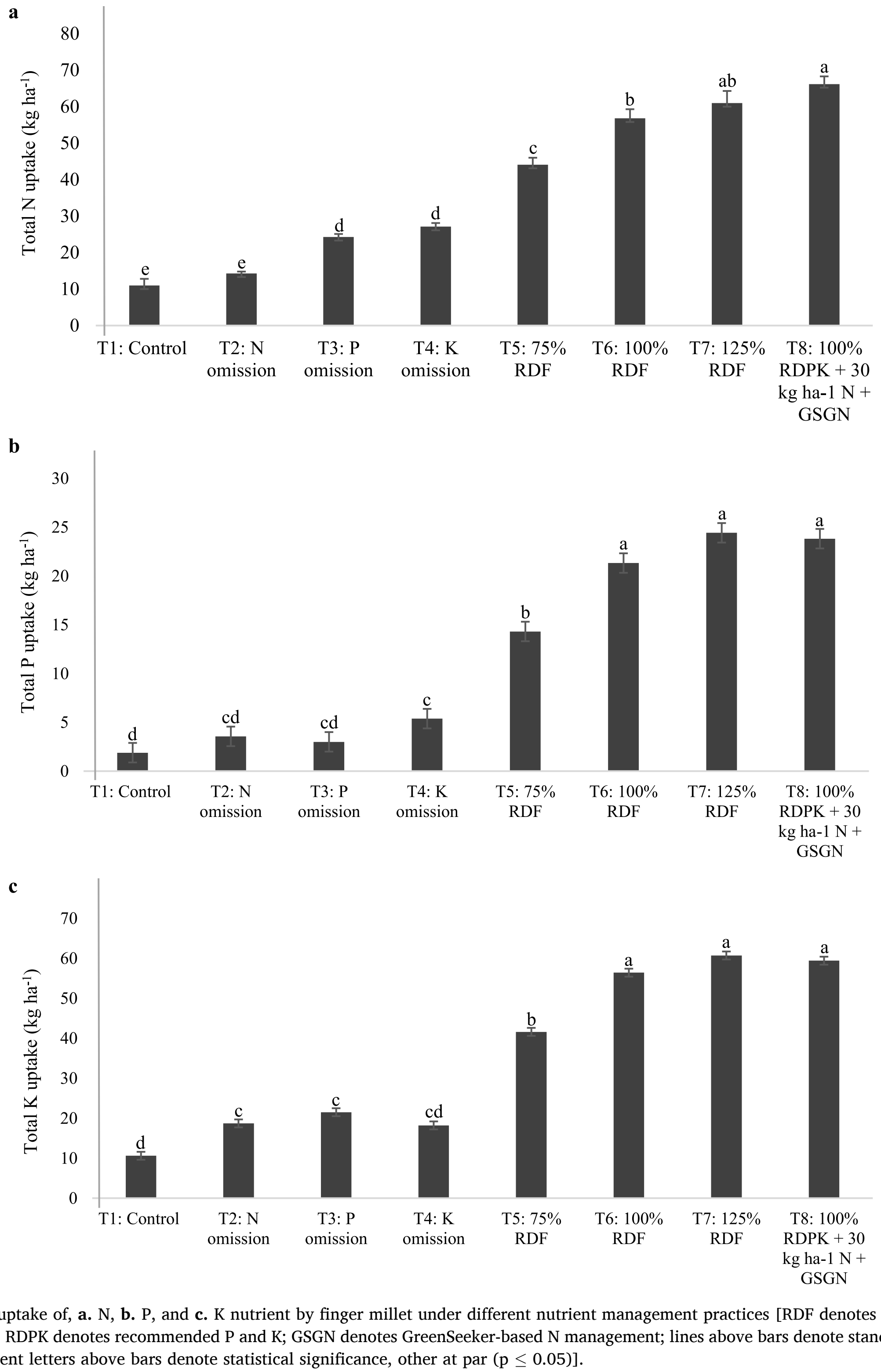


Fig. 2. Total uptake of, **a.** N, **b.** P, and **c.** K nutrient by finger millet under different nutrient management practices [RDF denotes recommended fertilizer dose; RDPK denotes recommended P and K; GSGN denotes GreenSeeker-based N management; lines above bars denote standard deviation ($n = 6$); different letters above bars denote statistical significance, other at par ($p \leq 0.05$)].

application of the optimum amount of plant nutrients at the proper time, as determined through GreenSeeker readings. The growth of plants is predominantly influenced by nitrogen (N), and the use of GreenSeeker-based nitrogen guarantees the precise timing and optimal quantity of nitrogen applied. GreenSeeker readings also serve as indicators of nitrogen deficiency in plants. The availability of N, P, and K also increased with the application of 100 % RD_{PK} + 30 kg ha^{-1} N + GreenSeeker (T_8) and 125 % RFD (T_7) compared to the

Table 6
Efficiency of the nutrient use by the finger millet crop as influenced by different treatments.

Treatments	Agronomic efficiency (AE) (kg kg^{-1})			Recovery efficiency (RE) (kg kg^{-1})			Internal efficiency (IE) (kg kg^{-1})			Partial factor of productivity (PFP) (kg kg^{-1})			Partial nutrient budget (PNB) (kg kg^{-1})		
	AE of N	AE of P	AE of K	RE of N	RE of P	RE of K	IE of N	IE of P	IE of K	PFP of N	PFP of P	PFP of K	PNB of N	PNB of P	PNB of K
N omission	–	8.7 ± 0.1	8.7 ± 0.1	–	0.06 ± 0.00	0.27 ± 0.00	74.6 ± 2.5	300 ± 10	57.1 ± 1.9	–	35.6 ± 0.9	35.6 ± 1.8	–	0.12 ± 0.00	0.62 ± 0.03
P omission	8.1 ± 0.2	–	16.1 ± 0.2	0.22 ± 0.01	–	0.36 ± 0.01	53.0 ± 3.3	429 ± 15	59.9 ± 5.2	21.5 ± 1.0	–	42.9 ± 2.2	0.41 ± 0.02	–	0.72 ± 0.02
K omission	10.4 ± 0.5	20.7 ± 0.5	–	0.27 ± 0.01	0.12 ± 0.01	–	52.6 ± 1.9	265 ± 18	78.4 ± 3.3	23.8 ± 1.5	47.5 ± 1.5	–	0.45 ± 0.01	0.18 ± 0.01	–
75 % RFD	28.3 ± 0.3	56.6 ± 0.3	56.6 ± 0.3	0.79 ± 0.01	0.55 ± 0.01	1.38 ± 0.05	47.1 ± 2.1	145 ± 11	50.0 ± 5.4	49.5 ± 3.1	92.4 ± 1.9	92.4 ± 5.3	1.05 ± 0.06	0.64 ± 0.02	1.85 ± 0.09
100 % RFD	29.3 ± 0.8	58.6 ± 0.8	58.6 ± 0.8	0.76 ± 0.02	0.65 ± 0.02	1.53 ± 0.02	45.1 ± 1.1	120 ± 9	45.4 ± 2.6	42.7 ± 2.8	85.4 ± 3.3	85.4 ± 5.7	0.95 ± 0.05	0.71 ± 0.03	1.88 ± 0.10
125 % RFD	25.2 ± 0.4	50.3 ± 0.4	50.3 ± 0.4	0.67 ± 0.01	0.60 ± 0.01	1.34 ± 0.03	44.1 ± 1.5	110 ± 5	44.3 ± 2.3	35.9 ± 3.3	71.8 ± 5.5	71.8 ± 3.6	0.81 ± 0.03	0.65 ± 0.02	1.62 ± 0.11
100 % RD_{PK} + 30 kg ha^{-1} N + GS	30.6 ± 0.5	68.9 ± 0.5	68.9 ± 0.5	0.82 ± 0.02	0.73 ± 0.01	1.63 ± 0.05	43.4 ± 1.6	121 ± 12	48.4 ± 3.3	42.6 ± 1.9	95.8 ± 4.3	95.8 ± 9.1	0.98 ± 0.05	0.79 ± 0.01	1.98 ± 0.13

RFD for finger millet is 60, 30, 30 kg ha^{-1} N, P, and K, respectively; RD_{PK} denotes the application of recommended doses of P and K; GS denotes GreenSeeker-based N management; Values followed by the standard deviation ($n = 6$).

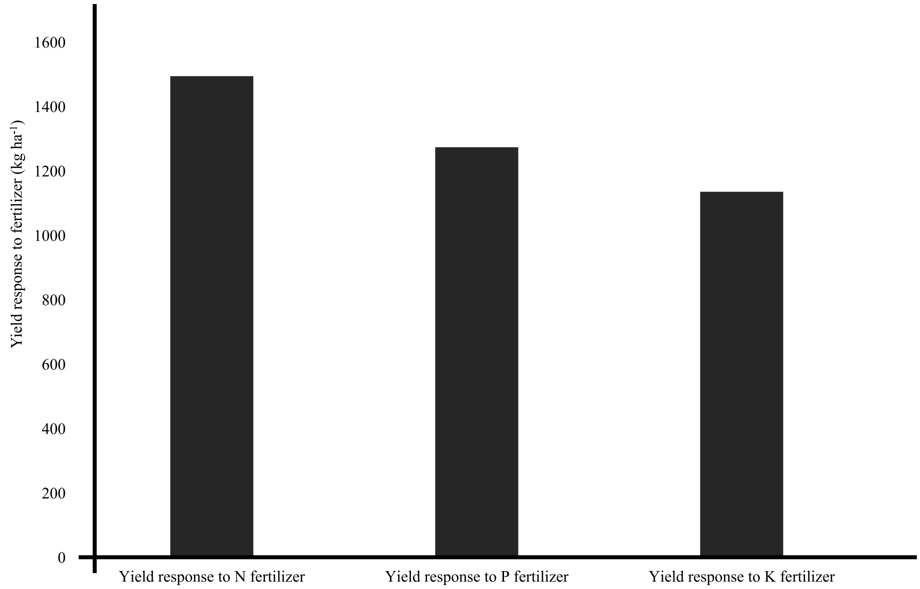


Fig. 3. Yield response to N, P, and K fertilizers in the study area.

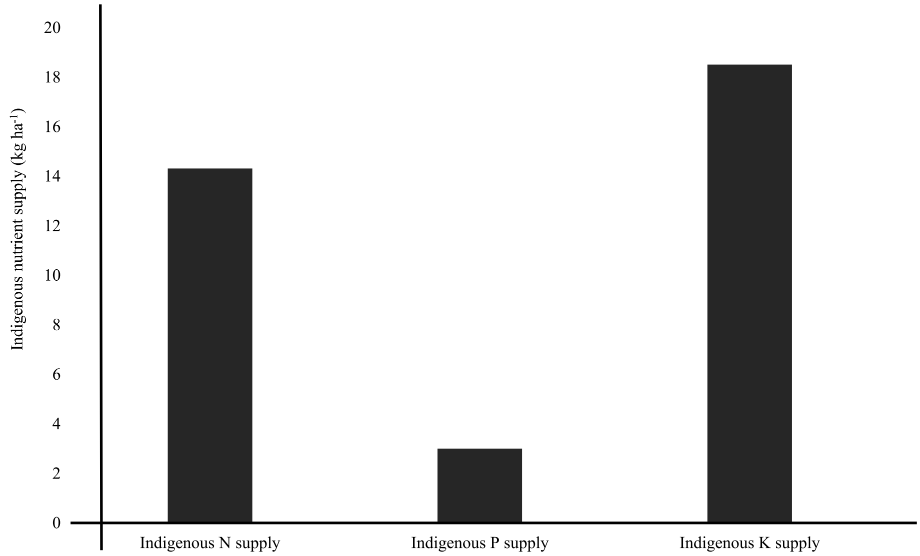


Fig. 4. Indigenous N, P, and K supply from the study soil.

other treatments (Fig. 5). The available N was greater in the T_8 treatment than in the 125 % RFD treatment (T_7), where the fertilizer N application rate was greater. In calcareous soils, the volatilization loss of N is greater. Thus, applying more N fertilizer will not ensure greater N availability in the soil since N loss is much greater. On the other hand, applying N per crop demand via GreenSeeker under SSNM resulted in increased N availability in the soil. The greater nutrient availability across the growth period of the crops under these treatments could be the reason for the taller plants and greater accumulation of dry matter as well as CGR. Plants need N for metabolism, which aids in greater cell division, cell elongation, and dry matter production; therefore, better crop growth can occur [15]. The minimum values of growth parameters under the control plot and nutrient omission plots also indicated the importance of proper nutrition for crop growth. Many previous studies on GreenSeeker-based N management on different crops like rice, wheat, maize, etc. also provided similar information on the growth increment due to better N availability to the crops when they required [4]. However, plenty of scientific information on such site-specific N management on finger millet is not available.

Similarly, higher yields and yields of the crops were observed under the application of 100 % RD_{PK} + 30 kg ha^{-1} N + GreenSeeker (T_8). This difference might be attributed to greater nutrient use efficiency (Table 6) and greater nutrient availability in the soil through the application of optimum nutrients in the T_8 treatment (Fig. 5). GreenSeeker-based N management helped in determining the exact

Table 7
Energetics of finger millet under different treatments (pooled over two years).

Treatments	Input energy (GJ ha^{-1})	Gross output energy (GJ ha^{-1})	Net output energy (GJ ha^{-1})	Energy use efficiency (%)	Energy productivity (kg GJ^{-1})
T_1: Control	2.99	37.0 ± 1.6^g	34.0 ± 1.6^g	11.4 ± 0.6^c	942 ± 88^c
T_2: N omission	3.52	46.4 ± 1.0^f	42.9 ± 1.0^f	12.2 ± 0.3^b	1001 ± 49^b
T_3: P omission	6.81	55.3 ± 1.5^e	48.4 ± 1.5^e	7.1 ± 0.2^e	616 ± 38^e
T_4: K omission	6.96	60.0 ± 1.3^d	53.0 ± 1.3^d	7.6 ± 0.2^d	654 ± 37^d
T_5: 75 % RFD	6.12	84.2 ± 1.9^c	78.1 ± 1.9^c	12.8 ± 0.3^a	1041 ± 101^a
T_6: 100 % RFD	7.16	98.1 ± 1.4^b	90.9 ± 1.4^b	12.7 ± 0.2^a	1033 ± 35^a
T_7: 125 % RFD	8.20	100.7 ± 1.8^b	92.5 ± 1.8^b	11.3 ± 0.2^c	925 ± 95^c
T_8: 100 % RD_{PK} + 30 kg ha^{-1} N + GS	7.61	103.9 ± 1.5^a	96.3 ± 1.5^a	12.7 ± 0.2^a	1026 ± 77^a

RFD for finger millet is 60, 30, 30 kg ha^{-1} N, P, and K, respectively; RD_{PK} denotes the application of recommended doses of P and K; GS denotes GreenSeeker-based N management; Values followed by the standard deviation ($n = 6$); different letters followed by mean values show statistical significant at $P = 0.05$, otherwise at par.

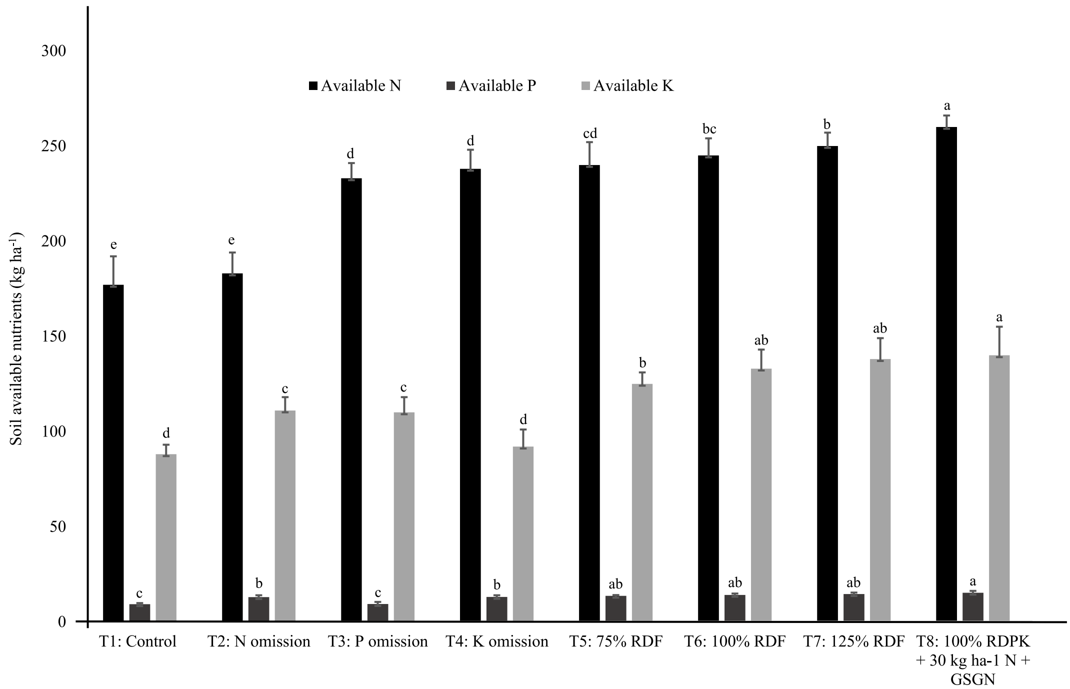
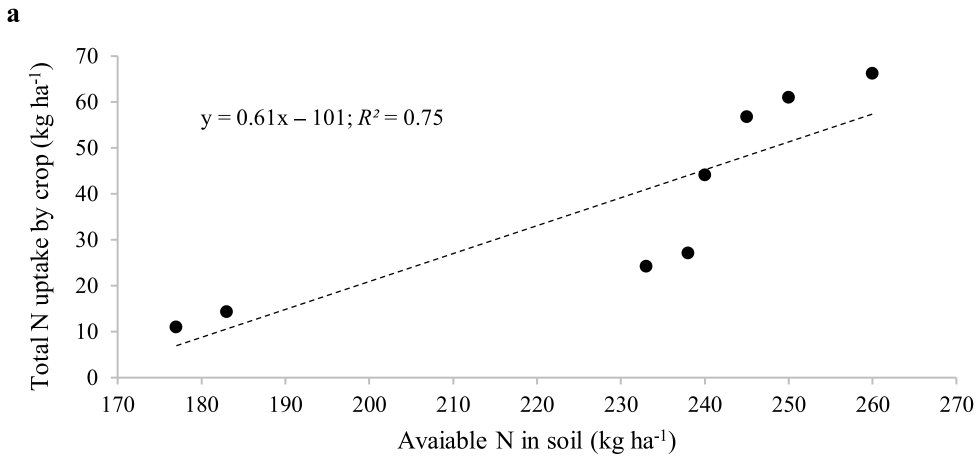
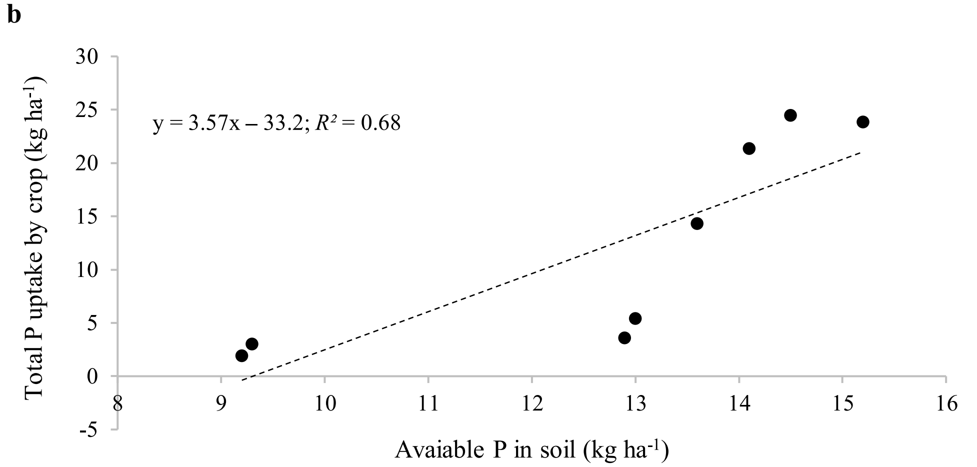


Fig. 5. Soil available N, P, and K during crop season [RDF denotes recommended fertilizer dose; RDPK denotes recommended P and K; GSGN denotes GreenSeeker-based N management; lines above bars denote standard deviation ($n = 6$); different letters above bars denote statistical significance, other at par ($p \leq 0.05$)].

rate of nitrogen application with time when the crop needed this nutrient most. Hence, the N loss was lower, facilitating greater availability in the soil for the crop. Such conditions help plants better transport essential nutrients [43,44]. Therefore, the yield-related characteristics and yield of the crop increased. Among the yield-related characteristics, finger length, weight of grain ear head^{-1}, and test weight did not vary widely. This might be because these parameters are genetic characteristics of a plant that are not influenced widely by varied nutrient management practices [45]. Sreelatha et al. [46], Mohanty et al. [47], Kaur et al. [48], and Swami et al. [49] also noted that GreenSeeker-based nitrogen management practices resulted in augmented yield-related characteristics and biomass production of different crops like rice, cotton, sweet corn, etc. In addition to the information available from the previous studies regarding GreenSeeker-based N management, this study added new insight into such nutrient management on finger millet for calcareous soils to achieve higher yield. Comparing previous studies on the growth and yield of finger millet to our current study, it was observed that optimal nutrient management such as soil test-based fertilizer application and integrated nutrient management using chemical fertilizers and organic amendments can also enhance crop growth and yield, as also reported by our study. Ayushi et al. [50] reported that the optimum N, P, and K application rates of finger millet to achieve the highest growth and yield in Mollisols were 33.74, 6.04, and 24.27 kg ha^{-1}, respectively when applied along with 5.0 t ha^{-1}. Mohamed et al. [51] reported that the requirements of N, P, and K nutrients for producing 1 tonne of finger millet grain were 48 kg, 23 kg, and 44 kg, respectively.





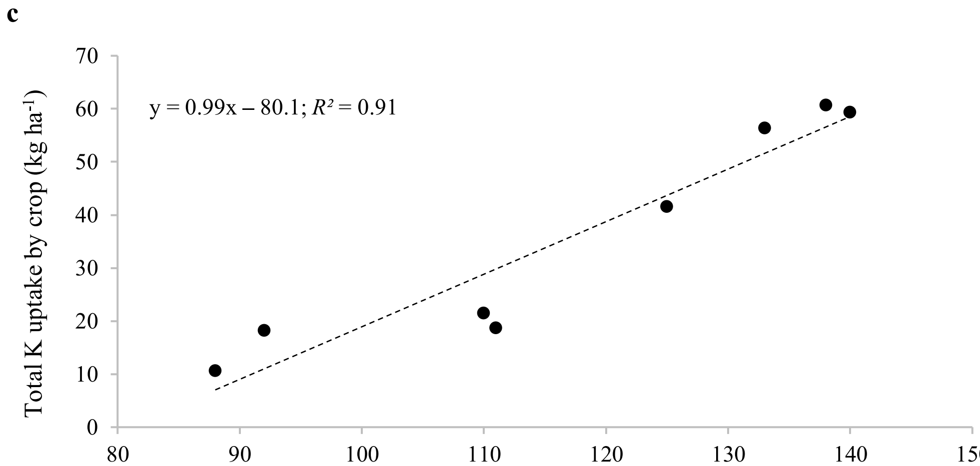


Fig. 6. Relationship between, **a.** soil available N and total N uptake by finger millet; **b.** soil available P and total P uptake by finger millet; **c.** soil available K and total K uptake by finger millet.

4.2. Nutrient uptake

The maximum amount of N uptake was estimated with the GreenSeeker-based nitrogen management treatment (T_8) compared with the control, N-omission, P-omission, K-omission, and 75 % RDF treatments. The primary reasons for the increase in nitrogen uptake by finger millet were likely attributed to the optimal timing and division of fertilizer nitrogen applications facilitated by GreenSeeker technology. Nitrogen losses were minimized since nitrogen was applied during the critical stages when the crop demanded it the most. Higher values of N availability in the soil with the application of 100 % RD_{PK}+30 kg ha^{-1} N + GreenSeeker (T_8) (Fig. 5) also facilitated better N uptake. The mechanism of N uptake involves root uptake, assimilation, metabolism, translocation, and N-recycling. All these processes might be facilitated through higher availability of N in the soil. Better Fig. 6 a–c also shows the strong relationships between N, P, and K availability in soil and N, P, and K uptake by finger millet in this study. This information confirms the existing data on nutrient uptake by various crops under SSNM. Our study has contributed to the understanding of nutrient uptake by finger millet in calcareous soils under the framework of SSNM using GreenSeeker-based N management. The findings of the study were similar to those of Kumar et al. [52] and Sulochna et al. [53]. The crop uptake of P and K was somewhat greater under treatment T_7 (125 % RDF) than under T_8. However, the uptake of P and K in T_7 was not significantly greater than that in T_8. Despite applying 25 % more phosphorus (P) and potassium (K) under 125 % of the recommended dose of fertilizer (RDF) compared to T_8, the plants showed significant uptake of P and K in conjunction with balanced nutrient application and an appropriate ratio of nitrogen (N), phosphorus (P), and potassium (K) under T_8. Nutrient uptake by plants depends on balanced nutrient availability in the soil. Optimum nutrient availability reduces the loss or fixation of nutrients from the soil. Ali et al. [54] and Sulochna et al. [53] reported similar results for maize.

4.3. Nutrient use efficiency

The agronomic efficiencies (AEs) of N, P, and K were found to be the highest under the application of 100 % RD_{PK}+30 kg ha^{-1} N + GreenSeeker (T_8). This might be because this treatment (T_8) resulted in substantial yield escalation compared to the other treatments at unit fertilizer application. Nitrogen is the primary nutrient for crop growth and is quickly lost from the root zone due to leaching as well as volatilization, particularly in calcareous soils. Therefore, the duration of nutrient application is crucial and must be met when the crop is needed. The application of 100 % RD_{PK} + 30 kg ha^{-1} N + GreenSeeker (T_8) might confirm the importance of N supplementation to the crop as needed and when needed. Additionally, the increased availability of soil nitrogen could affect the soil microbiome, ultimately enhancing nutrient dynamics for the plants and resulting in improved nitrogen use efficiency [55]. The application of 125 % RDF (T_7) resulted in a greater crop yield than did the application of 100 % RDF (T_6) or 75 % RDF (T_5). However, 25–50 % more nutrients were applied in T_5 than in T_6. The increased application of nutrients did not proportionally boost crop yields, as various nutrient losses from the soil occurred. Moreover, the application of excessive fertilisers might alter the dynamics of the soil microbiome. Such a situation might also explain why a lower AE was obtained under T_7 than under T_5 and T_6. Kumar et al. [52] explained that it is necessary to optimize fertilizer efficiency by managing the N supply from soil and other natural sources. Maximizing nitrogen (N) recovery from mineral fertilizer or organic amendments is of particular importance for crops, given the close relationship between yield and nitrogen uptake, with fertilizer losses being most pronounced. A similar conclusion was also drawn by Ray et al. [19] concerning winter maize. Hence, the findings of our study align with those of prior researchers who investigated SSNM, particularly regarding the efficient utilization of nitrogen by finger millet. The greater recovery efficiency (RE) was estimated to be associated with GreenSeeker-based nitrogen management practices, possibly due to the greater uptake of nutrients per unit of externally applied nutrients. In smart nutrient management, nutrients are applied when a crop needs to increase its nutrient uptake per unit of externally applied fertilizer [44], which may be the reason behind the higher RE under GreenSeeker-based management practices. Considering the internal efficiency (IE), the internal efficiencies of the respective nutrient omission plots for N, P, and K were greater than those of the fertilized plots. Internal efficiency signifies the yield efficiency inherent to a plant. As a C_4 plant, finger millet is more photosynthetically efficient than other plant species and may facilitate the production of biomass even under low nutrient uptake scenarios. Thus, the IE of N and P was greater in the respective omission plots. Most previous researchers have also reported that the IE of crops decreases with the application of fertilizers [19,44,56]. The application of 75 % RFD (T_5) and 100 % RD_{PK} + 30 kg ha^{-1} N + GreenSeeker (T_8) resulted in higher partial factor productivity (PFP) and a greater partial nutrient budget (PNB). Generally, the PFP and PNB values decrease with increasing applied fertilizer due to losses from the root zone, and the yield does not increase linearly with increasing nutrient application. However, the PFP and PNB in the GreenSeeker-based N management plots were greater than those in the control plots, as this treatment confirmed better N management, resulting in reduced losses of N fertilizers, which ultimately helped in producing greater yields. Interestingly, the PFP and PNB of N were ∼16 % and 7 % lower, respectively, in the GreenSeeker-based treatment than in the 75 % RFD treatment. Such findings added new insight into the nutrient use efficiencies for finger millet crop production. The possible reason for this difference might be that ∼25 % reduction in externally applied N did not reduce yield or N uptake by the crop at the same time. Henceforth, the PFP and PNB were slightly greater under these treatments. Pramanick et al. [44], and Chivenge et al. [57,58] also suggested that smart nutrient management results in greater nutrient use efficiency.

4.4. Energy utilization, balance, and productivity

The workflow of this study was designed by converting the inputs and outputs of the millet cultivation system into energy equivalents. This study has several limitations and chances of error. Hence, it would be better to measure the actual energy involved in the production system. However, we estimated this to be related to the energetics of the production system. The input energy in the control plot was minimal, as no external N, P, or K fertilizers were applied. On the other hand, the maximum amounts of N, P, and K fertilizers were applied at 125 % RDF. Thus, the input energy was the maximum in this treatment. The greater amount of output energy found in treatments T_8, T_7, and T_5 was due to the greater yield of the crop compared to all the other treatments. Energy use efficiency is a measurement of gross output energy per unit of input energy. The output energy in treatment T_8 was much greater than that in the other treatments as a result of the greater yield of the crop. Thus, the energy use efficiency was greater in this treatment than in the other treatments. Similarly, the energy productivity was greater under the application of 100 % RD_{PK} + 30 kg ha^{-1} N + GreenSeeker (T_8). Energy productivity and energy use efficiency were considerably greater under the N omission than under the P or K omission. N fertilizer consumes much more energy than P and K fertilizers. Harika et al. [8] and Dey et al. [27] reported that integrated nutrient management can improve the overall energetics of crop production, *viz.* finger millet and flax, respectively. Thakur and Sidar [59] reported that finger millet cultivated with summer ploughing and herbicide application for weed management exhibited the best attainment of energy use efficiency. Similarly, a study by Harika et al. [8] showed that the nutrient management in finger millet with the application of 8 t ha^{-1} of FYM combined with *Azospirillum* resulted in the highest energy use efficiency and energy productivity. All these previous studies have not extensively documented the energetics of finger millet cultivation within the SSNM framework, especially in calcareous soils. Hence, our study contributes novel insights into the energetics of finger millet cultivation in calcareous soils.

In essence, the practical application of the findings of this study involves implementing this innovative nutrient management approach for finger millet across vast areas of calcareous soils. Such nutrient management options could improve the yield of crops and the efficiency of applied inputs. This approach would ultimately benefit finger millet growers.

5. Conclusion

In this two-year study, we identified several critical findings that significantly impact finger millet cultivation. GreenSeeker-based SSNM (T_8) resulted in the maximum growth, yield, N uptake, energy efficiency, and use efficiency of the applied nutrients in finger millet cultivation. As demonstrated in Table 7, this approach exhibited a net output energy of 96.3 ± 1.5 GJ ha^{-1} and an energy use efficiency of 12.7 %, surpassing those of all the other treatments. In GreenSeeker-based N management, an additional 37.5 kg ha^{-1} N was applied in addition to the 30 kg ha^{-1} basal N application. An additional split application of N at 8 kg ha^{-1} during the 70-day growth stage was found to be more beneficial than applying two conventional splits. Among the various nutrient management approaches examined, the application of 100 % RD_{PK} (recommended doses of phosphorus and potassium) with an additional 30 kg ha^{-1} N, guided by GreenSeeker readings, is the most favourable strategy for achieving the maximum biomass production, nutrient use efficiency, and energy efficiency of finger millet crops. Therefore, based on the findings of this study, it is recommended to apply 100 % of the recommended phosphorus (P) and potassium (K) along with 30 kg ha^{-1} of nitrogen (N) as a base, and the remaining nitrogen (N) should be applied based on GreenSeeker readings. These results have significant implications for sustainable agriculture, as they offer a tailored approach to maximize crop yield while optimizing nutrient and energy use, ultimately contributing to more efficient and eco-friendly farming practices. The practical significance of this outcome lies in enabling finger millet growers to optimize nitrogen application through the utilization of GreenSeeker technology, thereby ensuring increased production. A limitation of our study is the lack of a comprehensive periodic soil analysis throughout the various stages of crop growth. Such analysis could provide valuable insights into the nutrient dynamics of finger millet cultivation when employing GreenSeeker-based management practices. The future scope of this study includes conducting in-depth analyses focusing on the energetics and environmental impact associated with implementing the SSNM for finger millet cultivation.

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The data will be made available upon request to the corresponding authors.

CRediT authorship contribution statement

Biswajit Pramanick: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sanju Choudhary:** Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Mukesh Kumar:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Santosh Kumar Singh:** Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Conceptualization. **R.K. Jha:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Satish Kumar Singh:** Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Conceptualization. **Saleh H. Salmen:** Writing – review & editing, Software, Project administration, Funding acquisition, Formal analysis, Data curation. **Mohammad Javed Ansari:** Writing – review & editing, Software, Resources, Funding acquisition, Formal analysis, Data curation. **Akbar Hossain:** Writing – review & editing, Supervision, Software, Resources, Project administration, Funding acquisition, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Saleh H. Salmen reports financial support was provided by King Saud University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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