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Analytical Evaluation of Soil Physicochemical Dynamics Across Varied Millet-Producing Agronomic Zones

[1]Muneeb Ahmed, [2]Waseem Uddin MD, [1]Maruthi K.R., [1]Mohammad Faizan, and [1]*S. Maqbool Ahmed

[1]Botany Section, School of Sciences, Maulana Azad National Urdu University, Hyderabad-500032 (India)
[2]PGT-Biotechnology, Maulana Azad National Urdu University Model School, Hyderabad-500053 (India)
***Corresponding Author :** maqboolmanuu@gmail.com

Abstract

Millets are climate-resilient crops known for their adaptability to marginal soils and low-input agricultural systems. Understanding the soil characteristics associated with millet cultivation is essential for enhancing productivity while maintaining soil health. The present study was conducted in Department of Botany, School of Sciences, Maulana Azad National Urdu University, Hyderabad where the physical (Soil Porosity, Water-Holding Capacity, Soil Texture) and chemical properties (like Electrical Conductivity, pH, Organic Carbon (%) and available Macro-Nutrients (like Nitrogen, Phosphorus and Potassium) of the soil samples of millet-grown fields were studied. A total of 5 soil samples were collected from diverse millet-grown fields of Telangana State, and the soil samples were labelled as S1, S2, S3, S4 and S5. These samples were used to study the physico-chemical aspects of the soil to determine the soil health and soil nutritional status of the soil which is needed for high millet yields. The results indicated that the pH of different soil samples ranged from slightly acidic to slightly alkaline. The electrical conductivity (EC) of the soil sample-2 was found to be 0.21dS/m, and least value was observed for the soil samples-3 and sample-5 which is 0.13 dS/m. The organic carbon (%) was found to be average. The available Nitrogen was found to be highest in sample-4 (90 Kg/ha) and least in sample-1 & sample-3 (40 Kg/ha).The available Phosphorous was found to be highest in sample-3 (35Kg/ha) and least in sample-2 (10Kg/ha).The available potassium was found to be highest in sample-3 and sample-5 (which is 250 Kg/ha) and least in sample-2 (65Kg/ha).The highest water holding capacity was found in the sample-4 and least was observed in the sample-2.The porosity of the soil was measured and it was found to be highest for the sample-4 (54.55%) and least value was observed for sample-5 (46.38%).This study provides valuable insights for soil management strategies aimed at promoting millet-based cropping systems for long-term soil health and food security.

Key words : Finger-Millet, Soil Health, Food Security, Sustainable Agriculture, Soil Fertility, Nutrient Availability.

Finger millet (*Eleusine coracana* L.), commonly known as ragi, is an important climate-resilient cereal crop widely cultivated in semi-arid and tropical regions of Asia and Africa, particularly in India. It is valued for its high nutritional quality, drought tolerance, and adaptability to marginal soils[1]. The productivity and sustainability of finger millet cultivation are strongly influenced by soil quality, which is determined by various physico-chemical parameters such as soil texture, bulk density, pH, electrical conductivity (EC), organic carbon, and macro- and micronutrient availability. These soil properties regulate nutrient cycling, water availability, microbial activity, and ultimately crop yield[2]. Soil health is often assessed through a combination of physical and chemical indicators that reflect the functional capacity of soil within an ecosystem.

Physical properties such as bulk density, particle density, pore space, and water-holding capacity determine soil structure and root penetration, while chemical properties such as pH, organic carbon, and available nitrogen (N), phosphorus (P), and potassium (K) directly influence nutrient availability and plant growth. Studies on finger millet fields have shown that variations in these properties significantly affect crop performance and soil fertility status[2]. Among chemical parameters, soil organic carbon plays a central role in maintaining soil fertility, improving soil structure, and supporting microbial activity. Long-term experiments under finger millet-based cropping systems have demonstrated that integrated nutrient management can increase soil organic carbon and improve overall soil health and productivity over time. For instance, long-term fertilization studies have reported increases in soil organic carbon levels and sustained crop yields under balanced nutrient application[3]. Similarly, nutrient management practices significantly influence soil chemical properties in finger millet cultivation. Application of organic manures and fertilizers has been shown to increase soil pH, organic carbon content, and availability of major nutrients such as N, P, and K compared to sole chemical fertilizer application. These improvements in soil properties are associated with enhanced grain yield and sustainable soil productivity[4].

In addition to macronutrients, micro-nutrients and soil biological interactions also contribute to soil fertility in finger millet fields. Studies have reported that integrated nutrient application involving biofertilizers and phosphorus fertilizers can improve soil nutrient status and crop yield, highlighting the importance of monitoring multiple physico-chemical parameters simultaneously[5]. The majority of farmers are unable to attain optimal yields because of carelessness in various farming techniques and poor genotype selection[6]. In order to preserve sustainable yields and enhance soil health, organic manures are increasingly being used in place of chemical fertilizers[7].

Variability in soil physico-chemical properties is often observed across different agro-ecological zones due to differences in parent material, climate, altitude, and management practices. Using inorganic fertilizers to maximize locally accessible organic inputs and resolving site-specific limitations to restore and enhance soil fertility in accordance with the integrated soil fertility management paradigm are two possible approaches to restore soil fertility[8]. For example, studies in finger millet-growing regions have shown variation in soil acidity and organic carbon content across elevation gradients, indicating that soil parameters are highly site-specific and require localized assessment[9]. Despite extensive research on soil fertility and nutrient management, there is still a need for detailed comparative analysis of physico-chemical properties of soils under finger millet cultivation across diverse soil types and agro-climatic conditions[10]. Such studies help in identifying soil constraints, optimizing nutrient management strategies, and improving crop productivity sustainably. Millets help control weight loss, high blood pressure, and basal metabolic rate, Packed with phenols, tannins, and phytates that help prevent diseases like high blood pressure, diabetes, and high cholesterol[24]. It is a staple food for diabetics, expecting mothers, the sick, nursing mothers, and kids since it contains easily digestible, nutrient-dense ingredients[11]. Plant-associated microbial communities contribute significantly to crop productivity by improving nutrient acquisition, phytohormone production, disease suppression, and stress resilience[12,13,14,15]. Harnessing beneficial microorganisms offers an environmentally sustainable alternative to excessive chemical fertilizer use and supports long-term agricultural productivity[15,16,17]. Nitrogen-fixing bacteria enhance plant growth by converting atmospheric nitrogen into forms readily available to plants, thereby reducing dependence on synthetic nitrogen fertilizers[16,17]. The rhizosphere microbiome contains diverse microbial taxa involved in nutrient cycling, plant growth promotion, pathogen suppression, and adaptation to environmental stresses[18]. Metagenomic approaches enable comprehensive characterization of microbial diversity and functional potential within crop-associated microbiomes without the need for cultivation[19]. The microbiomes associated with cereal crops play important roles in plant health, nutrient acquisition, and resilience to environmental stresses, thereby contributing to food security[19]. Crop-associated microbial communities can improve plant tolerance to drought, salinity, and other abiotic stresses through multiple physiological and biochemical mechanisms[20]. Metagenomic and metabolomic analyses have revealed that specific microbial communities contribute to enhanced drought tolerance in millet crops through modulation of metabolic pathways and stress-response mechanisms[20]. Rhizospheric microbial communities influence soil physicochemical properties and can facilitate crop adaptation to saline and alkaline environments. Studies on finger millet have demonstrated that both rhizosphere and seed-associated microbiomes harbor diverse microbial communities with potential roles in plant growth promotion and stress adaptation[18]. Metagenomic analysis of the kodo millet rhizosphere revealed a diverse microbial community possessing multifunctional traits associated with nutrient cycling, plant growth promotion, stress tolerance, and maintenance of soil health, highlighting the ecological significance of the crop-associated microbiome[18]. Carotenoid accumulation in orange-red carrot roots is regulated through coordinated expression of carotenoid biosynthetic genes and metabolic pathways that influence pigment synthesis, storage, and nutritional quality of the crop[21]. Soil microbial biomass carbon serves as a critical indicator of soil fertility and ecosystem functioning, and its distribution is strongly influenced by climatic variables, vegetation characteristics, soil properties, and land-use patterns[22]. Metagenomic investigation of termite mound soils revealed diverse microbial communities possessing functional genes involved in nutrient transformation, organic matter decomposition, biogeochemical cycling, and environmental sustainability[23].

Five soil samples from the Finger-Millet grown fields from selected areas of Telangana *i.e.* two samples from farmlands of DDS Krishi Vigyan Kendra Zaheerabad, Sangareddy District were taken and named as S-001 and S-002 samples and two samples S-003 and S-004 were taken from Lacha Naik Thanda of Zaheerabad mandal, and one sample S-005 from Arjun Naik Thanda of Zaheerabad mandal were collected. Systematic Sampling (Grid Method) has been used to collect the soil samples and approximately 500 gm of soil sample is collected from each field. These five samples were collected to study their physico-chemical properties. Initially, they were air-dried and the soil porosity is estimated by water-saturation method. Soil Texture Analysis was done for all the samples using Jar-Sedimentation method. Water-Holding capacity of the soil samples were studied. pH of collected soil samples was determined using commercially available soil pH testing kit. Available Macro-Nutrients (Nitrogen (N), Phosphorous (P), Potassium (K)) concentrations were determined using commercially available soil testing kits. Percentage of Organic Carbon (OC%) was measured by Walkley-Black Method. The Electrical Conductivity (EC) of the soil samples were measured using the Electrical Conductivity meter. The generated data were subjected to statistical analysis.

The soil porosity was found to be highest in sample-4 (58.33) and the least value for soil porosity is observed for sample-5 which is 46.38. Highest water holding capacity was shown by the sample-4 which is 44% and least was shown by sample-2 which is 31%. The highest pH value is shown by the sample-3 and sample-5 that is 7.5 and least pH was shown by sample-2 which is 4.5. The electrical conductivity (in dS/m) was found to be highest in sample-2 which is 0.21 dS/m and least EC value was shown by the sample-3 & sample-5, which is 0.13 dS/m. The available N was found to be high in the sample-4 which is 90 kg/ha and least is observed in the sample-1 and sample-3 which is 40 kg/ha.The available P was found to be high in the sample-3 that is 35 kg/ha and least is observed in sample-2 which is 10 kg/ha. The available K was observed highest in sample-3 and sample-5 which is 250 kg/ha and least value is observed for the sample-2 which is 65 kg/ha.The five different soil samples showed moderately high percentage of organic carbon (OC%).

Table-1. Showing Physical Parameters of Soil Samples

Sl. No.	Sample ID	Physical Parameter		
		Soil Texture	Porosity (%) Mean ± SD	Water Holding Capacity (%) Mean ± SD
01	S - 001	Sandy Loam	47.00 ± 1.6 bc	41.00 ± 1.6 b
02	S - 002	Sandy Loam	48.00 ± 0.31 b	44.00 ± 0.31 a
03	S - 003	Sandy Loam	43.00 ± 2.3 d	33.00 ± 2.30 c
04	S - 004	Sandy Loam	55.00 ± 0.94 a	31.00 ± 0.94 de
05	S - 005	Sandy Loam	55.00 ± 0.94 a	31.00 ± 0.94 d

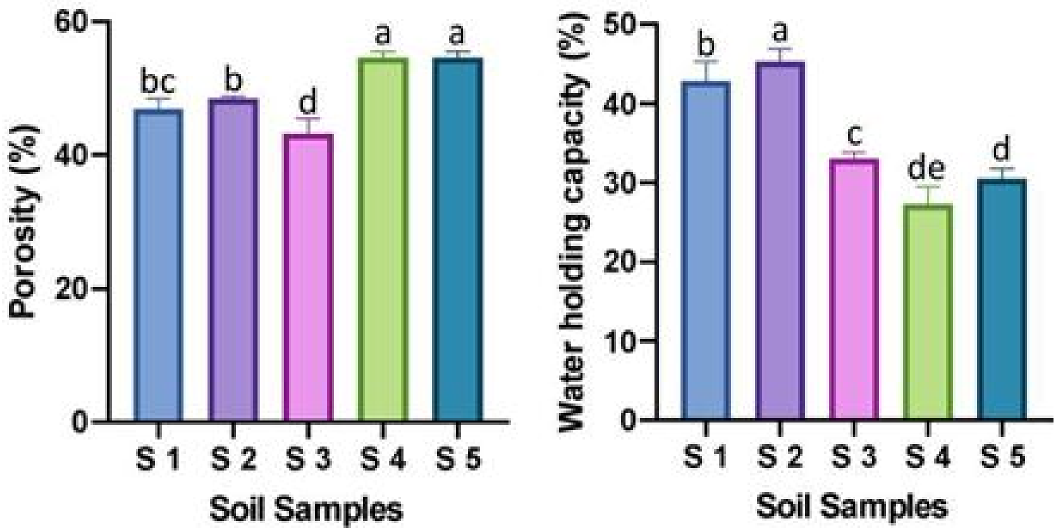

Fig. 1. Showing Physical Parameters of Soil Samples.

Table-2. Showing Chemical Parameters of Soil Samples.

Sl. No.	Sample ID	Chemical Parameter		
		EC (mS/cm) Mean ± SD	pH Mean ± SD	OC % Mean ± SD
01	S - 001	0.17 ± 0.03 a	6.3 ± 0.40 a	1.20 ± 0.02 a
02	S - 002	0.21 ± 0.02 b	6.2 ± 0.25 ab	1.10 ± 0.02 b
03	S - 003	0.13 ± 0.02 e	5.4 ± 0.25 c	0.90 ± 0.01 c
04	S - 004	0.20 ± 0.03 d	5.1 ± 0.26 d	0.80 ± 0.01 d
05	S -005	0.13 ± 0.03 c	4.8 ± 0.29 d	0.71 ± 0.01 e

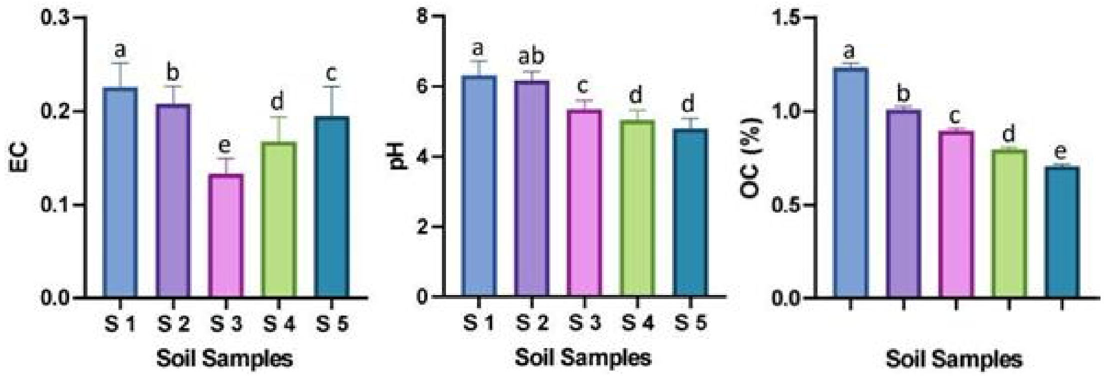

Fig. 2. Showing Chemical Parameters of Soil Samples

Table-3. Showing Micro-Nutrient Parameters of Soil Samples

Sl. No.	Sample ID	Chemical Parameter		
		Macro-Nutrients		
		N (kg/ha) Mean ± SD	P (kg/ha) Mean ± SD	K (kg/ha) Mean ± SD
01	S - 001	90.00 ± 4.1 a	16.00 ± 2.16 d	144.80 ± 4.03 c
02	S - 002	69.00 ± 4.5 b	11.00 ± 2.58 e	129.30 ± 7.46 d
03	S - 003	45.00 ± 4.2 c	34.00 ± 4.08 a	242.00 ± 32.29 a
04	S - 004	40.00 ± 4.0 cd	25.00 ± 3.25 c	212.50 ± 7.42 ab
05	S -005	38.00 ± 4.8 d	28.00 ± 3.25 b	207.00 ± 6.06 b

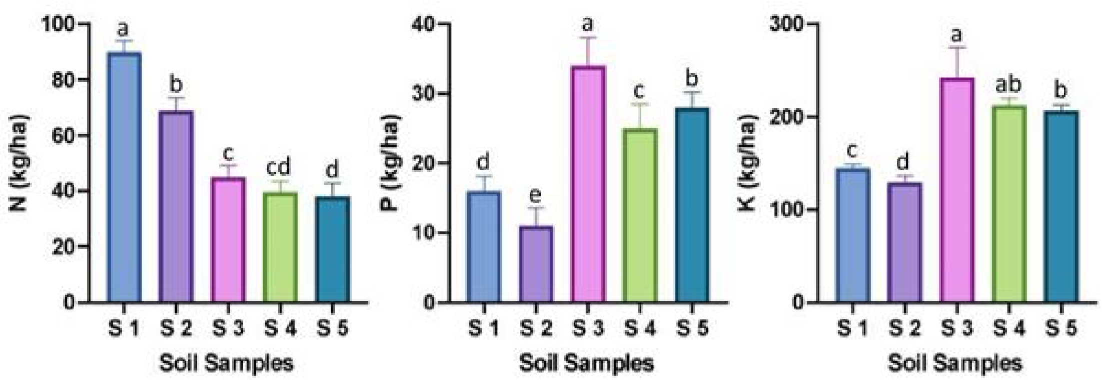

Fig. 3. Showing Micro-Nutrient Parameters of Soil Samples.

a) *Physical Properties :*

All soil samples being classified uniformly as sandy loam suggests that coarse-textured soils are prevalent in the study area. Sandy loam soils are typically regarded as optimal for millet farming, as they strike a good balance between drainage and moisture retention. Comparable results have been observed in millet-growing areas of South India, where light-textured Alfisols and Entisols are the main soil types[2]. These soils favour proper root penetration and needful aeration, that are required for drought-tolerant crops like finger millet.

Soil porosity in this study varied from 46.38% to 54.55%, with the maximum value found in sample S4. This range suggests the presence of well-structured soils that have adequate pore space for the movement of air and water. Similar porosity levels have been reported in integrated nutrient management systems, where organic materials enhance soil aggregation and pore connectivity[3].

The water holding capacity (WHC) ranged from 31% to 44%, with S4 exhibiting the highest WHC. This variation highlights the differences in soil composition, organic matter levels, and porosity. Increased WHC is beneficial in rainfed systems because it increases moisture availability during dry spells. Research conducted in comparable agro-climatic regions has indicated WHC values within this range, underlining the significance of organic amendments in enhancing soil moisture retention[7].

b) *Chemical Properties :*

Since salinity can negatively impact plant growth and nutrient uptake, the electrical conductivity (EC) of all samples was less than 1 dS/m (0.13–0.21 dS/m), indicating non-saline conditions (Table-2, page 4). In millet-growing soils throughout Southern India, similar low EC values have been regularly reported[2,5].

Soil pH varied from strongly acidic (4.5) to slightly alkaline (7.5) and was quite variable among the samples, which may be attributed to variation in rainfall, leaching, and fertilizer use. Acidic conditions can limit nutrient availability, especially phosphorus due to fixation, while neutral to slightly alkaline soils (S3 and S5) are more conducive to nutrient availability and microbial activity. This level of pH variability has been reported for millet-based systems throughout India, due to site-specific soil conditions[2].

The range of the organic carbon (OC) content, which indicates moderate levels of soil organic matter, was 0.878 percent to 1.057 percent. A major factor in determining soil fertility is organic carbon, which affects microbial activity, water retention, and nutrient availability. Reports from long-term fertilization experiments, where integrated nutrient management techniques preserve or raise soil organic carbon levels, are in line with the observed values[3,4].

c) *Macronutrient Status :*

Nitrogen (N) availability ranged from low to moderate (40 to 90 kg/ha). Nitrogen is a limiting nutrient in millet-growing soils because of rapid mineralization and leaching losses, especially in light-textured soils. The high N content in S4 could be due to a higher organic matter content or recent fertilizer application. Comparable trends have been reported in degraded smallholder farms, which are often limited by nitrogen availability[8].

The available phosphorus (P) ranged from 10 to 35 kg/ha, with most samples having low to moderate levels. Phosphorus deficiency is a common problem in tropical soils because P becomes fixed to iron and aluminium oxides, particularly under acidic conditions. S2 has low P content, which is in line with its acidic pH that likely increases P fixation. Phosphorus is an important limiting nutrient for finger millet cultivation and has been previously reported as a limiting nutrient in finger millet[5,8].

On the other hand, available potassium (K) was relatively high (65–250 kg/ha), with highest values in S3 and S5, indicating that the soils are inherently rich in potassium, likely from K-bearing minerals like feldspars and micas. Potassium availability is usually high in Indian soils, and it is rarely a limiting factor for millet growth[3].

It is observed that among five different soil samples (Finger-Millet grown) the available K is found to be high in almost all the soil samples compared with available N which is more in quantity when compared with available P indicating, the collected finger-millet grown soil samples are rich in available N and available K and poor in available P. All the 5 soil samples showed EC value less than 1dS/m indicating non-saline soils.

The collected soil samples are non-saline with varying nutrient quantity but with adequate organic carbon. Hence, Supplementation of Nitrogen and Phosphorus along with organic matter can be done for improving soil fertility and sustainable finger-millet crop productivity.

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Conflict of Interest :

The authors declare that there is no conflict of interest.

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