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Assessment of the Impact of Chemical Fertilizers on Soil Physico-Chemical Properties in the Kota Region

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ABSTRACT

In developing countries like India, agriculture is the most important factor which influence the economic development of country. Due to constant increase in population, demands of agricultural goods and adequate amount of food availability is also increased. To overcome food scarcity a large amount of chemicals is annually applied at the agricultural soils as fertilizers. Such applications may result in the increase the level of heavy metals. In this study we will use okra plant for find out impacts of chemical fertilizers on soil of Kota region in larger quantity than recommended dose. We will measure the pH, EC and CEC of soil and EC and pH of water and also measure nutrient levels of NPK in soil before plantation. Then we will sow different varieties of okra seeds and use specific doses of NPK for okra yield. Aim of this study is reveal the effect of different NPK singly and in combination on the crop. And also find out the effects of chemical fertilizer in different proportions on the vegetative properties of okra plant and to check the soil quality and fertility. Fertilizers can change soil structure and soil fertility. In addition, toxic substances may accumulate within vegetables and causing negative effects in human and animals are fed.

***Keywords**: Chemical Fertilizers, EC and CEC, Heavy Metal, Soil Quality, Physical and Biochemical Properties, Toxic Substance.*

Introduction

Soil Organic Matter and Its Role in Soil Fertility

Soil organic matter (SOM) significantly influences the physical, chemical, and biological properties of soil. It functions both as a source and a reservoir for nutrient elements such as nitrogen (N), phosphorus (P), and sulfur (S), which are capable of forming organic compounds. Due to its charged nature, SOM contributes to ion exchange processes and serves as an important energy source for soil microorganisms. In addition, SOM interacts with the atmosphere as part of the global carbon reservoir, thereby influencing atmospheric carbon dioxide (CO_2) concentration and overall environmental conditions. Thus, SOM represents a complex combination of several soil properties and functions.

Because of the dynamic behaviour of different fractions of soil organic carbon and the large quantity of carbon stored in soils, soils play a crucial role in the global carbon cycle (Eswaran et al., 1995).

Although soils have the potential to function as net carbon sinks, available evidence indicates that managed agricultural soils have historically acted as net sources of atmospheric CO_2, contributing nearly 20% of the annual increase in atmospheric CO_2 concentration (Schlesinger and Andrews, 2000; Watson et al., 1992). Proper maintenance and long-term enhancement of SOM in terrestrial ecosystems can reduce the rate of CO_2 accumulation in the atmosphere. Climatic factors such as annual rainfall and temperature, along with agricultural management practices, are considered the major determinants of SOM maintenance (Jenny and Raychaudhary, 1960).

Despite the relatively low organic matter content in Indian soils, generally ranging from 0.1 to 1.0% and often below 0.5%, SOM plays a vital role in maintaining soil fertility and improving physical soil conditions. For sustainable crop production in tropical soils, the organic carbon content should ideally be maintained between 0.5% and 1.0% (Swarup et al., 2000). In temperate regions, restoration of soil organic matter to its original equilibrium level may require several decades, sometimes up to fifty years. Changes in SOM occur gradually in response to variations in soil carbon and nitrogen content, and these changes often become detectable only after many years.

Over the past two centuries, extensive research on SOM has considerably improved understanding of its composition, characteristics, and functions within the soil system. Significant advancements have also been made in studying different pools of soil organic carbon (SOC). However, total SOC alone is not considered an adequate indicator of soil quality because various carbon pools differ in their physical and chemical properties. Soil organic matter is broadly categorized into active and passive organic pools, both of which are highly sensitive indicators of soil fertility and productivity.

The maintenance of soil structure depends on both active fractions, such as particulate organic carbon, and passive fractions, commonly referred to as humic substances. The humic fraction is considered a major contributor to the soil's cation exchange capacity (CEC). While humus acts as an important reservoir of essential nutrients, the active SOM pool primarily supplies energy for biological activities in the soil. Humic substances also help maintain soil organic matter levels because of their strong resistance to microbial decomposition. Their role extends beyond nutrient supply and includes improvement of soil quality parameters such as aggregate stability. From an agricultural perspective, humic and fulvic acids are therefore highly important for sustaining productivity in cultivated soils.

The inert carbon pool also contributes significantly to the thermal properties of soil. Soil organic matter is composed mainly of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), and sulfur (S). However, most analytical methods estimate SOM indirectly by measuring soil organic carbon and multiplying it by a conversion factor of 1.724.

The accumulation of SOM within different soil pools is a slow and gradual process influenced by long-term management practices. Detectable changes in SOM may require more than 30 years to become apparent (Baldock and Skjemstad, 1999). Consequently, long-term field experiments are considered highly valuable for studying the dynamics of various SOM pools.

In recent years, modeling of soil organic matter has gained importance as a useful approach for understanding and managing the terrestrial carbon cycle. These models assist in predicting future changes in carbon sequestration over relatively short periods. Several researchers have developed carbon turnover models to estimate carbon dynamics under different management systems (Parton et al., 1987; Jenkinson, 1990; Smith et al., 1997).

Nutrient Fluctuation and Soil-Plant Interactions

Nutrition plays a vital role in the growth, development, and productivity of plants. In recent years, the use of both inorganic and organic nutrient sources has gained considerable importance in horticulture for achieving higher yields and improved crop quality per unit area. Nutrient imbalance is regarded as one of the major abiotic stresses limiting agricultural productivity. Crop performance is strongly influenced by several environmental factors, including temperature, climate, soil type, rainfall pattern, and overall soil health.

The increasing cost of chemical fertilizers, along with the limited purchasing capacity of small and marginal farmers, has created challenges in the use of expensive fertilizer inputs. Under such circumstances, there is a growing need to explore locally available and renewable sources of plant nutrients. Organic manures and inorganic fertilizers are becoming increasingly important in sustainable agriculture because crops can efficiently utilize nutrients supplied through these readily available sources.

The bioavailability of heavy metals in soil is greatly influenced by soil characteristics and the partitioning of metals between the soil solution and solid phases. Organic materials present in the soil can interact with heavy metals to form complexes and chelates of varying stability, thereby affecting their mobility and availability to plants. Different fertilization practices have also been shown to influence the overall structure and activity of soil microbial communities (Katiyar et al., 2012). However, establishing a direct relationship between changes in microbial activity and alterations in microbial community structure remains challenging.

Nutritional and Agricultural Significance of Vegetables

Since a large proportion of the Indian population follows a vegetarian diet, vegetables form an essential component of daily nutrition. Vegetables are important sources of carbohydrates, proteins, vitamins, minerals, fats, elemental salts, and crude fibre, all of which are necessary for maintaining nutritional balance. In addition, vegetables enhance the flavour, colour, texture, and overall appeal of food. India ranks among the leading vegetable-producing countries in the world, second only to China.

Organic manures and biofertilizers play a crucial role in crop production by correcting deficiencies of macro- and micronutrients while also improving the physical, chemical, and biological properties of soil. Sustainable agricultural production largely depends on efficient soil fertility management and a better understanding of the interaction between genetic and environmental factors affecting crop growth and development.

Although favourable environmental conditions may contribute to increased crop yield, it is not always possible to completely modify field conditions to achieve ideal plant growth. However, suitable environmental conditions can be created through proper management practices, selection of high-yielding cultivars, and balanced application of organic and inorganic fertilizers. Historically, excessive use of chemical fertilizers has helped meet crop nutrient demands, but their continuous and indiscriminate application has adversely affected soil physico-chemical properties, crop quality, and long-term productivity. Therefore, judicious and efficient use of organic manures, biofertilizers, and inorganic fertilizers is essential for sustainable crop production and soil health management.

During crop production, plants utilize sunlight, air, water, and nutrients available in the soil for synthesizing essential compounds, including nitrogen, phosphorus, and potassium (NPK). Continuous cultivation without proper nutrient management can gradually deplete soil nutrient reserves. Such depletion negatively affects crop growth, yield, soil fertility, agricultural productivity, and may ultimately lead to soil degradation.

The combined use of organic and inorganic fertilizers helps maintain and improve soil nutrient reserves by replenishing nutrients removed during harvesting. Fertilizers also assist farmers in regulating crop nutrition more effectively to achieve optimum yield. In addition to influencing productivity, fertilization practices affect post-harvest fruit quality and shelf life. These effects may include physiological changes, susceptibility to diseases, and alterations in fruit composition and texture resulting from nutrient deficiencies or imbalances.

Considering the above facts, the present investigation entitled *“Assessment of the Impact of Chemical Fertilizers on Soil Physico-Chemical Properties in the Kota Region”* was undertaken to evaluate the influence of chemical fertilizers on soil health and agricultural productivity.

Statement of Problem

“Assessment of the impact of chemical fertilizers on soil physico-chemical properties in the kota region”

Methods and Materials

Experimental Site

This experiment was carried out near Thekra canal road of Kata Land. It was prepared properly at the required depth for better root penetration and for equal distribution of irrigation and fertilization. Pure seeds of three different varieties of okra (Prabang Krantz, Area, Anemic) were used. We made some beds for our experiment. The seeds of different varieties of okra are sowed on ridges at a distance of 30 cm between rows and 30 cm between plants. We kept enough moisture for better germination. The crop had irrigated at a fixed interval. Weeding is also done at a proper interval. To find out the effects of chemical fertilizers in different quantities on the vegetative properties of the okra (A. esculentum L.) plant and biochemical properties of the soil of the Kota region, this experiment was conducted.

Kota is a city located in the south-east of the northern Indian state of Rajasthan. Kora has a semi-arid climate with high temperatures throughout the year. The temperature on averages above 40℃ - 48℃ in May and June. The average rainfall in Kota district is 660.6mm. It has an average elevation of 271m (889ft). The soil of the Kota region is black soil.

In this experiment at first, we determined the soil EC and water EC via electrodes, and soil pH and water pH were measured with the help of a digital electronic pH meter. Before application of chemical fertilizers in the soil, we took samples of soil randomly from the experimental site up to 15 cm depth and measured nutrient levels of NPC in the soil.

For the experiment in some beds, we used different NPC fertilizers singly and in the different combinations of the fertilizers at the recommended rates and above the recommended rates of fertilizers. Whether in other beds, we used levels of NPK fertilizers in the range of (20: 10: 10) kg/ha. The experiment was carried out at different rates, such as, control, at the rate of 150 kg/ha, at the rate of 200 kg/ha, at the rate of 300 kg/ha, at the rate of 350 kg/ha and more than 350 kg/ha.

For the comparison of the growth of different vegetative parts of different varieties of okra plants in the controlled manner and after the application of NPK fertilizers in various proportions, we took some pods randomly from the different rows of different varieties of okra and tagged them for sampling at various intervals of growth and development.

For this study, we used different parameters for the estimation of the effects of NPC fertilizers in different quantities on different varieties of okra plants, and also for measuring the yield of different varieties. Growth parameters include plant height, leaf area, and the day of first flower emergence, which was measured before the harvesting. After harvesting, we measured fruit length, no. of fruits, weight of a single pod etc.

Soil Sampling and Analysis

Before pursuance of the experiment, representative samples (15 cm depth) were collected from the experimental field to determine the initial physico-chemical status of the soil. Those were then subjected to mechanical and chemical analysis and results for the physical and chemical properties of the soil are presented in Table 3.1. The soil of the experimental field was sandy loam in texture, low in organic carbon and available nitrogen and medium in available phosphorus, potassium, zinc and iron and alkaline in reaction.

Table 1: Initial physico-chemical properties of the experimental field

Particulars	Values		Status	Method followed
	2022-23	2023-24		
I. Physical properties				
Coarse sand (%)	48.6	47.6		International pipette method (Piper,1966)
Silt(%)	19.0	20.0	-	
Clay(%)	32.7	32.1	-	
Soil textural class	Sandy clay loam			Triangular method (Brady and Well,1966)
II. Chemical properties of soil				
pH (1:2.5)	7.46	7.45	Alkaline	Bechman's Glass Electrode pH Meter (Jackson, 1967)
EC (1:2.5) (S m^{-1})	0.42	0.43	Normal	Solubridge Conductivity Meter in 1:2, Soil:Water suspension (Jackson 1967)
Bulk Density (g cc^{-1})	1.33	1.32	Normal	Core sampler (Jackson, 1967)
Particle density (g cc^{-1})	2.65	2.64	Normal	Picnometer (Jackson, 1967)
Aggregate stability (%)	57.31	57.30	Medium	Wet sieving method (Kemper and Rosenau, 1986)
Organic carbon (%)	0.43	0.43	Low	Walkely and Black's rapid titration method (Jackson 1967)
Available N (kg ha^{-1})	221.6	220.4	Low	kjeldahl method (Johan kjeldahl,1883)
Available P_2O_5 (kg ha^{-1})	15.6	15.4	Medium	Acid wet digestion method (HCl_4 / HNO_3) (dukfos, 1838)
Available K_2O (kg ha^{-1})	240.5	239.3	Medium	Acid wet digestion method (HCl_4 / HNO_3) method , using flam photometer (Barnes,et al, 1940)
Available Zn (ppm)	0.71	0.70	Medium	DTPA extractant and estimated on AAS (Lindsay and Norvell, 1978)
Available Fe (ppm)	4.15	4.13	Medium	DTPA extractant and estimated on AAS (Lindsay and Norvell, 1978)
III. Chemical properties of Water				
pH (1:2.5)	7.51	7.49	Alkaline	Bechman's Glass Electrode pH Meter (Jackson, 1967)
EC (1:2.5) (S m^{-1})	0.41	0.45	Normal	Solubridge Conductivity Meter in 1:2, Soil:Water suspension (Jackson 1967)

Result

Treatment Code	Treatments	pH	EC (S/ml)	Organic Carbon (%)	Available N (kg/ha)	Available P (kg/ha)	Available K (kg/ha)	Bulk Density (g/cm³)
T1	Control	7.8	0.27	0.37	165.4	12.3	278.6	1.44
T2	Organic	7.6	0.30	0.58	198.2	17.4	295.8	1.39
T3	100 mg N	7.5	0.36	0.40	225.6	13.5	282.4	1.42
T4	200 mg N	7.4	0.41	0.38	260.3	14.0	283.2	1.41
T5	400 mg N	7.2	0.64	0.34	298.5	15.6	287.5	1.39
T6	100mg P	7.7	0.35	0.42	180.5	18.4	284.8	1.43
T7	200mg P	7.6	0.39	0.40	186.2	22.6	286.0	1.42
T8	400mg P	7.4	0.58	0.36	190.4	28.9	288.1	1.40
T9	100 mg K	7.6	0.33	0.41	185.6	14.8	310.5	1.42
T10	200 mg K	7.5	0.39	0.39	192.0	15.1	325.8	1.40
T11	400 mg K	7.3	0.52	0.36	196.5	16.0	348.2	1.39
T12	20 N + 10 P + 10 K	7.4	0.38	0.50	240.2	20.8	315.6	1.40

The experiment entitled, "Assessment of the impact of chemical fertilizers on soil physico-chemical properties in the kota region". This experiment was carried out near Thekra canal road of Kota during the rabi season of 2023-24. The details of results during the course of investigation are presented in this chapter:

Effect of Different Levels of Nitrogen (N), Phosphorus (P), and Potassium (K) on Soil Physico-Chemical Properties in Kota Region

The influence of different fertilizer treatments on the physicochemical properties of soil was evident in this study. Soil pH varied from 7.2 to 7.8 across the treatments, with the control (T1) exhibiting the highest pH of 7.8 and the highest nitrogen application (T5, 400 mg N) showing the lowest pH of 7.2. This slight decrease in pH under nitrogen fertilization can be attributed to the acidifying effect of ammonium-based fertilizers, which release hydrogen ions into the soil upon nitrification. The pH under organic treatment (T2) was slightly lower than the control (7.6), indicating that organic amendments contribute to minor acidification while also buffering extreme pH changes. Treatments involving phosphorus and potassium showed intermediate pH values, suggesting minimal impact of these nutrients on soil acidity at the applied doses.

Electrical conductivity (EC), a measure of soluble salts in the soil, increased progressively with fertilizer application. The highest EC value of 0.64 S/m was recorded under T5 (400 mg N), indicating that excessive nitrogen application can elevate soil salinity. Organic treatment (T2) also showed a moderate increase in EC (0.30 S/m) compared to the control (0.27 S/m), reflecting the mineralization of organic matter and release of soluble ions. Treatments with phosphorus and potassium exhibited EC values ranging from 0.33 to 0.58 S/m, which were significantly lower than high nitrogen treatments but higher than the control. The combination treatment (T12, 20 N + 10 P + 10 K) maintained an intermediate EC value of 0.38 S/m, demonstrating a balanced increase in soluble salts without causing excessive salinity stress.

Organic carbon content, an important indicator of soil fertility and structural stability, was significantly influenced by the treatments. The highest organic carbon (0.58%) was recorded under the organic amendment (T2), confirming the role of organic inputs in enhancing soil organic matter and improving soil aggregation. Chemical fertilizer treatments, particularly high nitrogen doses, slightly decreased organic carbon levels compared to the organic treatment and control. This reduction may be due to accelerated microbial decomposition of existing soil organic matter under high nutrient availability. Phosphorus and potassium treatments exhibited moderate organic carbon values (0.36–0.42%), indicating that these nutrients alone have a limited effect on carbon accumulation. The combined nutrient application (T12) increased organic carbon to 0.50%, suggesting that integrated nutrient management promotes soil carbon retention while maintaining fertility.

Available nitrogen in the soil increased progressively with nitrogen fertilization. The control (T1) showed 165.4 kg/ha N, whereas T5 (400 mg N) recorded the highest nitrogen availability at 298.5 kg/ha. The organic treatment (T2) also enhanced nitrogen content to 198.2 kg/ha, reflecting the gradual mineralization of organic matter and its contribution to soil nitrogen. Phosphorus and potassium treatments had lower nitrogen levels compared to nitrogen-amended soils, ranging from 180.5 to 196.5 kg/ha, indicating that their influence on nitrogen availability is indirect. The integrated treatment (T12) maintained high nitrogen levels (240.2 kg/ha), demonstrating a synergistic effect of combined nutrient application on soil nitrogen dynamics.

Available phosphorus showed a marked increase with phosphorus fertilization. The control soil contained 12.3 kg/ha P, whereas the highest phosphorus treatment (T8, 400 mg P) reached 28.9 kg/ha. Organic treatment also improved phosphorus availability (17.4 kg/ha), highlighting the contribution of organic matter to phosphorus solubilization. Nitrogen and potassium treatments exhibited minor increases in phosphorus levels, indicating limited influence when applied individually. The combination treatment (T12) resulted in 20.8 kg/ha phosphorus, further supporting the benefits of integrated nutrient management in improving multi-nutrient availability.

Similarly, available potassium increased with potassium fertilization. The control had 278.6 kg/ha K, while the highest potassium treatment (T11, 400 mg K) recorded 348.2 kg/ha, demonstrating the direct effect of potassium application on soil K status. Organic amendments moderately increased potassium content (295.8 kg/ha), likely due to mineralization of organic matter. Nitrogen and phosphorus treatments showed minor improvements in potassium levels. The combination treatment (T12) provided 315.6 kg/ha K, confirming the positive impact of integrated nutrient application on multiple nutrient availability.

Bulk density, an important indicator of soil compaction and porosity, decreased slightly with fertilizer application. The control had the highest bulk density (1.44 g/cm³), indicating relatively compact soil. Organic treatment (T2) exhibited the lowest bulk density (1.39 g/cm³), reflecting improved soil structure and porosity due to organic matter incorporation. Nitrogen, phosphorus, and potassium treatments showed minor reductions in bulk density, ranging from 1.39 to 1.42 g/cm³, indicating marginal improvement in soil physical properties. The combination treatment (T12) had a bulk density of 1.40 g/cm³, suggesting that balanced nutrient management can enhancesoil structure while maintaining nutrients availability.

Overall, the results indicate that organic amendments and integrated nutrient management improve soil fertility by enhancing nutrient availability (N, P, K) and increasing organic carbon, while also improving physical properties such as bulk density. Excessive nitrogen application, although increasing available nitrogen, can lead to slight acidification and higher soil salinity, emphasizing the need for balanced fertilization. The study highlights the importance of combining organic and inorganic fertilizers to achieve sustainable soil fertility, improved soil structure, and optimal nutrient balance for crop production.

Effect of Absence of Fertilizers on Soil Nutrient Status and Plant Growth Parameters in Kota Region

Parameter	**Symbol / Unit**	**Normal Range in Fertilized Soil**	**Observed Value in Unfertilized Soil (Control)**	**Deficiency Status**	**Impact on Plant Growth**
Soil pH	–	7.0 – 7.5	7.9	Slightly alkaline	Reduces solubility of P, Fe, and Zn
Electrical Conductivity	S/m	0.3 – 0.6	0.22	Low	Poor ion movement and nutrient mobility
Organic Carbon	%	0.5 – 0.8	0.32	Deficient	Low microbial activity, weak structure
Available Nitrogen	kg/ha	250 – 350	160	Deficient	Stunted growth, yellowing of leaves
Available Phosphorus	kg/ha	20 – 25	10.8	Deficient	Poor root growth, delayed flowering
Available Potassium	kg/ha	300 – 350	260	Slightly low	Weak stems, poor fruit formation
Available Sulphur	kg/ha	15 – 25	8.5	Deficient	Thin stems, yellowing in young leaves
Available Zinc (Zn)	mg/kg	1.0 – 1.5	0.48	Deficient	Leaf bronzing, reduced yield
Available Iron (Fe)	mg/kg	4.0 – 6.0	2.3	Deficient	Interveinal chlorosis in young leaves
Available Manganese (Mn)	mg/kg	2.0 – 3.5	1.1	Deficient	Yellow mottling, low photosynthesis

The results of the present study evidentlydesignate that the application of fertilizers significantly influences the physico-chemical properties and nutrient status of soils in the Kota region. The observed variations in pH, electrical conductivity (EC), organic carbon, and available macronutrients (N, P, K) across treatments can be theoretically explained through fundamental soil–plant–fertilizer interactions.

- **Effect on Soil pH and Electrical Conductivity**

Soil pH serves as an important indicator of nutrient availability and overall soil health. In the present study, higher levels of chemical fertilizer application, particularly nitrogen and phosphorus at 200 mg and 400 mg rates, resulted in a slight reduction in soil pH along with an increase in electrical conductivity (EC). This trend can be explained by the formation of acidic by-products, such as nitric and phosphoric acids, during nitrification and related soil chemical processes, as well as the accumulation of soluble salts within the soil profile.

From a soil chemistry perspective, continuous application of high fertilizer doses contributes to the release of hydrogen ions (H^+), leading to ionic imbalance in the soil system. This ultimately results in a gradual decline in soil pH and a corresponding rise in soil salinity levels. These observations are consistent with the concept of soil acidification under intensive fertilizer use, as discussed by Brady and Weil (2019).

- **Role of Organic Matter and Microbial Activity**

The treatment involving organic manure (FYM) resulted in a noticeable improvement in soil organic carbon content along with a reduction in bulk density. From a theoretical perspective, the incorporation of organic materials enhances soil structural stability, increases cation exchange capacity (CEC), and promotes the development of microbial biomass within the soil.

Soil microorganisms actively decompose organic residues into humic substances, which contribute to the formation and stabilization of soil aggregates, thereby improving nutrient retention and overall soil quality. These processes align with the humification theory, which describes how organic residues are gradually transformed into stable organic compounds that act as a slow-release source of nutrients, supporting sustained soil fertility over time.

- **Nitrogen Dynamics in Soil**

Nitrogen availability was found to be highest in treatments receiving 400 mg nitrogen and in the combined fertilizer application (20 N + 10 P + 10 K). Nitrogen fertilizers contribute directly to soil nitrogen levels by increasing the concentration of ammonium and nitrate forms, which are readily available for plant uptake and significantly support vegetative growth.

However, excessive nitrogen application can result in considerable losses through leaching and volatilization. According to the Nitrogen Cycle Theory, a portion of applied nitrogen is naturally lost from the soil system through processes such as denitrification and gaseous emissions, particularly under conditions that favor microbial activity, such as in heavier soils found in the Kota region. Therefore, maintaining moderate nitrogen application levels along with organic matter incorporation is considered essential for achieving a balanced nitrogen supply and sustaining long-term soil fertility.

- **Phosphorus and Potassium Behavior**

Phosphorus availability showed a progressive increase with higher phosphorus application rates (100–400 mg). However, at elevated levels, a slight tendency toward soil acidity was observed along with possible phosphorus fixation. According to the Phosphate Fixation Theory, in alkaline soils phosphorus can react with calcium ions to form insoluble calcium phosphate compounds, thereby reducing its plant-available form.

Similarly, potassium content increased in response to higher potassium fertilizer doses. Nevertheless, excessive potassium application may create nutrient imbalances in the soil and may also induce antagonistic interactions with other essential nutrients such as magnesium and calcium, thereby affecting their uptake and overall plant nutrition.

- **Deficiency in Unfertilized Soil**

In the unfertilized (control) plots, clear deficiencies of nitrogen, phosphorus, potassium, and micronutrients were observed. The lack of external nutrient supplementation leads to continuous nutrient mining under repeated cropping, which gradually depletes the soil nutrient reserves and reduces overall soil fertility.

According to the Law of the Minimum (Liebig, 1840), plant growth is governed by the nutrient that is in the shortest supply relative to the plant's requirements. Therefore, in the absence of fertilizer application, nutrient limitations directly restrict plant growth, reduce chlorophyll formation, and ultimately lower the yield potential of the crop.

- **Effect of Balanced and Integrated Nutrient Management**

The combined application of nitrogen, phosphorus, and potassium (20 N + 10 P + 10 K) resulted in the most balanced soil nutrient status among all treatments. From a theoretical standpoint, balanced fertilization promotes synergistic interactions among nutrients, thereby improving nutrient uptake efficiency and enhancing root absorption capacity.

The concept of Integrated Nutrient Management (INM) emphasizes the judicious use of both organic and inorganic nutrient sources to maintain long-term soil fertility and ecological stability. The performance of this treatment aligns well with the INM framework, as it supports improved nutrient recycling, sustains soil productivity, and helps reduce the risk of environmental degradation caused by excessive or unbalanced fertilizer use.

- **Long-Term Soil Health Perspective**

From a theoretical perspective, sustainable soil management in the Kota region depends on maintaining a proper balance between nutrient inputs and nutrient losses. Excessive application of chemical fertilizers may provide a short-term increase in nutrient availability and crop productivity; however, continuous and unbalanced use can gradually deteriorate soil structure, reduce microbial activity, and negatively affect long-term soil fertility.

In contrast, the incorporation of organic matter helps to preserve soil ecological balance by improving physical condition, enhancing microbial diversity, and supporting nutrient cycling processes. Therefore, the integration of organic and inorganic nutrient sources is essential for sustaining soil health, maintaining productivity, and ensuring long-term environmental stability.

Discussion

The influence of chemical fertilizers and organic manure on soil pH was clearly evident in the present investigation. Soil pH values ranged from 7.2 to 7.8 across different treatments, indicating the slightly alkaline nature of soils in the region. The highest pH value (7.8) was recorded in the control treatment, suggesting that in the absence of external nutrient inputs, the soil retained its natural alkaline condition. However, application of nitrogen fertilizers resulted in a gradual decline in soil pH, with the lowest value (7.2) observed under the 400 mg nitrogen treatment. This reduction may be attributed to the acidifying effect of nitrification, during which ammonium released from nitrogen fertilizers is converted into nitrate by soil microorganisms, releasing hydrogen ions and thereby increasing soil acidity. These findings are consistent with the commonly reported effect of ammoniacal nitrogen fertilizers in lowering soil pH over time.

Application of organic manure also caused a slight reduction in soil pH compared with the control treatment, although the decline was relatively mild. This may be due to the buffering action of humic substances present in organic matter, which helps stabilize soil reaction and prevent drastic changes in pH. Treatments receiving phosphorus and potassium fertilizers exhibited intermediate pH values, indicating that these nutrients have comparatively less influence on soil reaction than nitrogen fertilizers.

Electrical conductivity (EC), an important indicator of soluble salt concentration in soil, increased with increasing fertilizer levels. The lowest EC value (0.27 S/m) was recorded in the control treatment, reflecting the low concentration of soluble salts in unfertilized soil. In contrast, higher nitrogen applications considerably increased EC, with the maximum value (0.64 S/m) observed under the 400 mg nitrogen treatment. This increase may be associated with the accumulation of soluble nitrate, sulfate, and other ions in the soil solution. Phosphorus and potassium fertilizers also caused moderate increases in EC, suggesting that chemical fertilizers generally contribute to higher soluble salt concentrations in soil. Organic manure increased EC only slightly because nutrients from organic sources are released gradually through mineralization processes. This issue is particularly significant in the Kota region, where high evapotranspiration and low rainfall favor salt accumulation in surface soil layers.

Soil organic carbon is a key indicator of soil fertility, structural stability, and biological activity. The present study revealed that application of organic manure resulted in the highest organic carbon content (0.58%), representing a significant increase over the control and chemical fertilizer treatments. This improvement may be attributed to the addition of organic residues that enhance soil aggregation, water-holding capacity, microbial activity, and overall soil structure. In contrast, higher nitrogen treatments slightly reduced organic carbon levels (0.34%), possibly because increased microbial activity accelerated the decomposition of existing organic matter. The integrated nutrient treatment (20N + 10P + 10K) also recorded relatively high organic carbon content (0.50%), indicating that combined application of organic and inorganic nutrient sources supports both nutrient availability and carbon enrichment. These findings support the established view that continuous use of chemical fertilizers alone may reduce soil organic matter over time, whereas integration of organic amendments helps maintain long-term soil health.

The availability of major nutrients - nitrogen, phosphorus, and potassium, improved significantly with fertilizer application. Available nitrogen increased markedly from 165.4 kg/ha in the control treatment to 298.5 kg/ha under the highest nitrogen application. This clearly demonstrates the direct contribution of nitrogen fertilizers toward increasing soil nitrogen availability. Organic manure increased available nitrogen to 198.2 kg/ha through gradual mineralization, while the integrated NPK treatment supplied 240.2 kg/ha, indicating a more balanced and sustained nutrient supply.

Available phosphorus also increased significantly with phosphorus fertilization, reaching 28.9 kg/ha under the 400 mg phosphorus treatment compared with 12.3 kg/ha in the control. Organic manure improved phosphorus availability to 17.4 kg/ha, possibly because organic acids released during decomposition reduced phosphorus fixation through chelation mechanisms. Potassium availability increased from 278.6 kg/ha in the control treatment to 348.2 kg/ha under the highest potassium application. Organic manure and integrated nutrient treatments also contributed to moderate increases in potassium availability due to improved cation exchange capacity and release of non-exchangeable potassium from clay minerals.

These observations confirm that chemical fertilizers rapidly enhance nutrient availability, while organic amendments play a crucial role in nutrient retention, buffering capacity, and long-term sustainability of soil fertility.

Bulk density, an important physical property of soil, affecting root penetration, aeration, and water infiltration, also varied under different nutrient treatments. The highest bulk density (1.44 g/cm³) was recorded in the control treatment, indicating compact soil with limited pore space. Slight reductions in bulk density were observed under chemical fertilizer treatments (1.39–1.42 g/cm³), possibly due to improved root growth resulting from better nutrient availability. However, the greatest reduction in bulk density occurred under organic manure and integrated nutrient treatments, where values decreased to 1.39–1.40 g/cm³. This reduction reflects improved soil aggregation and structural stability resulting from the incorporation of organic matter. Lower bulk density promotes better root development, improves water movement, and enhances microbial activity within the soil.

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