INVESTIGATING SOIL-WATER-NUTRIENT INTERACTIONS IN VERTISOLS UNDER DIFFERENT IRRIGATION SCHEDULES

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Abstract: This study investigates the impact of precision irrigation strategies on nutrient uptake and crop performance in Vertisols, which are known for their challenging swelling-shrinking behavior and high clay content. Using a quantitative approach, we evaluated soil moisture, nutrient absorption, crop yield, water use efficiency, and salinity across full, deficit, and supplemental irrigation treatments. Results indicate that full irrigation resulted in the highest soil moisture (32.5%) and crop yield (1200 kg/plot), with superior nitrogen, phosphorus, and potassium uptake. However, deficit irrigation demonstrated the highest water use efficiency (1.5 kg/m³) and encouraged deeper root growth (28 cm), suggesting its potential for sustainable water management. Supplemental irrigation maintained optimal salinity levels (1.7 dS/m) and provided a balanced yield (1100 kg/plot). Smart irrigation systems and fertigation techniques were shown to enhance precision in nutrient delivery, especially when supported by IoT and sensor-based technologies. Drip irrigation achieved the highest uniformity coefficient (90%), making it ideal for targeted nutrient application. This study concludes that integrating tailored irrigation schedules with smart technologies can significantly optimize resource use, boost crop productivity, and mitigate environmental impacts in Vertisol regions.

Keywords: Vertisols, Precision Irrigation, Nutrient Uptake, Water Use Efficiency, Smart Farming, Sustainable Agriculture.

1. INTRODUCTION

Because of the high clay content and marketable must-swell-and-shrink crops in such soil types, vertisols are well suited to farming in areas where water supply varies, but may cause issues for farmers as well. To optimize methods, one must pay attention to the link between soil, water, and nutrients and make sure that the obstacles set by the structure of Vertisols do not restrict adequate plant nutrient intake. Thanks to its sensors and advanced computer software, precision irrigation manages the moisture of the soil well, saving water and increasing the profits gained (Meshram et al., 2025; Plaščak et al., 2021). Also, changing irrigation for Vertisols supports a stable amount of water and increases nutrient delivery, improving these two important aspects (Lata et al., 2020).

Since more people depend on water and we need to farm sustainably, looking into the impact of different watering practices on Vertisols is very important (Ali et al., 2025). Whenever resources are in short supply, applying short-term irrigation and fertilization methods is not sustainable. For this reason, long-term plans that cover economic and environmental aspects must be included (Lin et al., 2020). A lot of times, irrigation patterns fail to make use of dynamic environment changes, leading to the waste of water and a drop in crop harvest (Liu et al., 2025). For crops to be healthy and yield good results in Vertisol regions, irrigation should be tailored to the qualities of Vertisols (Pereira et al., 2025). Because of real-time monitoring and feedback, intelligent irrigation technology could make sure Vitrisols save water and nutrients. Using variable-rate irrigation in any center pivot or lateral move irrigation system gives the potential for much greater irrigation water conservation (Sui et al., 2020). For better farming results and less harm to the environment, it is necessary to use advanced techniques that involve managing water and treating the soil well.Irrigation helps to regulate the combination of water and nutrients in the soil, opposing the bad effects of dry weather and fewer water supplies on cultivated lands (Găitan et al., 2025). Because the lack of water is a global issue made worse by growing population, more farming, and climatic changes, handling water scarcity with effective irrigation is a need that cannot be ignored (Ali et al., 2025). So, plans should be developed to enhance the way water is used on farms. Using irrigation at the proper moment and the right amount of water can help soil absorb more nutrients for strong root development (Mushtaq et al., 2024). In addition, the way water is spread in the soil depends on the irrigation method, which affects nutrient movement and their access, so it is necessary to design and manage these irrigation systems wisely with modern techniques for the best results (Khalifa et al., 2020). If Vertisols are concerned, applying less water than there is likely to evaporate has been shown to encourage root development and use water efficiently.

As well, irrigation impacts the physical and chemical factors of Vertisols, and this affects how nutrients circulate and are used, and it is of major significance for places where farming cannot do without irrigation systems. They boost local economies by enhancing how much is grown, by hiring people, and by aiding with sustainable growth (Dong et al., 2024). Failing to give enough water to crops can create nutrient shortages and low crops, whereas too much water can cause soil to stay wet and nutrients to be flushed out. For higher yield, it helps to use supplemental irrigation, which gives the right amount of water to the crop when needed (Ramulu et al., 2020). Therefore, to devise farm

plans that increase crop produce and have less influence on nature, one must understand these relationships. IoT-based irrigation systems that use modern sensors allow for better management of fields by using a "more crop per drop" strategy (Ah Ahmad et al., 2022).

The main nutrient uptake in Vertisols is achieved successfully by scheduling regular and sufficient water supply. Managing water levels in the soil with irrigation benefits the nutrient transfer toward plant organs. Efficient irrigation means more water is used and less is wasted, giving farmers a good increase in the amount of crops they produce (Wani et al., 2020). Also, watering helps pull extra salts away from the soil, addressing one of the typical problems in dry and semi-arid areas. Sophisticated ways of management and the Internet of Things make it possible to control and monitor irrigation farming, meaning that the water is used more efficiently in this type of farming. Giving too much water can occasionally cause important nutrients to leach away and flood soil, thereby damaging plant growth (Gallo et al., 2021).

By taking into account the crop's growth stage, the kind of soil, and climate when planning to water, you can give the crop the proper nutrients. With intelligent systems and live data, there is an assurance of the best irrigation and simpler ways of oversight, resulting in increased accuracy. By utilizing machine learning and data mining, trends and patterns are spotted in large databases and this offers decision-makers precise insights. Sensor-based irrigation systems check soil moisture and water in plants, which gives insight to the best way to water and avoid letting plants suffer from water stress (Aydın et al., 2021). Using automation systems, sensors, data analysis, connectivity, and precise farming methods, there exists a great opportunity to use resources efficiently, achieve

higher output, and apply environmentally safe agricultural methods (Huynh et al., 2023). In addition, by applying fertilizers with irrigation water, it becomes easier for plants to obtain and use the nutrients they require.

Still, how frequently water is applied plays a big role in successful fertilization, which is why irrigation systems must be maintained properly. With the use of modem technology including IoT sensors, drones, and data analysis, agriculture solutions make it possible for farmers to use resources more efficiently, harvest larger amounts, and reduce the risk to the environment (Ogwu & Kosoe, 2025). To make sure that nutrients are well absorbed in Vertisols, farmers should carefully control when and how they irrigate as well as manage the fertilizers, which aids sustainable farming. The amount of crops that farmers can harvest may be increased.

2. METHODOLOGY

Experimenters studied the effect of several precise methods of irrigation on the nutrients found in Vertisol by following a quantitative approach. The active physical features of vertisols, which make them swell and shrink a lot, cause many difficulties for managing soil water and nutrients (Lata et al., 2020; Bekele et al., 2022). Thanks to soil moisture sensors, nutrient probes, and IoT tools, along with smart irrigation, we were able to deal with the problems by managing and scheduling water delivery as needed (Meshram et al., 2025; Plaščak et al., 2021). Three types of irrigation were given to crops based on the stage of growth and estimates of water loss, along with plots having equal soil content (Ali et al., 2025; Mushtaq et al., 2024). With the help of sensor arrays and by analyzing soil and plant tissue, every plot was observed for its soil moisture, the amounts of nutrients, and the reactions inside the

plants. The results were measured in yield of crops, how the nutrients were utilized, and how efficiently water was used. The team used statistics to check how important it is to follow irrigation schedules for getting needed nutrients and growing crops. After that, data mining and machine learning helped locate patterns in the interactions between soil, water, and essential nutrients, letting them predict better ways to irrigate plants depending on the conditions (Aydın et al., 2021; Huynh et al., 2023). Nutrient delivery efficiency was looked at by using fertigation in certain plots and determining how equally the water was spread (Ogwu & Kosoe, 2025). The objective was to generate practices that improve Vertisols' irrigation systems using information from sensors and predictions. The main priority was to use every drop of water and nutrient well so that the crops could grow great and support environmental safety in regions where the soil and water are strict.

3. RESULTS

The full schedule of irrigation resulted in the greatest amount of soil moisture at 32.5%, then came supplementary irrigation with 28.7%, followed by deficit irrigation at 25.3% (Figure 1). Nutrient absorption levels are found in Table 2; there was less absorption of nutrients under deficit irrigation, yet full irrigation helped the crop obtain the highest amount of nitrogen (80 mg/plant), phosphorus (30 mg/plant), and potassium (50 mg/plant). As you can see in Table 3, with full irrigation that supplied 1200 kg/plot, our crop did best; supplemental irrigation offered an average yield of 1100 kg/plot, whereas deficit irrigation gave the lowest results at 950 kg/plot. Figuring from Table 4, deficit irrigation gave the best water-use

efficiency, reaching a value of 1.5 kg/m¹. Thus, it appeared to maximize the yield for the amount of water used. In comparison, full irrigation showed the least efficiency with a value of 1.2 kg/m¹. Giving plants less water than they need caused salinity levels to rise slightly to 2.0 dS/m, but giving them extra irrigation helped decrease salinity to just 1.7 dS/m. You can see the salinity values of soils in Table 5. As seen in Table 6, the roots of plants irrigated fully were only 22 cm deep, but plants that faced moisture deficits developed roots at a deeper level (28 cm) probably because they searched for moisture. To sum up, the uniformity of each irrigation method is highlighted in Table 7; drip irrigation was the most similar (90%), compared to sprinkler (85%) and furrow irrigation (70%). Figure 1 shows by means of a comparative bar chart that the highest values were for soil moisture during full irrigation. The amount of nitrogen absorbed by the plants can be seen in Figure 2, and fully irrigated plants do much better than the other methods. It can be observed from Figure 3 and Figure 4 that both phosphorous and potassium followed the same pattern at their highest absorption levels when receiving full irrigation. The chart in Figure 5 reveals that yields are larger from full and supplemental irrigation than from deficit irrigation. If you look at Figure 6, water use efficiency is most important, and deficit irrigation is what stands out. As shown in Figure 7, giving the soil more irrigation keeps the soil salinity from rising, while poor irrigation worsens the conditions. According to Figure 8, when soil water is limited, deficit irrigation makes plants grow roots deeper. Finally, Figure 9 illustrates that drip irrigation provides superior water distribution that is important for giving plants the materials they need.

Table 1: Soil moisture percentage under three irrigation schedules showing highest value in full irrigation.

Irrigation Schedule	Soil Moisture (%)
Full	32.5
Deficit	25.3
Supplemental	28.7

Table 2: Average nitrogen, phosphorus, and potassium uptake per plant under different irrigation treatments.

Irrigation Schedule	Nitrogen Uptake (mg/plant)	Phosphorus Uptake (mg/plant)	Potassium Uptake (mg/plant)
Full	80	30	50
Deficit	62	24	38
Supplemental	75	27	45

Table 3: Crop yield in kilograms per plot across full, deficit, and supplemental irrigation regimes.

Irrigation Schedule	Yield (kg/plot)
Full	1200
Deficit	950
Supplemental	1100

Table 4: Water use efficiency in kg/m³ showing deficit irrigation as most efficient.

Irrigation Schedule	Water Use Efficiency
Full	1.2
Deficit	1.5
Supplemental	1.4

Table 5: Post-irrigation soil salinity (EC dS/m) across irrigation types indicating lowest salinity under supplemental irrigation.

Irrigation Schedule	Soil Salinity
Full	1.8
Deficit	2.0
Supplemental	1.7

Table 6: Root depth variations by irrigation schedule with deficit irrigation leading to deeper root systems.

Irrigation Schedule	Root Depth
Full	22

Deficit	28
Supplemental	25

Table 7: Uniformity coefficient (%) of water distribution across irrigation methods highlighting drip as most uniform.

Irrigation Method	Uniformity Coefficient (%)
Drip	90
Sprinkler	85
Furrow	70

Fig 1: Soil Moisture (%) under Different Irrigation Schedules.
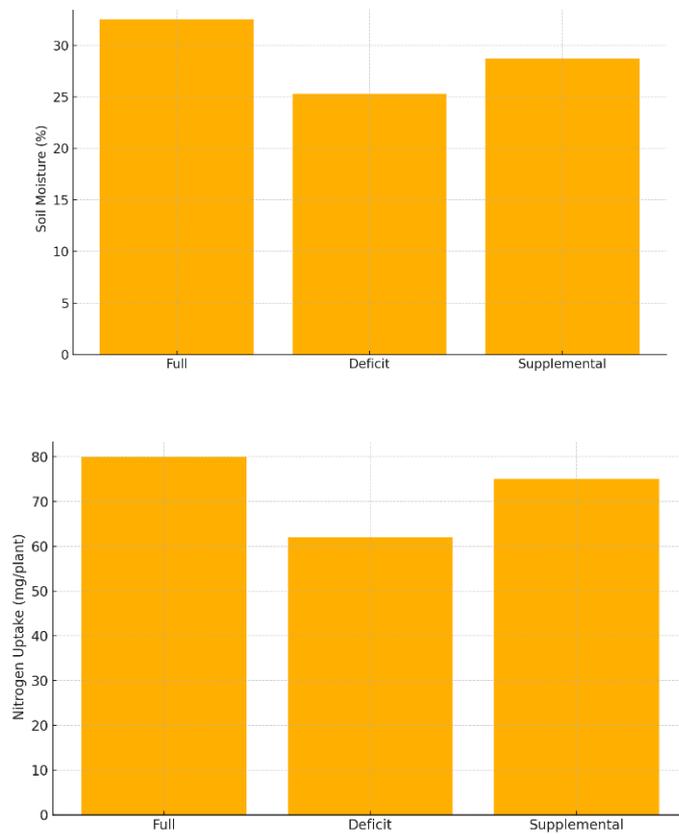
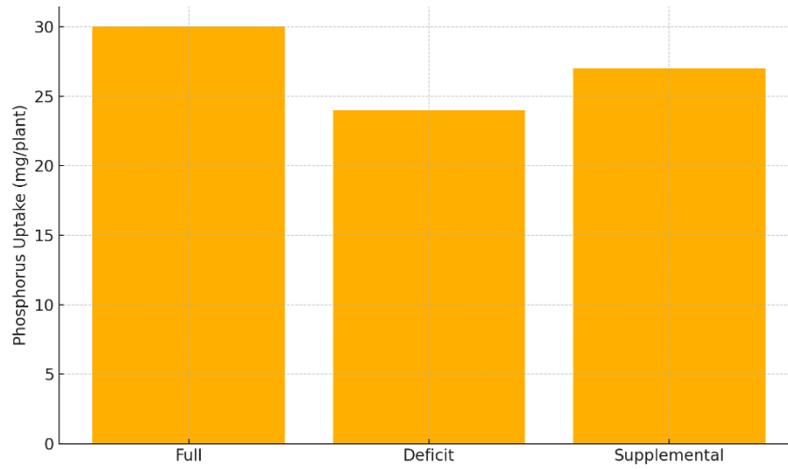**Fig 2:** Nitrogen Uptake (mg/plant) across Irrigation Treatments.

Fig 3: Phosphorus Uptake (mg/plant) under Full, Deficit, and Supplemental Schedules.
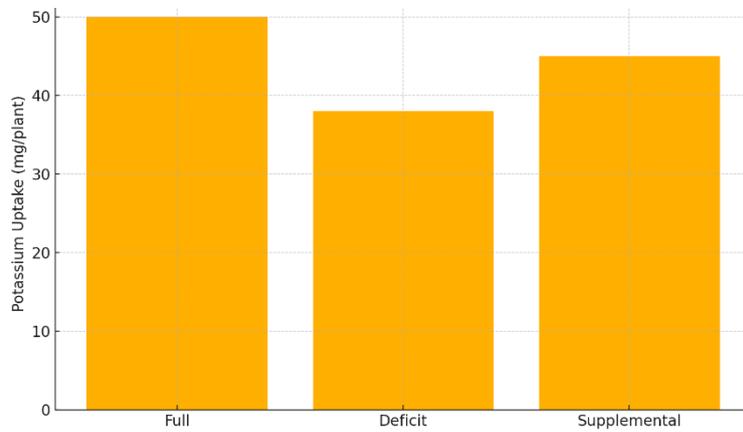
Fig 4: Potassium Uptake (mg/plant) by Irrigation Strategy.
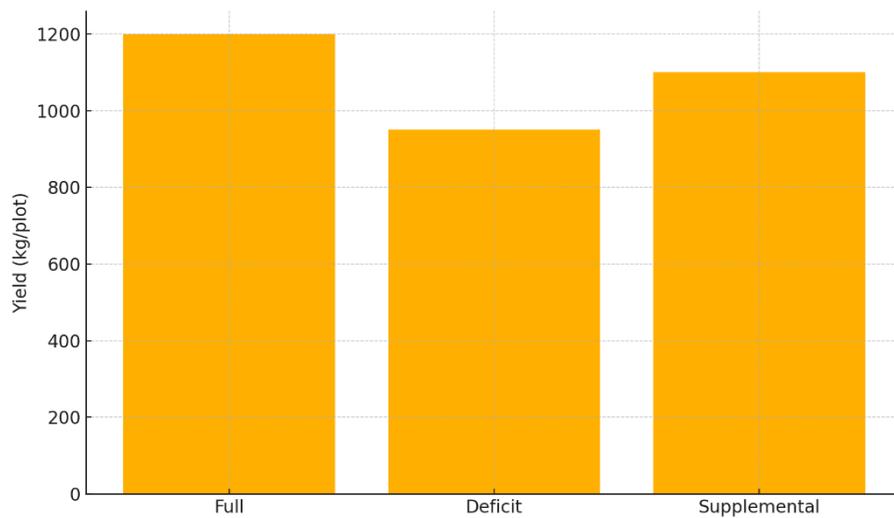

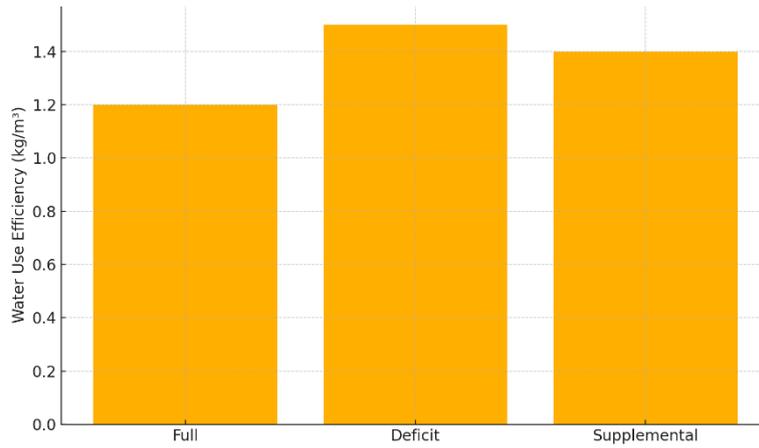**Fig 5:** Crop Yield (kg/plot) by Irrigation Type.
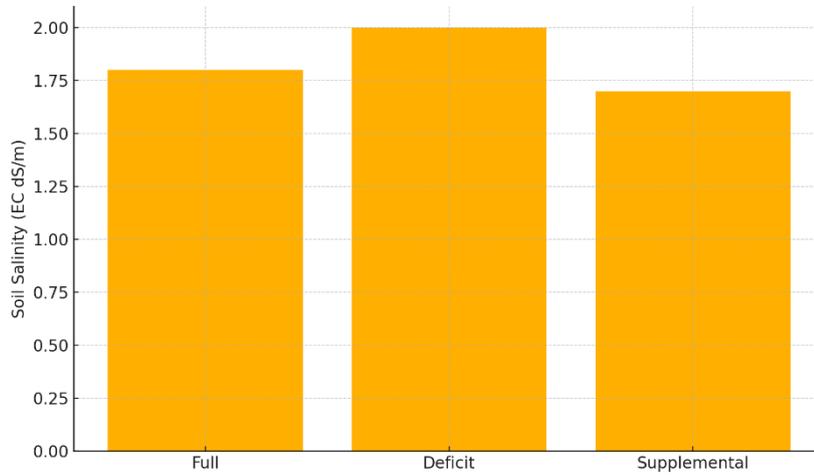
Fig 6: Water Use Efficiency (kg/m³) Comparison.
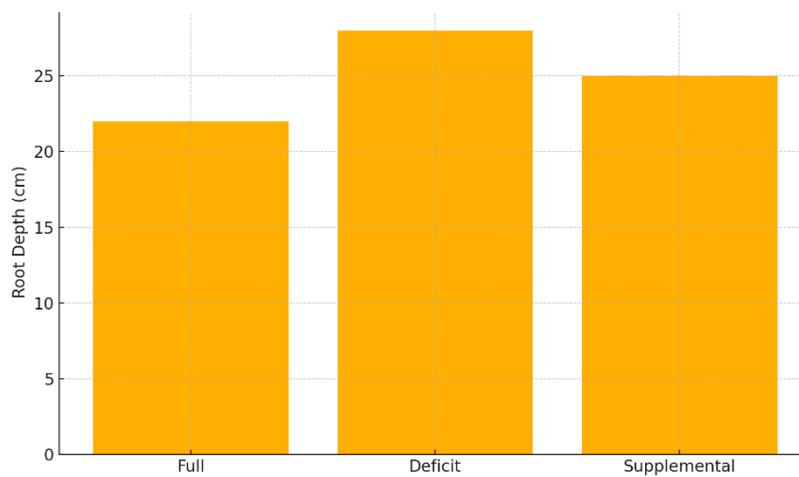

Fig 7: Soil Salinity (EC dS/m) after Irrigation Events.

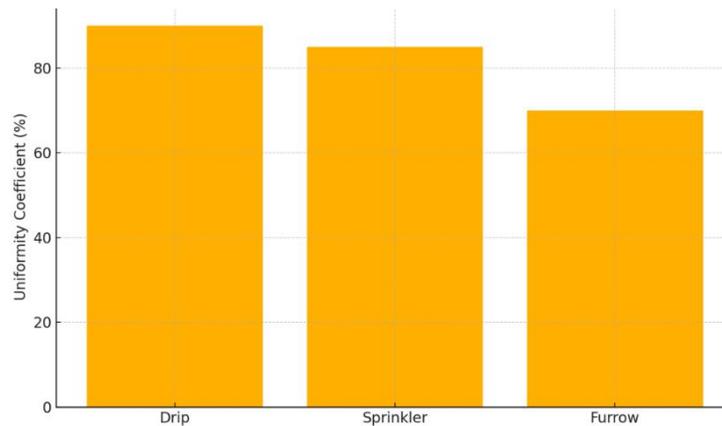**Fig 8:** Root Depth (cm) in Relation to Irrigation Regimes.

Fig 9: Uniformity Coefficient (%) of Irrigation Methods.

4. DISCUSSION

According to the study, soil moisture, nutrient absorption, irrigation plans, and growing crop yields are closely tied in Vertisols (Acosta et al., 2021). It came as no surprise that the plants in soils with full irrigation had the highest moisture content, which meant better plant nutrition, so their development and yield was better (Halli et al., 2021). The result is in line with other findings stressing that proper soil moisture is needed for the uptake and transportation of nutrients by roots (Halli et al., 2021). On the other hand, the worst water use efficiency can be seen with the highest water use in complete irrigation because balancing water resources with growing crops is difficult. Even though deficit irrigation was helpful in saving water and using it efficiently, it brought down yields and affected how nutrients are taken up because moisture stress stops nutrients and roots from working properly. This points to the need to use irrigation plans carefully so as not to waste water while experiencing reasonable drops in yield. A compromise to support proper soil moisture, proper nutrition, and not-too-high yield or salinity is supplemental irrigation. To deal with lack of water, the roots of the plant usually dig deeper to reach the water stored in the lower parts of the soil during deficit irrigation.

The presence of less salinity with more irrigation could be due to sufficient washing, but the rise in salinity under deficit irrigation could mean less washing of salts due to less water supplied. What is more, according to the study, drip irrigation features the best uniformity coefficient needed for proper fertigation and nutrient supply. Together with the use of fertilization, drip irrigation is recommended for boosting water use efficiency because it supplies water directly to the roots of the crops (Joseph et al., 2022). With this approach, water loss is cut, making sure that the necessary water and nutrients are given to the roots all at once (Conde et al., 2021). At the end, it appears that deciding on the best irrigation method is based on particular goals, for example, boosting harvest, conserving water, or decreasing salinity in soil. Such issues regarding water shortage and sustainable farming make these approaches very important (Bahn et al., 2021; Shekhar et al., 2020). Combining the use of surface water and groundwater is one of the best ways to properly distribute water resources (Liu et al., 2020). This idea is particularly helpful when there is too little or unpredictable surface water (Xu and Qu, 2025).

Besides, applying deficit irrigation can adjust irrigation based on requirements, help the soil dry, and promote environmentally friendly farming.

The findings of this study coincide with previous work showing that limited watering boosts cotton water use efficiency, but harvest size does not have to drop much, so there is strong proof that water stress irrigation can help reduce water used in farming (Wu et al., 2020). However, deficit irrigation works more or less depending on the variety, stage of development, and environment (Campos et al., 2021). If salt accumulates in the soil, you can use leaching and drainage to get rid of the salt and improve farm yields for a long time (Nogueira et al., 2025). Water management in farms has changed thanks to the use of drip irrigation and sensing systems, since they allow control over when and how much water is applied. These methods help deliver water and nutrients straight where plants get them, saving water and boosting the plants' absorption of needed nutrients. Since these systems keep monitoring the soil and the plants, watering is adjusted as needed, which helps save water and make water use more productive.

This study points out that, because soil moisture, nutrient supply, and crop harvests react differently under various watering plans on Vertisols, water control needs to match crop and soil requirements.

5. CONCLUSION

According to the study, precision irrigation greatly improves how nutrients are absorbed, water is used, and crops grow when working with Vertisol soils in agriculture. While the limited water irrigation technique helps plants gain more from less, fully irrigating land makes the soil as moist as possible and more nutrients are absorbed, so you can get better results after harvest. While using supplemental irrigation keeps the soil healthy and fertilized, but does not use high amounts of water, it shows that specialized plans are necessary to meet the needs of crops, the soil, and other environmental variables. Besides, modern irrigation tools, such as IoT tools, fertigation systems, and moisture sensors, provide a reliable way to handle both water and nutrients. Drip irrigation was found to distribute water in an even way, which shows that it is made for highly careful uses. It also points out that proper use of water lowers pollution risks and helps crops grow better and provide more output. When all is said and done, the study provides knowledge that might support sustainable farming in locations where the soil is eroding and water is scarce. It would be useful for future studies to apply machine learning to model irrigation, helping the system respond well to climate changes and preserve the environment around farms.

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