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Sustainable Agriculture: The Role of Soil Physics and Irrigation Technology in Water Conservation

Salih M. Salih[1*], Harith Sadaa Madhan Al-Fahdawy[2], Khdyar Yaes Khdyer Al-Kubissi[3], Ahmed Ashour Enad[1], Mohammed Ismail Khalaf Al-Fahdawy[2]

[1] Upper Euphrates Center for Sustainable Development Research, University of Anbar, 31001 Ramadi, Iraq
[2] Center for Desert Studies, University of Anbar, 31001 Ramadi, Iraq
[3] Department of Chemistry, College of Science, University of Anbar, 31001 Ramadi, Iraq

[*] Correspondence: Salih M. Salih (Salih.alfahd@uoanbar.edu.iq)

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Abstract: This research explores the important role of soil physics and irrigation technology in water conservation in sustainable agriculture. With increasing global water shortage and wasteful irrigation practices posing a threat to agricultural productivity, water use optimization is critical. The study seeks to evaluate soil physical properties influencing irrigation efficiency, contrast various irrigation techniques, examine the effect of fertilization on water quality, and categorize farms according to irrigation performance. Mixed methods utilize statistical modeling, exploratory data analysis (EDA), and K-means clustering to assess soil properties, irrigation efficiency, and water-saving methods. The research identifies that precision irrigation methods like subsurface and drip irrigation substantially increase water-use efficiency through reduced evaporation and runoff. Organic matter and soil texture are important in retaining moisture, affecting irrigation requirements. Overfertilization is associated with nitrogen runoff, highlighting the significance of the regulated application of nutrients to avoid groundwater pollution. Another unique contribution of the research is using clustering methods to categorize farms according to their irrigation efficiency and providing specific suggestions for improving water use. The study offers actionable recommendations for farmers, policymakers, and environmental agencies to promote precision irrigation, sustainable soil management, and data-driven decision-making to maximize agricultural water conservation. Such findings add value to global efforts towards sustainable food security and environmental conservation.

Keywords: Sustainable agriculture; Soil physics; Irrigation technology; Water conservation; Soil moisture retention; Water-use efficiency (WUE)

1 Introduction

Food security and economic stability depend on agriculture worldwide, but increased demand puts pressure on natural resources, particularly water [1–3]. Population growth and climate change only augment water scarcity, challenging sustainable food production. Effective water management is necessary to ensure productivity with reduced environmental impact [4]. Irrigation is critical in crop production, especially in dry areas, but traditional approaches usually involve wastewater and overuse of resources [5]. Merging soil physics concepts with new irrigation technologies can improve water-use efficiency and aid sustainable agriculture [6].

Water is a fundamental agricultural catalyst affecting plant development, land quality, and farming sustainability [7]. Optimizing water usage becomes essential because of water scarcity and increasing climate stress [8]. Water loss, soil erosion, and decreased yield result from destructive irrigation practices combined with poorly managed soils, so sustainable water practices become crucial [9].

Soil physics is responsible for water retention, infiltration, and availability. Soil texture and organic matter influence irrigation efficiency [10, 11]. Precision irrigation methods, such as drip and subsurface irrigation, minimize water wastage relative to conventional methods, such as flood irrigation, to enhance sustainability [12].

Agriculture is amongst the biggest users of freshwater resources in the world. The soaring demand for food production with reduced water availability calls for efficient water conservation methods [13]. Proper irrigation methods can enhance water use efficiency (WUE), regulate soil moisture levels, and increase crop yield while reducing harmful environmental effects like groundwater depletion and soil salinization [14].

Soil physics plays a significant role in irrigation efficiency and water retention. Soil's capacity to capture and hold water depends on porosity, permeability, and the presence of organic matter [15]. Various soil types must be addressed to achieve maximum moisture retention through irrigation [16]. Clay and loam soils tend to hold more water and hence do not require frequent irrigation, whereas sandy soils have high drainage rates, so better soil management practices like mulching and organic matter application are required [17].

1.1 Theoretical Framework

Soil physics plays a foundational role in understanding irrigation performance, as soil properties directly influence water availability, infiltration, retention, and loss. Key parameters such as soil texture, porosity, and organic matter content determine a soil's capacity to store and transmit water, which in turn affects the timing, method, and quantity of irrigation required.

Soil texture—the relative proportion of sand, silt, and clay—governs the pore size distribution within the soil matrix. Coarse-textured soils like sandy soils have larger pores and therefore high permeability but low water-holding capacity. In contrast, fine-textured clay soils retain water more effectively due to smaller pores and capillary forces, albeit at the cost of slower drainage and potential waterlogging.

Porosity is another critical parameter that influences how much water a soil can hold at field capacity. Higher total porosity generally indicates a greater water retention capacity, but the arrangement and connectivity of pores (i.e., pore geometry) determine whether water will be retained in plant-available form or lost to deep percolation.

Organic matter improves both porosity and water retention. It acts like a sponge, absorbing water and holding it in a form that plants can access, while also improving soil structure and nutrient availability.

The K-Means clustering methodology utilized in this study classifies farms based on combined indicators of irrigation efficiency, soil texture class, infiltration rates, and water retention parameters. However, to ensure this method is theoretically grounded, the clustering algorithm implicitly assumes that differences in these soil properties lead to distinct irrigation needs and efficiencies. For instance, a cluster characterized by clay-rich, organic-matter-heavy soils with high porosity would inherently reflect lower irrigation frequency and higher water use efficiency (WUE). In contrast, clusters associated with sandy soils may display high irrigation frequency and lower water retention.

To operationalize soil physics within the clustering framework, each key soil parameter—texture, porosity, infiltration rate, and organic matter content—was numerically quantified and included as input variables in the K-Means clustering algorithm. Soil texture, categorized based on sand, silt, and clay proportions, influences water movement and retention capacity, enabling the algorithm to distinguish between farms requiring frequent irrigation (e.g., sandy soils) and those with longer water retention (e.g., clay-rich soils). Porosity and infiltration rates, derived from field measurements, help differentiate farms where water is absorbed quickly and possibly lost to percolation versus those where water stays within the root zone. Organic matter content enhances both water-holding capacity and nutrient availability, thereby increasing irrigation efficiency; its presence in the dataset allows clustering to reflect biologically enriched soils versus degraded ones. As a result, farms with similar soil-water dynamics naturally group into clusters—such as high-efficiency zones with clayey, organic-rich soils requiring minimal irrigation, or low-efficiency zones with sandy, low-organic soils demanding more frequent irrigation. This integration ensures that the clustering reflects functional agronomic behavior, not just statistical proximity, making it a practical decision-support tool for zone-specific irrigation management.

2 Literature Review

Although sustainable agriculture requires water conservation that impacts crop production, soil fertility, and the environment, by reducing waste and improving water use, efficient irrigation and the management of soil wastes are more efficient. High-tech agricultural practices have been developed due to research on irrigation technologies, soil properties, and conservation techniques.

Hatfield and Dold [18] showed that crops' WUE was the amount of biomass or grain output per unit of water intake. At leaf and canopy levels, they explored the impact of climatic conditions, such as temperature, precipitation, and CO_2 levels, on WUE. Their work found that elevated CO_2 initially improved WUE but that excessive temperature stress reduced this benefit. Canopy-level WUE was affected by soil water evaporation, crop residue management, and transpiration. To improve WUE and mitigate climate change effects, improving mulching, optimum row spacing, and irrigation management was important. Lakhiar et al. [19] proposed PISs as a means of alleviating global freshwater deficiencies. The study reviewed how PISs increase water efficiency, enhance yields, and minimize environmental impact. They reviewed advanced irrigation practices, real-time monitoring, data exchange technologies, and the incorporation of AI into irrigation management. According to the study, PISs led to more precise application of irrigation, meaning they increased the efficiency of irrigation much better than traditional systems. According to the study, as the environment continues to become more aware, its PISs will be central to sustainable agriculture.

Umair et al. [20] examined the application of groundwater in the North China Plain (NCP), where water scarcity is also increasing due to over-exploitation as a consequence of double cropping. They compared water loss and evapotranspiration (ET) under surface drip, flood, and subsurface drip irrigation. Subsurface drip irrigation resulted in ET reductions of 26% less than flood irrigation and 15% less than surface drip irrigation with no reduction in yield. The water productivity of the crop improved by 24.95% and irrigation water by 19.59% [20]. It showed that subsurface drip irrigation is effective in improving WUE and maximizing yields, and thus, it provided a conclusion that subsurface drip irrigation is an option to improve WUE and maximize crop yield. Jägermeyr et al. [21] estimated global irrigation efficiencies using a process-based model (LPJmL) to estimate water consumption and potential savings. They estimated surface, sprinkler, and drip irrigation and reported extreme variations in efficiency by region. The lowest efficiency ($< 30\%$) was in South Asia and sub-Saharan Africa, and the highest efficiencies ($> 60\%$) were in Europe and North America. World irrigation water withdrawal was put at 2469 km^3, of which 1257 km^3 were utilized, and 608 km^3 were lost through evaporation and inefficiencies. A sprinkler or drip irrigation transition would reduce non-beneficial use by 54% and 76%, respectively [21]. The article emphasized the need for advanced irrigation systems to minimize water loss and maximize crop yields.

El-Beltagi et al. [22] investigated the role of mulching in soil and water conservation, particularly in dryland agriculture. The study set out to verify that mulching inhibited surface evaporation, maintained soil temperature, checked erosion, and increased nutrient cycling. Organic mulches, including crop residues and manure, conditioned the soil to be more aggregated and increased microbial growth, making it more watertight [22]. The study established that mulching is a green activity that significantly contributes to the conservation of water and soil and, hence, should take priority over artificial replacements for sustainability over the long term. Sarvade et al. [23] examined soil and water conservation practices to fight land degradation in India. Finally, they realized that soil erosion had cost the Planet the loss of 5.3 billion tonnes of topsoil per year, and 146.8 million hectares of land was degraded. These issues were worsened by intensive agriculture and excessive exploitation of groundwater. The study suggested that vegetation-based and mechanical methods can be used to conserve soil erosion and increase water-holding capacity. In addition, sustainable land management was also promoted through government programs [23]. The results from this study indicated that addressing soil health for sustainable agricultural productivity will require integrating conservation practices with policy support.

2.1 Problem Statement and Research Significance

Despite the progress in soil conservation and irrigation, ineffective water utilization is a significant challenge for agriculture. Excessive irrigation, inadequate drainage, nutrient leaching, and low levels of adoption of precision irrigation are some of the challenges facing agriculture due to factors like high costs and low technical skills. Wastage of water and soil erosion, along with groundwater pollution, emerge from these factors. Furthermore, despite collaborative attempts in water-saving research, there remain gaps in consolidating irrigation technologies, soil physics, and precision agriculture in a unified conceptual framework. Even though a few have debated irrigation efficiency [18, 20], soil water storage [22], and conservation practices [23], fewer have debated their interlinks in detail using data-centric means. Additionally, while precision irrigation [19] and global efficiencies [21] have been explored, empirical support from state-of-the-art statistical and machine-learning techniques is lacking.

This study addresses the above gaps by applying exploratory data analysis (EDA) and K-Means clustering to integrate soil physics, irrigation performance, and water quality metrics, offering specific suggestions on how water usage can be optimized, and sustainable irrigation management improved. The study adds value to sustainable water management alongside precision agriculture by identifying optimal irrigation methods and soil preservation strategies. The advantages for farmers include efficient water resource management, better soil quality preservation, and budget savings. Policy executives can create lasting irrigational regulations based on these outcomes, whereas environmental officials can track farming-related water pollution while implementing reduction methods. Further research on sustainable agriculture continues through the scientific approach made possible by this study. This research combines soil surveys with contemporary irrigation methods alongside data analytics to enhance water utilization while promoting sustainable farming for broader food security goals.

3 Research Method

This research adopts a mixed methods approach, combining both qualitative and quantitative data to evaluate water conservation practices in sustainable agriculture. Case studies were conducted across diverse farm types selected to reflect variability in agro-climatic conditions, soil composition, and irrigation methods. The quantitative component involves statistical modeling and K-Means clustering to assess the performance of soil and irrigation systems, while the qualitative analysis evaluates land management strategies and irrigation scheduling practices.

A systematic methodology was followed, beginning with an extensive literature review of soil physics, irrigation techniques, and water conservation measures. This was supplemented by primary data collected through on-site observations and surveys and secondary data from agricultural databases. Data preprocessing ensured consistency, followed by EDA and clustering to classify irrigation performance and moisture conservation. Comparative analysis was used to determine the relative efficiency of irrigation techniques in preserving soil moisture.

3.1 Data Collection and Preprocessing

The data was collected from 10 representative agricultural sites across various climatic zones, including arid, semi-arid, and sub-humid regions. The farms were chosen using stratified purposive sampling, ensuring inclusion of different soil types (sandy, loamy, clayey), topographies, and irrigation practices (drip, sprinkler, flood). The goal was to ensure representativeness and capture the diversity of Indian agricultural settings.

The study selected 10 representative agricultural sites using stratified purposive sampling to capture diversity across India's major climatic zones (arid, semi-arid, and sub-humid). Inclusion criteria required that farms: (1) were under active cultivation for at least two consecutive seasons, (2) used a consistent and clearly defined irrigation method (drip, sprinkler, or flood), (3) had accessible historical and on-site data for soil and irrigation, and (4) allowed regular field monitoring. Farms were excluded if they exhibited mixed or inconsistent irrigation practices, showed signs of severe land degradation or urban encroachment, or lacked complete meteorological records. To account for external influences such as weather variability, daily meteorological data (rainfall, temperature, humidity, wind speed) were integrated for each site throughout the study period. Seasonal and daily variability in soil moisture and irrigation performance was adjusted using weather normalization techniques, ensuring that observed patterns reflected true soil- and management-based differences rather than climatic fluctuations.

The datasets encompass:

- Soil Characteristics: Texture, moisture content, porosity, bulk density, pH, and organic matter content.
- Irrigation Performance: Water application rate, irrigation duration, system type, and drainage capacity.
- Agricultural Practices: Tillage methods, crop residue management, fertilizer and pesticide usage.
- Water Conservation Indicators: Groundwater level, precipitation, evapotranspiration, and surface runoff.
- External factors, especially weather conditions, were accounted for by including daily meteorological data such as rainfall, temperature, humidity, and wind speed during the study period. This helped control for seasonal variability that might influence irrigation effectiveness or soil moisture retention.

Data preprocessing steps included:

- Median imputation for missing values and logical substitution for categorical gaps.
- Encoding of categorical data for model compatibility.
- Outlier detection using boxplots for extreme values in water use and soil metrics.
- Standardization of continuous variables, such as irrigation depth and soil porosity, for consistent scaling.

3.2 Data Analysis Techniques

(1) Exploratory data analysis (EDA)

EDA identified underlying patterns and relationships between soil and irrigation variables using:

- Descriptive statistics (mean, SD)
- Visual tools (boxplots, heat maps, scatterplots)
- Correlation matrices to detect multicollinearity

(2) Clustering analysis

K-Means clustering was employed to group farms based on irrigation efficiency:

- Cluster 1: High-efficiency farms with minimal water loss
- Cluster 2: Moderate-efficiency farms with partial drainage issues
- Cluster 3: Low-efficiency farms with excessive water usage

Feature scaling and the Elbow Method determined the optimal number of clusters (k = 3).

3.3 Focus Areas in Soil Physics, Irrigation Efficiency, and Drainage Management

The clustering model in this study was integrated with key theoretical soil physics parameters such as soil texture, porosity, and organic matter content, which are known to influence water retention, infiltration, and drainage characteristics. Soils with finer texture and higher organic matter generally demonstrated greater irrigation efficiency due to their enhanced capacity to retain moisture. The study evaluated multiple irrigation systems in this context. Drip irrigation was assessed for its point-source delivery effectiveness and its ability to minimize evaporation. Sprinkler systems were examined based on their area coverage and susceptibility to water loss through wind drift. Flood irrigation, a traditional method, was analyzed for its inherent inefficiencies and was used as a baseline to compare the performance of more advanced systems. Additionally, controlled drainage systems and water table management strategies were examined for their contribution to reducing unnecessary water loss and maintaining optimal soil aeration, thus supporting sustainable agricultural practices.

3.4 Validation and Cross-Referencing

The reliability of the findings was reinforced through a multi-layered validation strategy that strengthened the credibility and applicability of the study's conclusions. First, cross-validation with established research on irrigation methods and soil–water interactions ensured that the observed patterns aligned with prior empirical and theoretical evidence. Secondly, comparative case studies highlighted real-world efficiency differences among drip, sprinkler, flood, and subsurface irrigation systems—providing a practical benchmark for the clustering results. Finally, literature triangulation was employed to substantiate the link between fertilization practices and nitrogen runoff, drawing on research on nutrient leaching and water quality effects. Together, these methods provided a robust, context-aware evaluation of water conservation strategies, enhancing confidence in the study's recommendations for sustainable agriculture. To ensure consistency and accuracy in data collection, the study employed standardized protocols for evaluating both irrigation performance and soil characteristics.

3.5 Irrigation Efficiency Assessment

Irrigation efficiency was quantified using Water Application Efficiency (WAE), calculated by measuring the ratio of water retained in the root zone to the total volume of water applied. Field data were collected using Time Domain Reflectometry (TDR) soil moisture sensors before and after irrigation events. In addition, gravimetric soil moisture analysis was performed to verify sensor readings. For each farm, water input was recorded using flow meters or estimated through irrigation schedules and discharge rates, enabling comparative analysis across different irrigation systems (drip, subsurface, and flood).

3.6 Soil Texture Measurement

Soil texture was determined using the Bouyoucos hydrometer method, following standard USDA soil classification guidelines. Soil samples were collected from the top 0–30 cm layer, air-dried, sieved (2 mm), and treated with dispersing agents to break down aggregates. The proportions of sand, silt, and clay were computed based on sedimentation rates. Each sample was analyzed in triplicate to ensure reliability and reproducibility of results.

3.7 Justification for Clustering Method and Determination of Optimal Clusters

The K-Means clustering algorithm was selected due to its computational efficiency, scalability to large datasets, and ability to generate compact, easily interpretable clusters based on continuous numerical features. Compared to hierarchical clustering, which becomes computationally intensive with increasing sample size, and DBSCAN, which is sensitive to parameter tuning and less suited for high-dimensional continuous data with overlapping density, K-Means offered a more robust and interpretable framework for segmenting farms based on multivariate irrigation and soil characteristics.

To determine the optimal number of clusters (K), the Elbow Method was applied. This involved plotting the within-cluster sum of squares (WCSS) against increasing values of K and identifying the point where additional clusters resulted in marginal reductions in WCSS—a visual inflection referred to as the "elbow." In this study, the elbow point was clearly observed at $K = 3$, indicating that three clusters provided an optimal balance between model simplicity and explanatory power. This was further validated through visual inspection of the WCSS curve and supported by agronomic domain knowledge, which suggested three distinct farm typologies based on irrigation efficiency and soil-water dynamics.

4 Results and Discussion

Water saving is a central component of sustainable agriculture, and understanding the interactions among soil physics, irrigation technologies, and water-use efficiency is key to maximizing agricultural practices. The study results are reported in this section, including EDA and clustering analysis of irrigation efficiency. Furthermore, data exploration was conducted to examine important variable distributions, assess the correlation between soil characteristics and irrigation efficiency, and determine trends in water savings. Statistical and graphical methods were used to reveal significant patterns and insights.

4.1 Distribution of Harvest Yield

A histogram test was carried out to examine the diversity of yield harvests on various farms, as shown in Figure 1. Figure 1 indicates that the majority of the farms produce between 6 to 10 tons per hectare (tons/ha) and hence is the most frequent productivity range. Fewer farms have productivity levels greater than 10 tons/ha, whereas some have as low as 2 tons/ha. The distribution seems moderate, even with some fluctuations. The KDE curve indicates a minor right skew; hence, a few farms have extremely high productivity levels. These results underscore the contribution of contemporary irrigation methods to productivity, whereas bad soil and water management can be responsible for diminished yields.

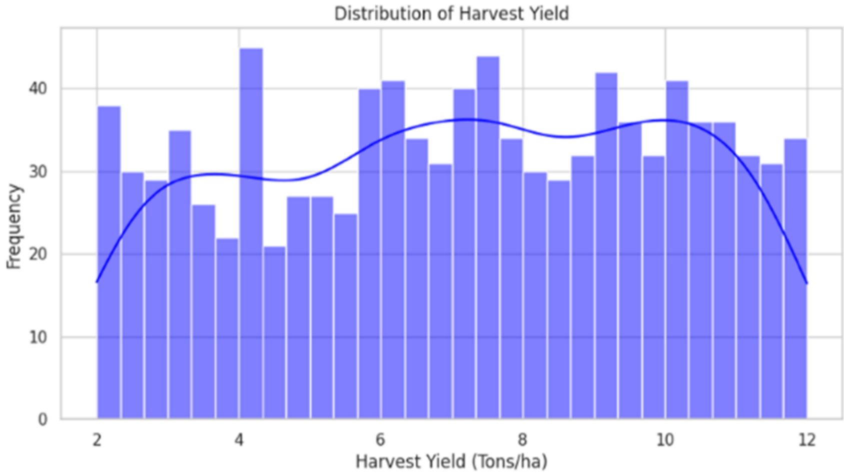

Figure 1. Distribution of harvest yield across farms

4.2 Irrigation Type vs. Water Usage

A comparative study was conducted through a boxplot (Figure 2) and a tabular comparison (Table 1) to compare the efficiency of four prominent irrigation methods—drip, sprinkler, flood, and subsurface irrigation. The table compares these irrigation systems systematically, emphasizing their water use efficiency (WUE), significant benefits, and drawbacks. Table 1 indicates that subsurface and drip irrigation are the most efficient methods, with efficiency rates ranging from 85-95%. These methods reduce evaporation and directly distribute water to the roots, providing optimal use of the resource. Sprinkler irrigation is moderately efficient at 70-85% and is adaptable for many crops but suffers from some evaporation losses as well as energy needs. Flood irrigation is the least efficient (30-50%) because of the high wastage of water through runoff and deep percolation and, therefore, is less sustainable even though it is low in the initial cost. Figure 2's boxplot reveals that flood irrigation has the highest water usage, up to 500 mm/year, as expected of an inefficient system. Drip and subsurface irrigation have the lowest use, approximately 250-300 mm/year, underpinning their efficiency. Sprinkler irrigation is in between but varies based on climate and soil differences. The results reinforce the necessity of transitioning from flood irrigation to more water-efficient systems such as drip and subsurface irrigation.

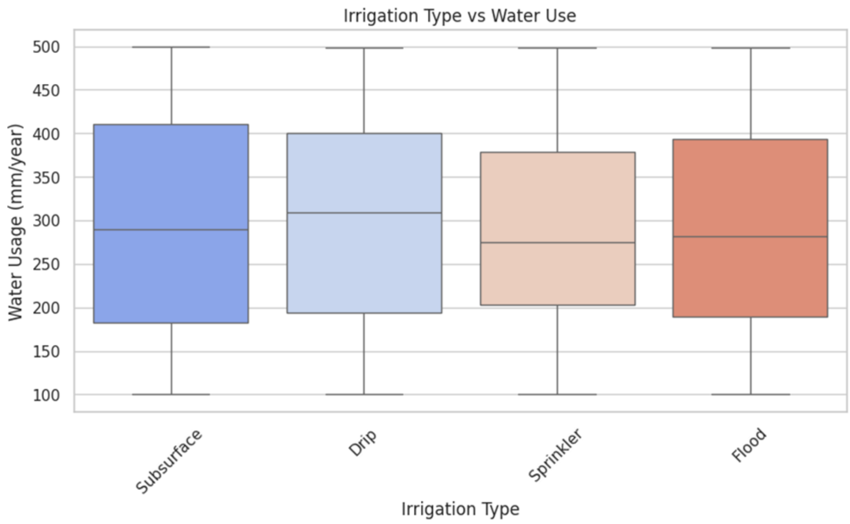

Figure 2. Comparison of water usage by irrigation type

The research emphasizes the importance of efficient irrigation techniques in the conservation of water. Accordingly, the results are in line with previous studies [18, 19] and indicated that drip and subsurface irrigation were the most efficient at reducing water loss and optimizing crop uptake. Overall, flood irrigation consumed the most water and consequently was inefficient because of evaporation and runoff [21]. Such evidence shows the need for precision irrigation, especially in regions with scarce water.

Table 1. Comparison of major irrigation methods

Irrigation Type	WUE	Advantages	Limitations
Drip irrigation	90–95%	Highly efficient, reduces evaporation, delivers water directly to roots	High installation costs, requires maintenance
Sprinkler irrigation	70–85%	Even distribution, applicable to various crops	Moderate evaporation losses, require energy for pumping
Flood irrigation	30–50%	Simple, low-cost system	High water wastage, runoff, and deep percolation losses
Subsurface irrigation	85–95%	Prevents surface evaporation, effective in dry areas	High setup cost, potential clogging issues

4.3 Soil and Water Quality Assessments

Adequate water and soil management is essential to sustainable agriculture, influencing crop health, irrigation, and environmental quality. Water retention is influenced by soil texture, whereas fertilizers determine water usage and quality. This section discusses the issues of soil moisture retention and nutrient leaching, providing optimal water use in agriculture strategies.

4.3.1 Soil texture and moisture retention

Soil texture determines the water-holding capacity and water requirements for irrigation. A boxplot (Figure 3) compares moisture levels in silty, sandy, clayey, and loamy soils, showing which holds more water and requires more frequent irrigation. This can assist farmers in choosing appropriate irrigation and soil management techniques to minimize water loss. According to Figure 3, loamy and clayey soils retain the highest moisture (about 25%), lowering irrigation requirements. Sandy soils retain the least (as little as 5%), necessitating regular irrigation. Silty soils exhibit moderate retention but with fluctuation. Organic amendments, mulching, and more efficient irrigation scheduling can improve farms with sandy soils to enhance water retention. These results indicate the significance of soil texture ineffective irrigation planning.

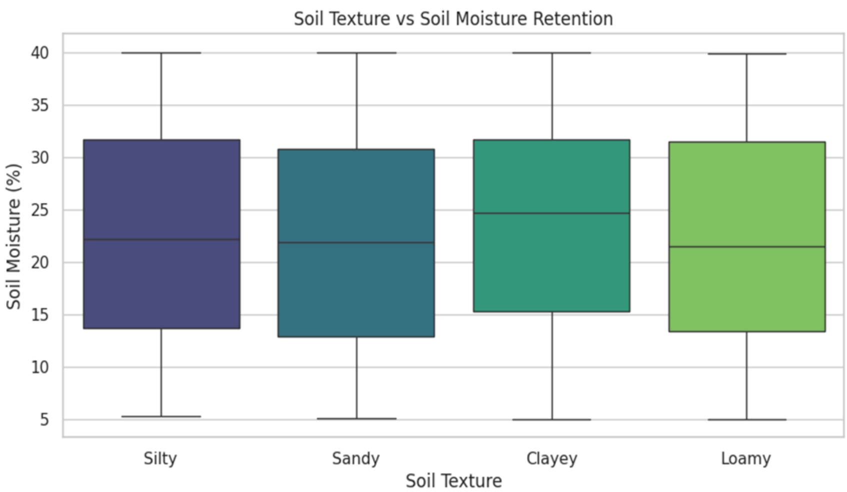

Figure 3. Soil texture vs. soil moisture retention

The finding was that soils with different textures determined different moisture holding and irrigation needs. The results showed that clayey soils and loamy soils have much higher moisture retention compared to sandy soils and, therefore, decrease irrigation frequency. This follows well with studies [20, 22], stating that soil texture determines water retention and irrigation planning. Drainage was higher, and irrigation requirements were greater for areas with lower water holding capacity, as with sandy soils. This implies that conservation methods such as mulching and organic matter amendments are needed on sandy soil farms to increase water retention, thereby reducing the probability of quick drainage losses.

4.3.2 Fertilizer application vs. nitrogen runoff

Overuse of fertilizer results in leaching of nutrients and groundwater pollution, particularly with poor irrigation. The scatterplot of Figure 4 indicates the relationship between fertilizer application rates (kg/ha) and nitrogen load (mg/L) in drainage water. It indicates trends in nitrogen runoff and over-fertilization risks, stressing the importance of sustainable fertilizer management to minimize environmental impact. Figure 4 indicates that greater fertilizer application rates (over 200 kg/ha) increase nitrogen runoff, usually over 40 mg/L. Lower application rates (less than 100 kg/ha) produce less runoff, usually less than 20 mg/L. Variability indicates that soil type, irrigation practices, and rainfall also affect leaching. Flood irrigation exacerbates nitrogen runoff, which points to the importance of precision fertilization methods such as split applications and slow-release fertilizers in reducing nutrient loss and water quality protection.

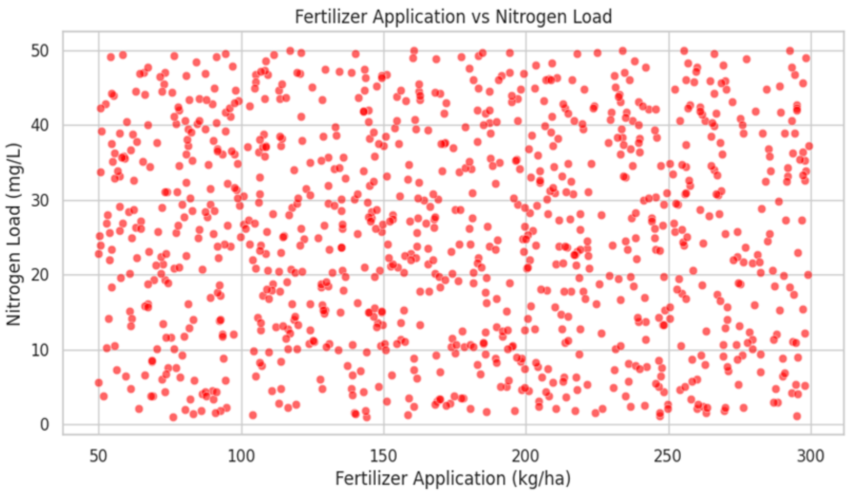

Figure 4. The relationship between fertilizer application and nitrogen runoff

This research makes the link between excessive fertilizer use and nitrogen runoff evident, as it is what have found [23]. The results confirmed that the farms that used fertilizers above 200 kg/ha leached considerable nitrogen into drainage water, often in excess of 40 mg N load/L of drainage water. Excessive runoff is likely to lead to contamination of groundwater and eutrophication. High water application aggravated nitrogen leaching as it enhanced the movement of nutrients into the drainage system and increased the drain efficiency of Gutfreund. The results indicate that precision fertilizer application methods, including split application and slow-release fertilizers, help curb nutrient loss but maintain soil fertility without environmental damage.

4.3.3 Water quality distribution

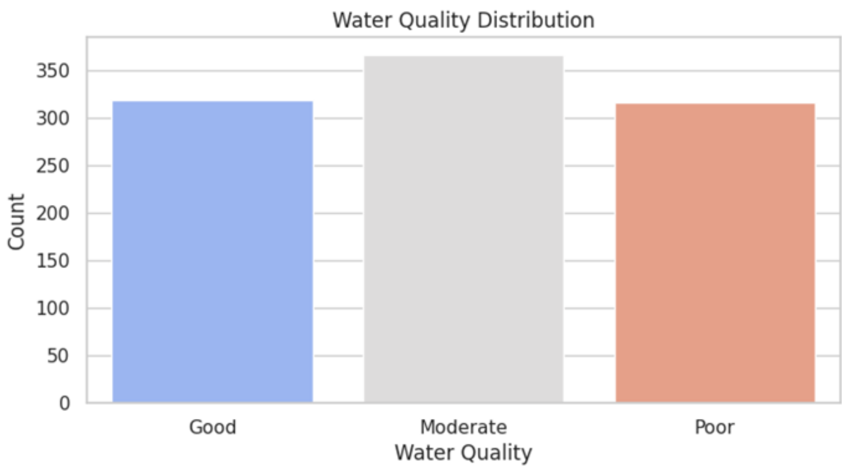

Figure 5. Water quality distribution across farms

Figure 5 bar chart classifies water quality as Good, Moderate, and Poor levels, noting differences between farms. Fertilizer runoff, irrigation practices, and soil conditions affect water quality. The classification identifies farms requiring interventions to mitigate contamination and enhance water management to support sustainable agriculture. Figure 5 indicates that the majority of farms have moderate water quality (350 samples), followed by good (320) and poor (310). Poor water quality is caused by high nitrogen and phosphorus runoff due to excessive fertilizers. Farms with drip irrigation and controlled drainage had improved water quality, while flood irrigation resulted in high runoff and pollution. These findings emphasize the importance of sustainable irrigation and fertilization practices.

4.4 Correlation Analysis of Irrigation and Soil Factors

A K-Means clustering model categorized farms in terms of irrigation efficiency based on soil moisture, amount of irrigation, and drainage flow. This indicated farms with ideal water management and farms with more water loss. Figure 6 (Correlation Heatmap) also explored correlations between irrigation habits, soil properties, and water retention, emphasizing major factors determining water conservation. The heatmap comparison shows little association between fertilizer use and irrigation efficiency, meaning their independence. An average positive relationship implies alkaline soils have a greater water retention capacity, whereas a low negative relationship indicates uncontrolled drainage does not necessarily result in nutrient loss. These indicate the intricacies of irrigation efficiency, which is affected by the soil texture, irrigation method, and drainage regulation.

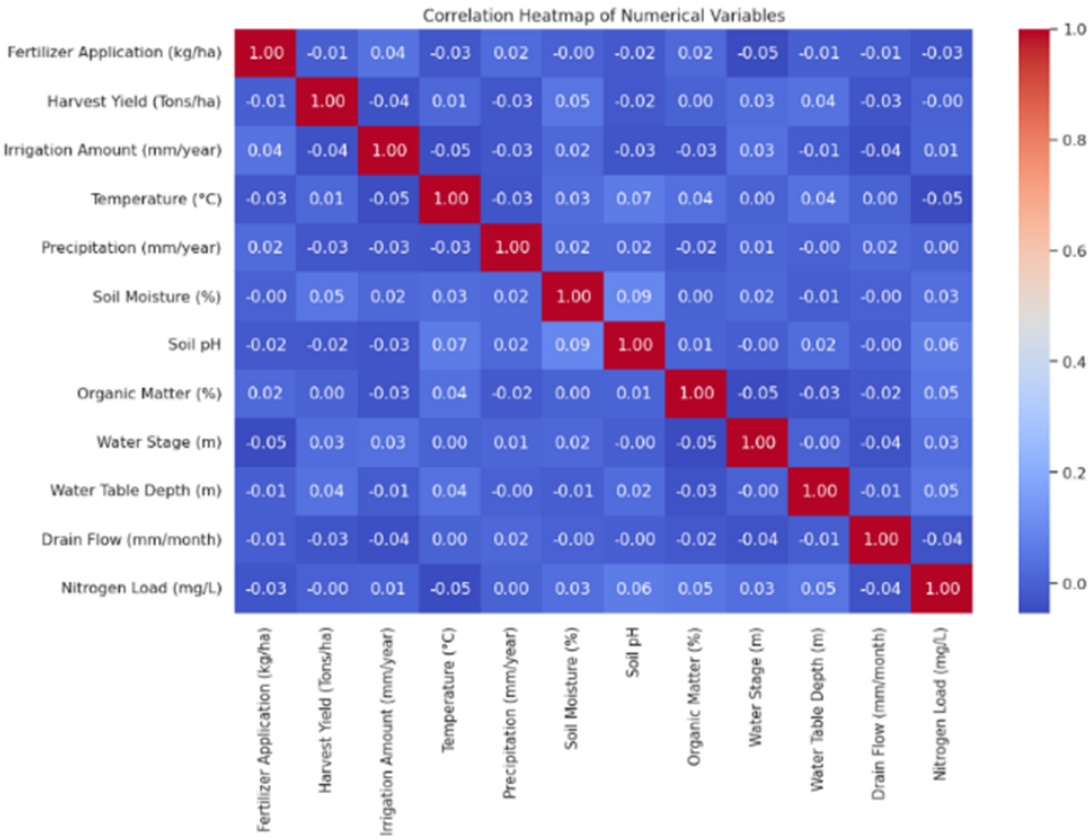

Figure 6. Correlation heatmap of numerical variables

4.4.1 Farm categorization based on irrigation performance

Table 2. Categorization of farms based on water usage efficiency

Cluster	Category	Key Characteristics
Cluster 1	High-Efficiency Farms	Low irrigation use, high soil moisture retention, minimal drainage loss
Cluster 2	Moderate-Efficiency Farms	Balanced irrigation efficiency, moderate moisture retention, some drainage loss
Cluster 3	Low-Efficiency Farms	High irrigation use, excessive drainage flow, lower soil moisture retention

K-Means clustering classified farms into high, moderate, and low-efficiency categories, as shown in Table 2, providing a data-driven analysis of irrigation performance. This helped identify key traits influencing irrigation efficiency across different farm types.

• High-efficiency farms predominantly used drip and subsurface irrigation, had lower water usage, and exhibited optimal soil moisture retention.

• Moderate-efficiency farms utilized sprinklers and controlled flood irrigation, demonstrating balanced irrigation strategies but with room for further optimization.

• Low-efficiency farms relied on flood irrigation, experienced excessive drainage loss, and suffered from inefficient water retention, leading to significant resource wastage.

This categorization provides practical insights for policymakers and farmers to implement targeted water conservation strategies based on farm-specific irrigation performance. Clayey soils retain more water than silty soils due to their finer particle size and greater surface area, which significantly enhances their capacity for capillary water retention. In the specific conditions of this study, clayey soils demonstrated superior moisture-holding ability because they form small, tightly packed pores that slow down water movement and reduce drainage. This is particularly beneficial in regions where water conservation is critical, as it allows more water to remain available to crops for longer periods. In contrast, silty soils, although finer than sandy soils, have relatively larger pore spaces than clay, which results in faster drainage and slightly lower water retention. Furthermore, under intensive agricultural practices in the study area, silty soils tended to compact more easily, reducing pore space and limiting the soil's ability to hold water effectively. These dynamics contributed to the observed differences in irrigation efficiency and moisture retention between soil types.

4.5 Implications of the Clustering Results for Real-World Farm Management

The clustering results provide actionable insights for optimizing farm-level water management practices. Farms grouped into the high-efficiency cluster were typically those using modern irrigation methods such as drip systems combined with moisture-retaining soils like clay or loam. These farms can serve as role models or pilot sites to demonstrate best practices in sustainable irrigation. For moderate-efficiency farms, the clustering suggests areas for improvement such as better irrigation scheduling, partial system upgrades, or soil amendments to improve water retention. Farms in the low-efficiency cluster, often relying on traditional flood irrigation on sandy soils, highlight the urgent need for intervention. These farms could benefit from targeted support, including government subsidies for infrastructure upgrades, training programs on efficient irrigation techniques, and adoption of soil-enhancing practices like adding organic matter. Overall, the clustering framework helps policymakers and extension workers tailor water conservation strategies to farm-specific conditions, thereby enhancing sustainability in agricultural water use.

4.6 Comparison with Observed Trends and Literature

The clustering outcome and statistical results corroborate actual irrigation water consumption behavior and prior research, which validates the research approach. Subsurface and drip irrigation minimizes water loss considerably, validating findings by researchers [18, 19]. The texture of soil controls water-holding capacity; clayey and loamy soils hold more water with higher water-holding capacity, in accordance with the study [20]. Flood irrigation is responsible for the excessive wastage of water, which is in line with Jägermeyr et al. [21], who highlighted its inefficiencies Overuse of fertilizer is related to nitrogen leaching, as verified by this research [23], which requires controlled fertilization practice.

These findings provide a strong scientific foundation for precision irrigation and soil management practices, supporting the need for data-driven decision-making in sustainable agriculture.

The clustering outcomes and statistical analyses align closely with observed irrigation practices and corroborate findings from prior studies. However, this study extends the literature by uniquely integrating K-Means clustering with soil physics and irrigation efficiency metrics to identify nuanced patterns in farm performance, offering a novel, data-driven approach to sustainable agriculture.

Subsurface and drip irrigation were found to significantly reduce water loss, a conclusion consistent with earlier findings by Hatfield and Dold [18] and Lakhiar et al. [19], who emphasized the superior water use efficiency (WUE) of precision irrigation systems. However, unlike these prior studies, our clustering analysis provides a new layer of insight by segmenting farms based on their combined irrigation efficiency, soil retention, and drainage characteristics—thus allowing for targeted intervention strategies.

In line with Umair et al. [20], our study confirms that loamy and clayey soils retain more moisture, reducing irrigation frequency. Yet, by correlating soil texture with farm cluster efficiency, we reveal how soil types directly influence irrigation categorization, adding a novel cross-variable perspective that prior research did not explicitly connect.

Jägermeyr et al. [21] highlighted the global inefficiencies in flood irrigation, a finding that this study supports with empirical evidence. What differentiates our research is the visual and statistical validation of water consumption behavior using real-world farm data, segmented through clustering to reveal efficiency gaps.

Furthermore, the connection between excessive fertilizer use and nitrogen runoff is in agreement with Sarvade et al. [23]. However, our integration of nitrogen load data into the irrigation efficiency clustering model demonstrates how nutrient runoff correlates with poor irrigation practices—an interdisciplinary synthesis that has not been deeply explored in earlier literature.

Thus, the present study makes a unique contribution by bridging machine learning (K-Means clustering) with agronomic and environmental variables, producing actionable insights for policy-makers and farmers. This methodological advancement enables more precise decision-making and reinforces the case for intelligent, site-specific water and soil management strategies in sustainable agriculture.

The comparison of irrigation methods revealed that subsurface irrigation significantly outperformed flood irrigation in terms of water retention and usage efficiency. This performance can be attributed to several site-specific factors:

(1) Subsurface irrigation outperforms flood irrigation due to:

• Minimized evaporation losses: Since water is delivered directly to the root zone below the surface, evaporation from the soil surface is greatly reduced.

• Improved water distribution: The controlled and localized application in subsurface systems results in more uniform moisture levels across the soil profile, especially in soils with high clay content, as observed in the study.

• Reduced surface runoff: Unlike flood irrigation, which often leads to runoff and waterlogging, subsurface systems maintain optimal aeration and prevent nutrient leaching.

• Adaptability to soil structure: In the clayey soils prevalent in the study area, slower infiltration rates made subsurface systems more effective by maintaining consistent soil moisture without over-saturating.

(2) Limitations of irrigation methods in different environmental settings:

• Subsurface irrigation may be cost-prohibitive for smallholders and requires precise design and maintenance. It may also be less effective in sandy soils where water rapidly drains beyond the root zone.

• Flood irrigation, while less efficient, may still be suitable in regions with abundant water supply, flat terrain, and less permeable soils, where cost-effective infrastructure and simplicity are priorities.

• Sprinkler systems, though moderately efficient, are prone to wind drift and evaporative loss, limiting their effectiveness in arid, windy climates.

4.7 Cluster Analysis Interpretation and Management Implications

The application of K-Means clustering in this study resulted in the classification of farms into three categories—high, moderate, and low-efficiency clusters—based on irrigation performance and underlying soil properties. A deeper analysis of these clusters reveals that soil texture, organic matter content, and irrigation method collectively influence WUE.

Clayey soils, which were prevalent in high-efficiency farms, are composed of fine particles with high surface area and closely packed micro-pores. These characteristics enhance capillary action and allow clayey soils to retain substantial moisture for longer periods. This slower infiltration and drainage rate reduces irrigation frequency and minimizes water loss due to percolation, making them highly compatible with efficient systems such as drip or subsurface irrigation. Loamy soils, with balanced sand, silt, and clay proportions, also showed favorable moisture retention and were common in high- and moderate-efficiency clusters.

In contrast, silty soils, though finer than sandy soils, contain larger pore spaces than clay and are prone to faster water movement. Under intensive agricultural practices, silty soils in the study region exhibited compaction, which further reduced their effective pore space. This led to decreased water-holding capacity and inconsistent moisture distribution—especially under flood irrigation—contributing to their classification within moderate- to low-efficiency clusters.

Sandy soils, which dominated the low-efficiency cluster, were associated with low organic matter, rapid infiltration, and poor moisture retention. Farms with sandy textures often relied on flood irrigation, resulting in high water use and poor retention. These soils allow water to percolate quickly beyond the root zone, leading to inefficient irrigation and higher fertilizer leaching.

The clustering outcomes thus provide clear, actionable implications for real-world farm management:

• Farms in the high-efficiency cluster already employ optimized practices—such as using drip/subsurface irrigation in clayey or loamy soils—and serve as benchmarks or pilot sites for promoting water conservation.

• Moderate-efficiency farms offer potential for improvement by upgrading partial irrigation technologies, improving scheduling, or enhancing soil structure through compost application or cover cropping.

• Low-efficiency farms require targeted interventions. These include transitioning from flood to pressurized irrigation methods, applying organic matter to improve soil porosity and water-holding capacity, and adopting soil moisture monitoring tools to avoid over-irrigation.

Moreover, these cluster-based insights can inform spatially targeted policy instruments such as site-specific subsidy programs, localized farmer training workshops, and precision agriculture advisories that match irrigation systems to soil capabilities. In doing so, the K-Means clustering framework effectively bridges soil physics with irrigation strategy, enabling a scalable approach to sustainable water management in agriculture.

5 Conclusion

This study comprehensively examined the intersection of soil physics, irrigation technology, and water conservation by analyzing soil properties, comparing irrigation systems, assessing the impact of fertilization on water quality, and applying K-Means clustering for farm classification. The findings confirmed that precision irrigation methods—particularly drip and subsurface systems—achieve higher water-use efficiency, while soil texture and organic matter significantly enhance moisture retention. Excessive fertilization was linked with nitrogen runoff, underlining the need for controlled nutrient application. By leveraging machine learning, the study addressed a critical knowledge gap and proposed a data-driven framework to combat water overuse and environmental degradation.

To promote sustainable agricultural water management, the following targeted, implementable interventions are recommended:

(1) Transition from flood to drip and subsurface irrigation

Government support is essential to facilitate the adoption of efficient irrigation systems. Farmers can be supported through:

• Capital cost-sharing programs under India's Pradhan Mantri Krishi Sinchayee Yojana (PMKSY – Per Drop More Crop component), which subsidizes up to 55–60% of micro-irrigation costs for small and marginal farmers.

• Access to low-interest loans under the NABARD Micro Irrigation Fund (MIF) to ease upfront financial burdens.

• Technical training and on-field demonstrations organized through Krishi Vigyan Kendras (KVKs) to build farmer capacity in installing and managing drip systems effectively.

(2) Adopt soil moisture retention techniques

Practices such as mulching, composting, and cover cropping should be promoted through:

• Local extension campaigns that provide seasonal guides and community training sessions.

• Incentives under schemes like the Paramparagat Krishi Vikas Yojana (PKVY), which promotes organic inputs and residue management for improving soil health.

(3) Enhance fertilization efficiency and reduce nitrogen runoff

Farmers should be encouraged to adopt split applications, fertigation, and slow-release fertilizers by:

• Providing soil health cards and access to mobile-based advisory platforms that recommend crop- and region-specific fertilizer dosages.

• Implementing subsidies for bio-fertilizers and nutrient-use efficiency enhancers through programs like the Soil Health Management Scheme.

(4) Develop region-specific policies and subsidy instruments

Policymakers should consider:

• Tax incentives or GST reductions on the purchase of water-saving equipment and soil enhancement materials.

• Performance-based grants or green certification rewards for farms demonstrating measurable water savings and sustainable nutrient management.

(5) Integrate real-time, data-driven irrigation management.

To foster smart farming at scale:

• Invest in open-access digital platforms that integrate sensor-based soil moisture monitoring, weather data, and AI-driven irrigation recommendations.

• Public-private partnerships (PPPs) should be encouraged to develop scalable agri-tech solutions that are accessible to smallholders via smartphones and regional languages.

These recommendations collectively provide a practical roadmap to achieve water-efficient, climate-resilient, and economically viable agriculture. By aligning scientific insights with grounded implementation strategies and leveraging existing policy frameworks, stakeholders can accelerate the transition toward sustainable agricultural practices that support long-term food and water security.

5.1 Practical Implications for Water Conservation Strategies

The results of the study provide actionable advice on enhancing water conservation and irrigation management:

(1) High priority should be given to the adoption of precision irrigation technologies (subsurface and drip irrigation) to increase water-use efficiency.

(2) Using soil conservation methods, mulching and organic amendments can be applied in sandy soil areas to enhance moisture retention.

(3) Practices of controlled fertilization, like split application and nitrogen inhibitors, can prevent nutrient runoff and ensure water quality protection.

(4) Farm classification based on clustering can help policymakers formulate water conservation programs specifically designed for various levels of irrigation efficiency.

5.2 Limitations and Future Research Directions

While this study provides valuable insights into irrigation efficiency and water conservation, certain limitations must be acknowledged:

(1) Limited consideration of seasonal variations: The study does not account for changes in water use efficiency across different growing seasons, which could impact irrigation scheduling recommendations.

(2) Exclusion of crop-specific water requirements: The research primarily focuses on irrigation techniques rather than specific crop water demands, which could vary significantly.

(3) Geographic constraints: The dataset may not fully represent global agricultural conditions, and findings might require regional adjustments. Future research should explore machine learning models beyond K-Means clustering to refine irrigation classification models and develop real-time irrigation optimization frameworks.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] N. Mao, W. Li, X. Wei, and M. A. Shao, "Soil moisture-and texture-dependent effects of soil deposition on evaporation and carbon emission," *Soil Tillage Res.*, vol. 204, p. 104703, 2020. https://doi.org/10.1016/j.still.2020.104703

[2] N. K. A. Dwijendra, S. M. Salih, M. J. C. Opulencia, L. Morozova, E. S. Sergushina, M. N. Asnan, M. M. Kadhim, and M. Kavitha, "The effect of various irrigation technologies and strategies on water resources management," *J. Water Land Dev.*, vol. 53, no. IV–VI, pp. 143–147, 2022. https://doi.org/10.24425/jwld.2022.140790

[3] I. M. Sukerta, T. C. Chen, J. Mardizal, S. M. Salih, I. Zulkarnain, M. Z. Islam, M. S. Majeed, A. B. Mahdi, D. A. Mutlak, and S. Aravindhan, "Comparison of lateral spillway and morning glory spillway performance in flood control," *J. Water Land Dev.*, vol. 53, no. IV–VI, pp. 187–191, 2022. https://doi.org/10.24425/jwld.2022.140796

[4] Y. Cheng, Y. Li, H. Zhan, H. Liang, W. Yang, Y. Zhao, and T. Li, "New comparative experiments of different soil types for farmland water conservation in arid regions," *Water*, vol. 10, no. 3, p. 298, 2018. https://doi.org/10.3390/w10030298

[5] A. J. Franzluebbers, "Soil organic matter, texture, and drying temperature effects on water content," *Soil Sci. Soc. Am. J.*, vol. 86, no. 4, pp. 1086–1095, 2022. https://doi.org/10.1002/saj2.20425

[6] M. L. Jat, D. Chakraborty, J. K. Ladha, D. S. Rana, M. K. Gathala, A. McDonald, and B. Gerard, "Conservation agriculture for sustainable intensification in South Asia," *Nat. Sustain.*, vol. 3, no. 4, pp. 336–343, 2020. https://doi.org/10.1038/s41893-020-0500-2

[7] E. B. Jiru and H. T. Wegari, "Soil and water conservation practice effects on soil physicochemical properties and crop yield in Ethiopia: Review and synthesis," *Ecol. Process.*, vol. 11, p. 21, 2022. https://doi.org/10.1186/s13717-022-00364-2

[8] C. M. Kallenbach, S. D. Frey, and A. S. Grandy, "Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls," *Nat. Commun.*, vol. 7, p. 13630, 2016. https://doi.org/10.1038/ncomms13630

[9] A. Kumawat, D. Yadav, K. Samadharmam, and I. Rashmi, "Soil and water conservation measures for agricultural sustainability," in *Soil Moisture Importance*. IntechOpen, 2020. https://doi.org/10.5772/intechopen.92895

[10] Y. Li, A. Wright, H. Liu, J. Wang, G. Wang, Y. Wu, and L. Dai, "Land use pattern, irrigation, and fertilization effects of rice-wheat rotation on water quality of ponds by using self-organizing map in agricultural watersheds," *Agric. Ecosyst. Environ.*, vol. 272, pp. 155–164, 2019. https://doi.org/10.1016/j.agee.2018.11.021

[11] S. M. Salih, "Effect of super absorbent polymer and ceratophyllum powder application on some soil physical properties," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 1222, no. 1, p. 012030, 2023. https://doi.org/10.1088/1755-1315/1222/1/012030

[12] M. López-Vicente and G. L. Wu, "Soil and water conservation in agricultural and forestry systems," *Water*, vol. 11, no. 9, p. 1937, 2019. https://doi.org/10.3390/w11091937

[13] A. Moradi, C. T. B. Sung, K. J. Goh, A. H. M. Hanif, and C. F. Ishak, "Effect of four soil and water conservation practices on soil physical processes in a non-terraced oil palm plantation," *Soil Tillage Res.*, vol. 145, pp. 62–71, 2015. https://doi.org/10.1016/j.still.2014.08.005

[14] J. Rockström, J. Williams, G. Daily, and et al., "Sustainable intensification of agriculture for human prosperity and global sustainability," *Ambio*, vol. 46, pp. 4–17, 2017. https://doi.org/10.1007/s13280-016-0793-6

[15] M. Sankari, K. S. Kamatchi, G. M. KarpuraDheepan, and N. Sridevi, "Innovations in irrigation: Water conservation in agriculture," 2024. https://doi.org/10.47716/978-93-92090-50-9

[16] FAO, "The state of the world's land and water resources for food and agriculture–systems at breaking point (solaw 2021)," 2021. https://doi.org/10.4060/cb7654en

[17] M. K. Shukla and P. Sharma, "Fuzzy k-means and principal component analysis for classifying soil properties for efficient farm management and maintaining soil health," *Sustainability*, vol. 15, no. 17, p. 13144, 2023. https://doi.org/10.3390/su151713144

[18] J. L. Hatfield and C. Dold, "Water-use efficiency: Advances and challenges in a changing climate," *Front. Plant Sci.*, vol. 10, p. 103, 2019. https://doi.org/10.3389/fpls.2019.00103

[19] I. A. Lakhiar, H. Yan, C. Zhang, G. Wang, B. He, B. Hao, Y. Han, B. Wang, R. Bao, T. N. Syed, J. N. Chauhdary, and M. Rakibuzzaman, "A review of precision irrigation water-saving technology under changing climate for enhancing water use efficiency, crop yield, and environmental footprints," *Agriculture*, vol. 14, no. 7, p. 1141, 2024. https://doi.org/10.3390/agriculture14071141

[20] M. Umair, T. Hussain, H. Jiang, A. Ahmad, J. Yao, Y. Qi, Y. Zhang, L. Min, and Y. Shen, "Water-saving potential of subsurface drip irrigation for winter wheat," *Sustainability*, vol. 11, no. 10, p. 2978, 2019. https://doi.org/10.3390/su11102978

[21] J. Jägermeyr, D. Gerten, J. Heinke, S. Schaphoff, M. Kummu, and W. Lucht, "Water savings potentials of irrigation systems: Global simulation of processes and linkages," *Hydrol. Earth Syst. Sci.*, vol. 19, pp. 3073–3091, 2015. https://doi.org/10.5194/hess-19-3073-2015

[22] H. S. El-Beltagi, A. Basit, H. I. Mohamed, I. Ali, S. Ullah, E. A. R. Kamel, T. A. Shalaby, K. M. A. Ramadan, A. A. Alkhateeb, and H. S. Ghazzawy, "Mulching as a sustainable water and soil saving practice in agriculture: A review," *Agronomy*, vol. 12, no. 8, p. 1881, 2022. https://doi.org/10.3390/agronomy12081881

[23] S. Sarvade, V. B. Upadhyay, M. Kumar, and M. I. Khan, "Soil and water conservation techniques for sustainable agriculture," in *Sustainable Agriculture, Forest and Environmental Management*. Springer, 2019, pp. 133–188. https://doi.org/10.1007/978-981-13-6830-1_5

Nomenclature

WUE	Water Use Efficiency, kg/m^3 (yield/water)
ETc	Crop Evapotranspiration, mm
OM	Organic Matter Content, %
Di	Depth of Irrigation Applied, mm
QN	Nitrogen Runoff Load, mg/L
I	Irrigation Amount, mm/year
Ru	Runoff Volume, mm
k	Number of Clusters (K-Means), – (dimensionless)
pH	Soil Acidity/Alkalinity, – (dimensionless)

Greek symbols

θ	Volumetric Soil Moisture Content*, $\mathrm{m}^3 \cdot \mathrm{m}^{-1}$