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General Information

Overview

"Soil Studies (SoilSt)" is the successor to the "Soil Water Journal (Toprak Su Dergisi)" which has been published since 2012. Based on the experience and strengths of its predecessor, SoilSt has been developed to create a truly international forum for the communication of research in soil science. SoilSt is a refereed academic journal has been published free of charge and open accessed by Soil, Fertilizer and Water Resources Central Research Institute. The journal will be published 2 issues (July & December) starting from 2022. It covers research and requirements of all works within the areas of soil.

Aims and Scope

Soil Studies is an international peer reviewed journal that aims to rapidly publish high-quality, novel research of studies on fertility, management, conservation, and remediation, physics, chemistry, biology, genesis, and geography of soils. In addition, the main purpose of Soil Studies is to reveal the influences of environmental and climate changes on agroecosystems and agricultural production. In this context, Soil Studies publishes international studies address these impact factors through interdisciplinary studies. In the journal, articles on hypothesis-based experimental observation of the interactions of all components of agricultural ecosystems, field trials, greenhouse or laboratory-based studies, economic impact assessments, agricultural technologies, and natural resources management will be accepted within the peer-reviewed process. Topics include, but are not limited to:

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- Soil pollution
- Soil fertility and productivity and environmental soil chemistry
- Environmental soil physics and biophysics
- Soil microbiology, biodiversity and biotechnology
- Soil mineralogy and micromorphology
- Soil ecology and agroecosystems
- Soil degradation and conservation/restoration
- Organic farming, conservation agriculture and sustainability
- Best management practices in agricultural production
- Soil-water-plant relations and agricultural water management
- Cop water relations, crop yields and water productivity
- Soil and society
- Climate/environmental changes and sustainable agriculture
- Digital soil mapping
- Soil economy and agricultural production-environment policies
- Conservation agriculture systems and its impacts on soil
- Soil regeneration
- Land management
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- Diversity and sustainability of agricultural systems
- Organic and inorganic fertilization in relation to their impact on yields
- Quality of plants and ecological systems

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Yayının İdare Adresi : Gayret Mahallesi Fatih Sultan Mehmet Bulvarı (İstanbul Yolu) No: 32 P.K:5 Yenimahalle / ANKARA 06172 / Türkiye

Corresponding Address

Address : Soil, Fertilizer and Water Resources Central Research Institute (Toprak, Gübre ve Su Kaynakları Merkez Araştırma Enstitüsü Müdürlüğü)

Gayret District Fatih Sultan Mehmet Avenue No: 32 P.K:5 Yenimahalle / Ankara 06172 / Turkey (Gayret Mahallesi Fatih Sultan Mehmet Bulvarı (İstanbul Yolu) No: 32 P.K:5 Yenimahalle / Ankara 06172 / Türkiye)

Web : http://www.soilstudies.org/

E-mail : info@soilstudies.org

Phone : +90 312 315 65 60 - 64

Fax : +90 312 315 29 31

Editorial Information

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CONTENTS

Research Articles

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RESEARCH PAPER

Assessment of the impact of solid and liquid fertilizer applications on yield and yield components in cotton (*Gossypium hirsutum* L.)

Hatun Barut[1]*, Sait Aykanat[1], Selma Kaya[1], Fatma Gökmen Yılmaz[2], Sait Gezgin[2]

[1] Eastern Mediterranean Agricultural Research Institute Directorate, Adana 01370, Türkiye
[2] Selcuk University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Konya 42150, Türkiye

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***Corresponding Author**
Tel.: +90 322 3340055
E-mail: baruthatun@yahoo.com

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Abstract

This research aimed to compare the effects of liquid fertilizers on cotton yield and specific yield components relative to traditional solid fertilizers. The study employed 20-20-0, 15-15-15 and Di Ammonium Phosphate- DAP (18-46-0) fertilizers for base fertilization, with solid urea (46%) as top dressing. Liquid fertilizers, including orthophosphate and polyphosphate-based liquid base fertilizers (liquid 20-20-0, liquid 15-15-15 and liquid DAP) were developed and applied. Urea ammonium nitrate (UAN-32% N) was used for all top dressing in treatments. The experiments were conducted at the Eastern Mediterranean Agricultural Research Institute in Doğankent, following a randomized block trial design with three replications. Three separate field trials were established, each corresponding to a different compound fertilizer: 20-20-0, 15-15-15 and DAP. Within each trial, five treatments were applied, using the cotton variety "Karizma" consistently. The results indicated that liquid fertilizers containing phosphorus, particularly in the form of polyphosphate, yielded higher values for the examined properties of cotton cultivation when used for base fertilization. Although statistically insignificant, compared to conventional fertilizer applications (solid 20-20 + Urea, solid 15-15-15 + Urea, solid DAP + Urea), the use of liquid fertilizers with polyphosphate (liquid 20-20 + UAN, liquid 15-15-15 + UAN, liquid DAP + UAN) led to yield increases of 16.5%, 25.1% and 9.9%, respectively. Additionally, in the trials conducted, liquid UAN fertilizer proved to be more effective in enhancing cotton yields than solid urea fertilizer when used for top dressing.

Introduction

Agricultural production, effective land use and increased yield per unit area are of strategic importance for nations worldwide. These factors play a crucial role in ensuring food security, shelter, clothing, trade, and economic stability. Enhancing agricultural production, promoting sustainability, and implementing sound agricultural policies are essential for regional and national development. Therefore, it is necessary to effectively plan plant nutrition management strategies, adopt modern agricultural techniques, align crop patterns with regional and national needs, and address the goals of breeding programs in agricultural products.

Fertilizers play a significant role in increasing crop yield and quality. However, nutrients applied through solid chemical fertilizers are often susceptible to losses, which can vary depending on soil, plant, and fertilizer

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characteristics, as well as the method, timing, and quantity of application. Moreover, the nutrient uptake efficiency by plants is generally low, and influenced by plant specific traits. The rate at which plants utilize nutrients and their concentrations within the plant vary according to species and genus, growth stage and age. Therefore, while fertilization increases the levels of one or more nutrients in the soil, it is essential to maintain a balanced nutrient profile (Erdal, 2021).

The indiscriminate use of fertilizers can lead to nitrogen (N) leaching or lost as gas, while nutrients like phosphorus and potassium can transform into forms that are not accessible to plants (Gyaneshwar et al., 2002, Barlog and Grzebisz, 2004). Some studies have reported that up to 50% of the applied N is lost from the soil (Eickhout et al., 2006), and as much as 90% of phosphorus remain unavailable for plant uptake (Gyaneshwar et al., 2002, Korkmaz et al., 2009). The economic value of N that becomes unavailable amounts to approximately 17.7 billion dollars annually (Brentrup and Palliere, 2010, Karaşahin, 2014). Nitrogen loss from the soil/plant system not only reduces soil fertility and plant yields but also have detrimental environmental consequences. Ammonia emissions into the atmosphere contribute to acid rain, nitrate leaching into rivers and lakes leads to eutrophication, and nitrate contamination of drinking water supplies poses significant health risks. Furthermore, nitrous oxide emissions are a major contributor to ozone depletion and climate change (Cameron et al., 2013). Producing more food with less pollution is a grand challenge, which is crucial for global sustainable development goals (Gerten et al., 2020; van Dijk et al., 2021).

Nitrogen (N) is the main element in crop production. As one of the main building blocks, nitrogen is of special importance in plants because it is an integral part of the proteins from which protoplasm, cells and plant tissues are formed (Malou et al., 2006). The amount of N applied to the soil should be based on the chemical and microbiological characteristics of the soil. In addition, to prevent unused amounts of N by plants from being transported to deeper layers of the soil and causing groundwater eutrophication due to an excessive imbalance of this nutrient, air conditions should be taken into account (Hoffmann and Kluge-Severin, 2011). Improving nitrogen use efficiency can be achieved by using the right combination of nutrients, fertilizing at the right time and avoiding nutrient loss (Yadav et al., 2017). Nitrogen is a highly mobile element and can be lost in various ways. Losses are usually volatile in the air but can also occur through rainfall and groundwater leaching into deeper layers of the soil. Both situations cause economic losses but also lead to environmental problems. Nitrogen losses are influenced by the form of nitrogen (nitrate, ammonium, or urea) and soil properties (pH, texture, temperature, moisture, cation exchange ability, and organic matter) and fertilizer management (time and dosage) (Stevanato et al., 2019; Melino and Tester, 2022). Advanced agronomic management with contemporary technology and environmentally friendly practices should be adopted to achieve the optimum utilization of N fertilizer (Wang et al., 2021). While the global average N uptake efficiency varies depending on production practices and crop varieties, it is generally around 50% (İbrikçi et al., 2012). Similarly, phosphorus uptake efficiency in plants is also low, due to the rapid fixation of phosphorus in the soil, which has a low diffusion coefficient and poor mobility, hindering plant utilization of the remaining phosphorus once the portion in the root zone is depleted (Clarkson, 1981; Bertrand et al., 2006; Lynch, 2007; Balemi and Negisho, 2012). In alkaline or calcareous soils, phosphorus can precipitate into insoluble forms due to the reaction with calcium, aluminum oxides, and iron compounds at subsurface horizons (Bertrand et al., 1999; Alam and Ladha, 2004; Bertrand et al., 2006). Especially pH levels above 7.0, phosphorus tends to combine with cations such as calcium to form insoluble salts (Zhou et al., 2001). Studies using chemical phosphorus fertilizers have reported plant phosphorus uptake efficiency ranging between 10% and 30% (Holloway et al., 2001; Lombi et al., 2004; McBeath et al., 2007; Kusi et al., 2021; Zhao et al., 2021). The processes affecting P fixation in soils are complex and depend on factors such as soil mineralogy, pH, climate, and the form of phosphorus fertilizer added to the soil (Lombi et al., 2005; Degryse et al., 2013; Doydora et al., 2017).

The nutrient losses associated with solid chemical fertilizers and their low nutrient uptake efficiency due to plant characteristics are significant concerns. Furthermore, solid chemical fertilizers can negatively impact seed germination and plant development, primarily due to ammonia toxicity or salt effects. Additionally, the production of these fertilizers often contributes to environmental pollution. To address these issues and enhance fertilizer efficiency, the use of liquid fertilizers-which have significantly lower production costs- has become increasingly common in some countries, particularly developed nations. Liquid fertilizers are being adopted to eliminate the negative effects of solid chemical fertilizers in crop production. Research has shown that liquid phosphorus fertilizers not only improve yield but also enhance phosphorus utilization efficiency (Lombi et al., 2004; McBeath et al., 2005; Bertrand et al., 2006; Montalvo et al., 2015; Erenoğlu and Dündar, 2020).

In our country, solid chemical fertilizers are widely used in cotton farming. In this research, liquid base fertilizers containing orthophosphate and polyphosphate, formulated to match the composition of their solid counterparts, were developed, and applied. The study aimed to investigate the impacts of these novel liquid fertilizers on cotton yield and various yield parameters.

Material and Methods

Location and Experiments

This study was conducted during the cotton production season on the lands of Eastern Mediterranean Agricultural Research Institute in Adana province, Türkiye. The soil of the experimental field was characterized as clay loam, slightly alkaline, non-saline, highly calcareous and low in organic matter. While zinc, iron, copper, and potassium concentrations were adequate, manganese and phosphorus levels were deficient in the experimental soil (Table 1). Soil samples were collected from a depth of 0-30 cm to determine the concentrations of inorganic N (NO_3+NH_4–N) and phosphorus. The average inorganic N and phosphorus contents in the experimental field were 30.7 mg kg^{-1} and 4.3 mg kg^{-1}, respectively. Based on soil nutrient balance and the requirement of cotton plants, a total of 60 kg P_2O_5 ha^{-1} and 80 kg N ha^{-1} were applied at planting.

Table 1. Soil properties of the experimental site

Saturation	pH	Salt	Lime	O. M.	K_2O	NO_3+NH_4-N	P_2O_5	Zn	Fe	Cu	Mn
(%)	(1:2.5)	(%)	(%)	(%)	(kg da^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})			
52.80	7.65	0.46	18.11	1.58	84.06	30.7	4.3	0.73	5.70	1.12	4.90

In this study, commonly used chemical solid fertilizers in cotton agriculture-20-20-0, 15-15-15 and DAP (18-46-0) compound fertilizers, were applied at planting as fertilizer sources. The solid base fertilizers are orthophosphate. For the liquid fertilizers, liquid compound base fertilizers containing the same N-P_2O_5-K_2O ratios as solid fertilizers were developed and applied, utilizing two different forms of phosphorus: orthophosphate and polyphosphate. GÜBRETAŞ developed and provided liquid orthophosphate 20-20-0, liquid orthophosphate 15-15-15, liquid orthophosphate DAP, as well as liquid polyphosphate 20-20-0, liquid polyphosphate 15-15-15 and liquid polyphosphate DAP fertilizers. Solid urea (46% N) and liquid fertilizer urea ammonium nitrate (UAN-32 % N) were used for top dressing. Three separate trials were conducted based on the fertilizer source. Fertilizer applications during sowing and hoeing (50^{th} day) were adjusted according to the inorganic N (NO_3-N) and phosphorus levels in the experimental site, as shown in Table 2. No fertilizers were applied to the control group. The cotton variety "Karizma" was used as plant material in this study.

The field experiments were designed with 4 rows (2.8 m wide) and a planting density of 70 cm x 12 cm, using a randomized block design with 3 replications.

Table 2. Experimental treatments and amounts of nutrients applied in the experiment

Treatments	Sowing (kg ha^{-1})	50^{th} day (kg N ha^{-1})
	20-20+0 Fertilizer Trial	
1. Control	------	-------
2. Solid 20-20-0	60 N-60 P_2O_5	20 N (Solid Urea)
3. Solid 20-20-0	60 N-60 P_2O_5	20 N (Liquid UAN)
4. Liquid 20-20-0 (orthophosphate)	60 N-60 P_2O_5	20 N (Liquid UAN)
5. Liquid 20-20-0 (polyphosphate)	60 N-60 P_2O_5	20 N (Liquid UAN)
	15-15-15 Fertilizer Trial	
1. Control	------	-------
2. Solid 15-15-15	60 N-60 P_2O_5-60 K_2O	20 N (Solid Urea)
3. Solid 15-15-15	60 N-60 P_2O_5-60 K_2O	20 N (Liquid UAN)
4. Liquid 15-15-15 orthophosphate)	60 N-60 P_2O_5-60 K_2O	20 N (Liquid UAN)
5. Liquid 15-15-15 (polyphosphate)	60 N-60 P_2O_5-60 K_2O	20 N (Liquid UAN)
	DAP Fertilizer Trial	
1. Control	------	-------
2. Solid DAP	23 N-60 P_2O_5	57 N (Solid Urea)
3. Solid DAP	23 N-60 P_2O_5	57 N (Liquid UAN)
4. Liquid DAP (orthophosphate)	23 N-60 P_2O_5	57 N (Liquid UAN)
5. Liquid DAP (polyphosphate)	23 N-60 P_2O_5	57 N (Liquid UAN)

Each plot is 20 m long (56 m^2), with a 1 m distance between plots and 2 m between blocks. Solid fertilizers were applied in bands using a seeder at the time of sowing. For top-dressing with N, urea was manually applied to the soil surface before hoeing and then incorporated into the soil through hoeing.

In liquid fertilizer applications, a combined sowing machine (Figure 1) capable of applying liquid compound fertilizer in bands alongside the seed during sowing was used. For top fertilization, specialized hoeing machines designed for industrial crops such as sugar beet, cotton, corn, and sunflower were used (Figure 2). These machines can apply liquid fertilizer 7.5 cm from the plant rows and at a depth of 12-15 cm. The dosage of liquid fertilizers for each plot was precisely controlled by an electronically controlled dosing unit within the machines. Before each application, the regulator pressure was adjusted, filters were checked, nozzle flow rates were controlled, and the GPS system and tractor feed speed were calibrated.

In the trials, the necessary maintenance procedures and cultural practices were conducted in accordance with standard cotton cultivation on protocols. Observations and measurements were taken before and after harvest to ensure accurate results. To minimize edge effect, one row from the outermost edge of each plot and 1 meter from the beginning of each plot were excluded from the harvest. The cotton plants in the middle 2 rows were then hand-harvested.

When the plants reached the 4-leaf stage (about 10 cm tall), a light thinning was performed, spacing the plants 5-6 cm apart. The first thinning coincided with the first hoeing and the second, more thoroughly thinning occurred during the second hoeing. After planting, weeds were controlled mechanically with a hand hoe and crowbar to eliminate them effectively.

The water requirement of cotton plants ranges from 400 to 600 mm. Given that the total rainfall during cotton growing season is generally insufficient in cotton growing regions, irrigation is necessary to ensure optimal plant development. In this study, drip irrigation was used, with watering conducted at 7-day intervals from the onset of cotton flowering after the second top dressing until the last week of August, when 5-10% of the plant bolls had opened.

To protect against cotton diseases and pests, six chemical sprays were applied through the growing season. The first 2 sprays targeted early pests, such as aphids and fleas, common in the region. Following flowering, 4 additional sprays were applied to control green bollworm and red spider mites. Finally, about 15 days before harvest, defoliating and boll-opening chemicals were applied.

Figure 1. Seeder applying liquid fertilizer to the soil

Figure 2. Machine applying both hoe and liquid fertilizer

Characteristics studied in the Cotton Plants

In the experiments conducted as part of this research, the effects of various treatments were assessed on several key parameters: the number of bolls per plant^{-1}, ginning out-turn percentage, boll mass weight (g), 100 seed weight (g) and cotton yield (kg ha^{-1}).

Soil and plant analysis

Soil texture was determined using the hydrometer method as described by Bouyoucos (1951). Soil pH was measured following the method outlined by Jackson (1959), total carbonates were determined using the Scheibler calcimeter (Kacar, 2016). Organic matter content (%) was assessed using the Walkey-Black method (Jackson, 1959), and soil salinity was determined by Wheatstone bridge method (U. S. Salinity Laboratory Staff, 1954) through the preparation of a saturation paste. Inorganic N (NH_4+NO_3-N) was measured according to Bremner (1965), and available P concentration was determined in accordance with Olsen et al. (1954). Soil K concentration was measured following Carson (1980), available concentrations of Zn, Fe, Mn, and Cu were determined according to the method by Lindsay and Norvel (1978).

During the peak tassel emergence (flowering) period of the cotton plant, leaf samples were randomly collected from at least 8-10 plants in each plot, which had just reached maturity. These samples were analyzed to determine the N, P and K contents. Nitrogen content in the plant samples was determined using the Dumas Combustion Method (AACC 2004). For K and P analysis, 0.3 g of dried plant samples were digested in a closed-system microwave device (Cem Marsxpress) using 5 ml of 65% HNO_3 and 2 ml of 35% H_2O_2. The final volumes were adjusted to 25 ml with ultra-deionized water, and the solution was filtered through blue banded filter paper. The concentrations P and K in the filtrates were then determined using ICP-AES (Varian, Vista).

Statistical Analysis

All data were analyzed using the JMP statistical software package developed by SAS (SAS Institute, Cary, North Carolina, USA). Analysis of variance (ANOVA) was conducted to examine the differences between the treatments. Following the ANOVA, post-hoc comparisons were conducted to identify statistically significant differences among the means. The Tukey Honesty Significant Difference (HSD) test was employed to perform these multiple comparisons, ensuring a rigorous evaluation of the differences between treatment groups. Statistical significance was assessed at two levels: a threshold of $P<0.05$ (*) indicating moderate significance, and a more stringent threshold of $P<0.01$ (**) indicating strong significance.

Results and Discussion

In this study, the effects of solid and liquid fertilizer applications on cotton plant growth and yield were evaluated and the results presented below.

20-20-0 Compound Fertilizer Trial

In the 20-20-0 compound fertilizer trial, both solid 20-20-0 and liquid 20-20-0 fertilizers- produced using two different forms of phosphorus (orthophosphate and polyphosphate) but containing the same nutrient composition- were used, reflecting common practices in cotton cultivation. The effects of these treatments on cotton yield were found to be statistically insignificant (Figure 3). The lowest yield (3030.08 $kg ha^{-1}$) was recorded in the control treatment, followed by the conventional fertilizer treatment (solid 20-20-0 + Urea) with a yield of 3820.30 $kg ha^{-1}$. The application of liquid UAN (solid 20-20-0 + UAN) as a top dressing, in comparison to solid urea fertilizer, resulted in a 9.5% yield decrease (Figure 3). Furthermore, the application of orthophosphate and polyphosphate liquid 20-20-0 + UAN, developed as an alternative to solid 20-20-0 fertilizer, resulted in yield increases of 9% and 16.5%, respectively, compared to the conventional fertilizer treatment (Figure 3). Among the treatments, the highest yield was achieved with the liquid 20-20-0 + UAN containing phosphorus in the form of polyphosphate, surpassing the conventional fertilizer application (solid 20-20-0 + Urea) (Figure 3).

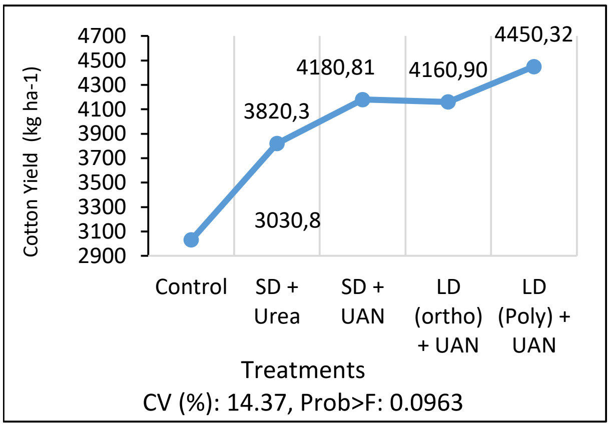

Figure 3. Cotton yield trends across different fertilizer treatments. The treatments are abbreviated on the X-axis as follows: Control (Control), SD+Urea (Solid 20-20-0 + Urea), SD+UAN (Solid 20-20-0 + UAN), LD (Ortho)+UAN (Liquid 20-20-0 with Orthophosphate + UAN), and LD (Poly)+UAN (Liquid 20-20-0 with Polyphosphate + UAN).

Table 3. Effects of Liquid and Solid 20-20-0 Fertilizer Applications on Cotton Yield and Key Yield Parameters

Treatments	Number of bolls (number per plant)	Ginning out-turn (%)	Boll mass weight (g)	100 seed weight (g)
Control	12.60	42.85	4.30	88.33
Solid 20-20-0 + Urea	13.17	41.53	4.54	91.67
Solid 20-20-0 + UAN	15.67	41.23	4.69	91.92
Liquid 20-20-0 (orthophosphate) +UAN	13.07	42.41	4.47	88.17
Liquid 20-20-0 (Polyphosphate) + UAN	14.40	42.65	4.33	86.25
CV (%)	24.05	2.83	8.08	3.72
Prob>F	0.7872	0.4519	0.6919	0.2569

The number of cotton bolls among the treatments was not significantly different. However, all treatments showed an increase compared to the control. Specifically, the number of bolls increased by 24% with solid 20- 20-0 + UAN treatment, by 3.7% with liquid 20-20-0 + UAN treatment, and by 14.3% with liquid 20-20-0 (Polyphosphate) + UAN (Table 3). Similarly, no significant differences were observed among the treatments for cotton ginning yield or boll weight (Table 3). The boll weight ranged from 4.30 to 4.69 g across the different treatments (Table 3). Regarding the 100-seed weight, although no statistical differences were detected among the treatments, there were increases compared to the control. The 100-seed weight ranged from 88.33 to 91.92 g (Table 3). Overall, when evaluating all the traits collectively, the liquid 20-20-0 + UAN application containing phosphorus in polyphosphate form demonstrated an increase in yield, suggesting its potential effectiveness in enhancing cotton production.

15-15-15 Compound Fertilizer Trial

In the 15-15-15 compound fertilizer trial, where both solid and liquid forms with the same content were evaluated, the effects of the treatments on cotton yield were not statistically significant (Figure 4). The control treatment yielded the lowest cotton yield at 2830.27 kg ha^{-1}, while the highest yield of 4130.57 kg ha^{-1} was achieved with the polyphosphate liquid 15-15-15 + UAN treatment (Figure 4). Compared to the conventional fertilizer application (solid 15-15-15 + Urea), the application of liquid UAN (solid 15-15-15 + UAN) for topdressing resulted in an 18.9% increase in cotton yield. Additionally, the liquid orthophosphate and polyphosphate 15-15-15 + UAN and applications led to yield increases of 22.2% and 25.1%, respectively, compared to the conventional fertilizer treatment (Figure 4).

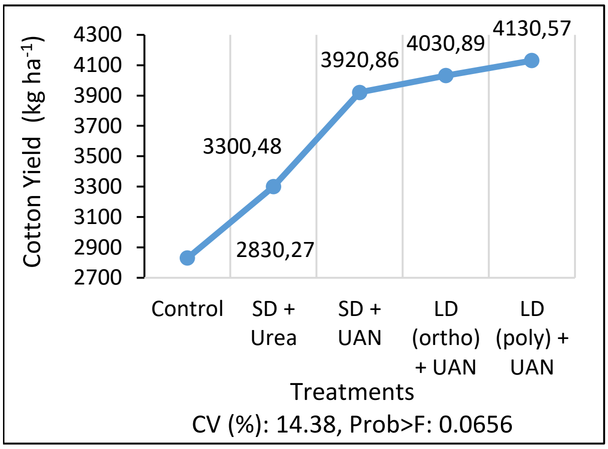

Figure 4. Cotton yield trends across different fertilizer treatments. The treatments are abbreviated on the X-axis as follows: Control (Control), SD+Urea (Solid 15-15-15 + Urea), SD+UAN (Solid 15-15-15 + UAN), LD (Ortho)+UAN (Liquid 15-15-15 with Orthophosphate + UAN), and LD (Poly)+UAN (Liquid 15-15-15 with Polyphosphate + UAN).

Table 4. Effects of Liquid and Solid 15-15-15 Fertilizer Applications on Cotton Yield and Yield Parameters

Treatments	Number of bolls (number per plant)	Ginning out-turn (%)	Boll mass weight (g)	100 seed weight (g)
Control	14.10	43.17	4.11	85.08
Solid 15-15-15 + Urea	14.13	42.63	4.43	85.17
Solid 15-15-15 + UAN	17.27	42.64	4.59	86.92
Liquid 15-15-15 (orthophosphate)+UAN	14.93	41.57	4.51	88.00
Liquid 15-15-15 (Polyphosphate)+UAN	16.33	41.79	4.35	84.83
CV (%)	16.15	1.64	6.43	1.88
Prob>F	0.4796	0.0986	0.3463	0.1570

The effect of liquid and solid 15-15-15 compound fertilizer applications on the number of cotton bolls per plant was not found to be statistically significant. However, all treatments showed an increase in ball numbers compared to the control. In the control treatment, the number of bolls per plant was 14, which increased by 22.4% with the solid 15-15-15 + UAN application, 5.9% with the liquid 15-15-15 + UAN application containing orthophosphate and 15.8% with the liquid 15-15-15 + UAN containing P in polyphosphate form (Table 4). Additionally, compared to the conventional fertilizer application (solid 15-15-15 + urea), the number of bolls per plant increased by 15.6% with the application of liquid 15-15-15 + UAN containing P in polyphosphate form (Table 4). No statistical differences were observed among the treatments in terms of cotton ginning yield or boll weight (Table 4). Boll weight varied between 4.11 and 4.59 g, with the highest values recorded from liquid fertilizer treatments (Table 4). Similarly, no statistical differences were found between the treatments in terms of the 100-seed weight in the liquid and solid 15-15-15 compound fertilizer trials.

DAP (18-46-0) Compound Fertilizer Trial

The liquid fertilizer applications demonstrated more positive effects in both base fertilization and top fertilization compared to traditional solid fertilizer applications. In the solid and liquid forms of DAP fertilizer trials, the treatments' effect on cotton yields were not found to be statistically significant (Figure 5). However, the lowest cotton yield (3220.06 kg ha^{-1}) was recorded in the control treatment, followed by the conventional fertilizer application (solid DAP + Urea), with a yield of 3740.29 kg ha^{-1}. The highest cotton yield (4110.43 kg ha^{-1}) was obtained from liquid DAP + UAN application containing phosphorus in the form of polyphosphate (Figure 5). Compared to the conventional fertilizer application (solid DAP + Urea), the solid DAP + UAN treatment resulted in a 9.2% yield increase, while the liquid DAP + UAN application with orthophosphate led to an 8.4% increase. The liquid DAP + UAN application containing phosphorus in polyphosphate form provided the highest increase (9.9%) in cotton yield (Figure 5).

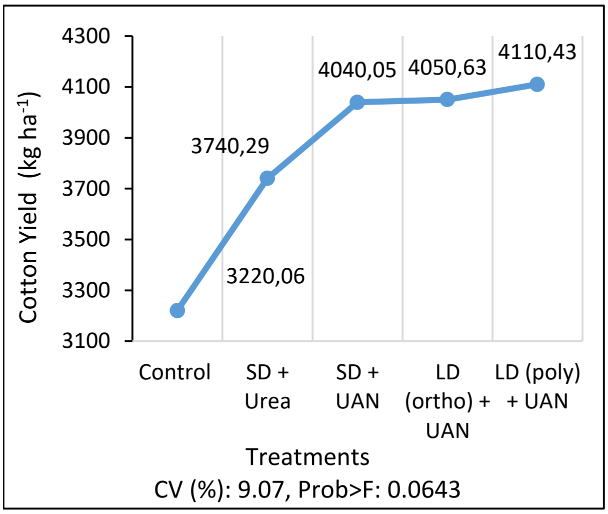

Figure 5. Cotton yield trends across different fertilizer treatments. The treatments are abbreviated on the X-axis as follows: Control (Control), SD+Urea (Solid DAP + Urea), SD+UAN (Solid DAP + UAN), LD (Ortho)+UAN (Liquid DAP with Orthophosphate + UAN), and LD (Poly)+UAN (Liquid DAP with Polyphosphate + UAN)

Table 5. Effects of Liquid and Solid DAP Fertilizer Applications on Cotton Yield and Key Yield Parameters

Treatments	Number of bolls (number per plant)	Ginning out-turn (%)	Boll mass weight (g)	100-seed weight (g)
Control	14.17 b	42.72	4.41	84.75
Solid DAP + Urea	16.67 ab	42.14	4.63	77.58
Solid DAP + UAN	22.33 a	41.29	4.78	73.92
Liquid DAP (orthophosphate) +UAN	16.03 ab	42.31	4.27	74.67
Liquid DAP (Polyphosphate) + UAN	17.13 ab	41.88	4.82	75.25
CV (%)	14.80	2.08	8.14	7.21
Prob>F	0.0386*	0.4171	0.3894	0.2077

The effect of liquid and solid DAP compound fertilizer applications on the number of bolls per cotton plant was found to be statistically significant ($p<0.01$). The lowest number of bolls per plant (14 bolls) was recorded in the control treatment. The other treatments did not show statistically significant differences from each other in terms of boll numbers per plant (Table 5). Specifically, compared to control, the number of bolls per plant increased by 17.6% with conventional fertilizer application (solid DAP + Urea), by 57.6% with the solid DAP + UAN application, by 13.1% with the liquid DAP + UAN application containing orthophosphate, and by 20.9% with the liquid DAP + UAN application containing P in polyphosphate (Table 5). No significant differences were observed among the treatments for cotton ginning yield and boll weight (Table 5). Boll weight ranged from 4.11 to 4.82 g with the highest values recorded in the liquid DAP + UAN treatment containing P in polyphosphate form (Table 5). Similarly, no statistical differences were found among the treatments for the 100-seed weight in the liquid and solid DAP compound fertilizer trials.

Effect of Fertilizers on Macronutrient Uptake in Cotton

Leaf sample analysis revealed significant increases in macronutrient concentrations in the leaves when treated with both solid and liquid fertilizers, compared to the control treatments (Table 6).

In all trials, the macronutrient contents of the plant leaves were within the adequacy limits for cotton reported by Jones et al. (1991) (Table 6). The nitrogen content was 2.62% in the control of 20-20 fertilizer trial, 2.59% in the control of 15-15-15 fertilizer trial, and 2.91% in the control of DAP fertilizer trial. These values, initially indicating a deficiency (<3%), were increased to sufficient levels (>3%) with the application of fertilizers. The increases in nitrogen content were more pronounced in the treatments with UAN compared to those with urea (Table 6). These results suggest that that the developed liquid base fertilizers effectively provided nutrition to the cotton plants.

Table 6. Effects of Fertilizer Applications on Macronutrient (N, P, K) Concentrations of Cotton Leaves.

Treatment	N	P	K
		(%)	
20-20-0 Fertilizer Trial			
Control	2.62	0.40	1.33
Solid 20-20-0 + Urea	4.11	0.45	1.81
Solid 20-20-0 + UAN	4.69	0.41	1.68
Liquid 20-20-0 (orthophosphate) + UAN	4.18	0.48	1.56
Liquid 20-20-0 (polyphosphate)+ UAN	4.52	0.44	1.72
15-15-15 Fertilizer Trial			
Control	2.59	0.38	1.59
Solid 15-15-15 + Urea	2.86	0.44	1.69
Solid 15-15-15 + UAN	3.88	0.46	1.68
Liquid 15-15-15 (orthophosphate) + UAN	3.33	0.46	1.77
Liquid 15-15-15 (polyphosphate)+ UAN	3.37	0.46	1.83
DAP Fertilizer Trial			
Control	2.91	0.44	1.53
Solid DAP + Urea	3.17	0.48	1.59
Solid DAP + UAN	3.59	0.48	1.87
Liquid DAP (orthophosphate) + UAN	3.31	0.45	1.65
Liquid DAP (polyphosphate)+ UAN	3.68	0.47	1.70
Threshold Limits for Sufficiency (Jones et al. 1991)	3.00-4.30	0.25-0.45	0.90-2.00

Discussion

Liquid base fertilizers containing phosphorus in the form of orthophosphate and polyphosphate-matching the nutrient content of traditional solid chemical fertilizers were evaluated as alternatives to solid chemical fertilizers. For top dressing, the study compared the use of solid urea, which is traditionally used in cotton cultivation, and liquid UAN fertilizers, which represent a potential alternative. While the treatments did not yield statistically significant differences in cotton yields across the 20-20-0, 15-15-15, and DAP trials, increases in yield were observed in all three trials when compared to both control and conventional solid fertilizer applications.

In the 20-20-0 fertilizer trial, the application of orthophosphate and polyphosphate liquid 20-20-0 + UAN resulted in cotton yield increases of 9% and 16.5%, respectively, compared to the conventional solid 20-20-0 + urea application. Furthermore, using liquid UAN for top dressing, as opposed to solid urea fertilizer led to a 9.5% increase in cotton yield. In the 15-15-15 fertilizer trial, both the orthophosphate liquid 15-15-15 + UAN and polyphosphate liquid 15-15-15 + UAN applications increased cotton yield by 22.2% and 25.1%, respectively, compared to the conventional solid 15-15-15 + urea application. The application of liquid UAN in top dressing, compared to the conventional solid 15-15-15 + urea fertilizer, resulted in an 18.9% increase in cotton yield. In the DAP fertilizer trial, the solid DAP + UAN application resulted in a 9.2% increase, liquid DAP + UAN application with orthophosphate increased yield by 8.4%, and the liquid DAP + UAN (polyphosphate) application provided a 9.9% increase compared to the conventional solid DAP + Urea application. The effects of liquid fertilizer applications on cotton cultivation were found to be more favorable than those of traditional solid fertilizer applications in both base fertilization and top fertilization. This aligns with previous research, where liquid fertilizers have been reported to increase plant yields more effectively than solid fertilizers (McBeath et al., 2005 and 2007; Wang and Chu, 2015; Akhtar et al., 2016; Erenoğlu and Dündar, 2020; Kusi et al., 2021). The positive effects on yield and yield parameters observed with liquid phosphorus fertilizers are likely due to their higher phosphorus uptake efficiency compared to traditional solid phosphorus fertilizers (Holloway et al., 2001; Bertrand et al., 2006; 2012; Erenoğlu and Dündar, 2020; Zhao et al., 2021; Kusi et al., 2021). Lombi et al. (2005) demonstrated, through x-ray, spectroscopy, and laboratory-based chemical analysis, that phosphorus supplied in liquid form improved phosphorus use efficiency in Australian soils compared to conventional granular products. Similarly, Hashmi et al. (2017) reported phosphorus uptake efficiency increased by 17% when applied as a liquid fertilizer, compared to solid fertilizer application. Previous studies have suggested that this increased efficiency with liquid phosphorus fertilizers may be due to reduced phosphorus fixation in the soil, as well as enhanced mobility and diffusion (Clarkson, 1981; Lombi et al., 2004). The slow diffusion of phosphorus from solid fertilizers, particularly from granular forms, creates a high concentration in the narrow zone, which facilitates precipitation as calcium-phosphate compounds, thus reducing availability (Bertrand et al., 2006). For instance, in a study conducted by Kulluk

(2022) on calcareous soil, the effects of orthophosphate solid fertilizer (solid 10-25-20, 8% S, 1% Zn + Urea) and liquid fertilizers in orthophosphate and polyphosphate forms (liquid orthophosphate 10-25-20, 8% S, 1% Zn + UAN and liquid polyphosphate 10-25-20, 8% S, 1% Zn + UAN) were examined in base fertilization in sugar beet plants. The highest yield and quality values were obtained from the application of liquid fertilizer containing phosphorus in polyphosphate form + UAN.

The effect of the application of liquid UAN in top dressing was more effective on traits examined in cotton compared to the traditionally used urea fertilizer. This finding is consistent with other studies (Cai et al., 2002; Schelegel et al., 2003; Rochette et al., 2009), where liquid UAN applications in top dressing were shown to improve yields, positively by reducing N losses and increasing N uptake efficiency through subsurface injection of UAN. Schelegel et al. (2003) reported that subsurface injection of UAN in wheat resulted in higher N uptake efficiency compared to surface application, leading to an average yield increase of 8%. It is well known that N losses occur with urea fertilizers, depending on the application method. Rochette et al. (2009) reported that under high temperature and drought conditions, N losses as ammonia increased to 64% when urea was surface-applied, compared to 34% with banded applications. Furthermore, studies by Kelly et al. (2004), Bryant-Schlobohm et al. (2020), and Milyutkin et al. (2021) have also indicated that subsurface N application can significantly reduce N losses.

In the conducted trials (20-20-0, 15-15-15 and DAP), the highest yield values were obtained from polyphosphate liquid fertilizer forms as phosphorus source (Figure 3, 4 and 5). Higher Yield with Liquid Fertilizers: As indicated by the trends, liquid fertilizers (especially those containing polyphosphate) have been shown to improve cotton yields compared to traditional solid fertilizers. Higher yields translate directly to higher revenue, which can offset the higher initial costs of liquid fertilizers. The increased efficiency in nutrient uptake with liquid fertilizers reduces the amount of fertilizer required, which can further mitigate the higher cost per unit. Over time, the reduced need for frequent applications and potential decreases in fertilizer quantity can lead to cost savings. Liquid fertilizers offer several sustainability advantages compared to traditional solid fertilizers. However, their sustainability profile also depends on factors like production methods, application techniques, and overall farm management practices. Liquid fertilizers can be precisely applied through various methods, such as drip irrigation, foliar spraying, or subsurface injections. This targeted application reduces nutrient losses through leaching, volatilization, or runoff, ensuring that more of the applied nutrients are utilized by the crops. Because of their precision, liquid fertilizers minimize the risk of over-application, which can lead to nutrient imbalances in the soil and reduce the need for corrective measures later on. Several other crops might benefit similarly from the use of liquid fertilizers, particularly those with high nutrient demands or those that are sensitive to nutrient availability. Corn has a high demand for nitrogen, particularly during the early growth stages. Liquid nitrogen fertilizers, like UAN (Urea Ammonium Nitrate), can provide a more consistent supply of nitrogen, leading to improved growth and yield. Corn also requires significant phosphorus, especially for root development. Liquid phosphorus fertilizers (e.g., polyphosphate-based) can enhance phosphorus availability, improving early root growth and overall plant health.

Conclusion

The use of liquid fertilizers place of the traditional solid fertilizers had a positive impact on cotton yield and key yield parameters of cotton plants. Although the three trials conducted showed that the effects of traditional fertilizer applications on cotton yield were statistically similar, the newly developed liquid polyphosphate-based fertilizers (liquid 20-20, liquid 15-15-15 and liquid DAP) resulted in yield increases of 16.5%, 25.1% and 9.9%, respectively. The results, including improvements in yield and yield parameters and macronutrient concentrations demonstrate that these liquid base fertilizers are viable alternatives for cotton cultivation. For liquid base and top fertilizer applications to become widespread, it is important to ensure the availability and use of agricultural tools and machinery capable of applying liquid fertilizers during both planting and top fertilization stages. Additionally, further research is needed to evaluate the effects of liquid fertilizers on cotton across different locations and growing seasons, as well as their economic viability.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that might appear to influence the work reported in this paper.

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SOIL STUDIES

RESEARCH PAPER

Modernizing irrigation at Acequia Real Del Jucar, Valencia: assessing the transition from surface irrigation to drip irrigation and the end-user perspective

Gökçe Çağla Arıkan[1,2]*, Emilio Quintana Molina[2], Evert Verweij[2], Havana-Kay Carmel Menezes[2], Eleni Tsimplaki[2]

[1] Soil, Fertilizer and Water Resources Central Research Institute, Ankara 06170, Türkiye
[2] Wageningen University and Research, Water Resources Management Group, Wageningen, 6708PB, The Netherlands

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***Corresponding Author**
Tel.: +90 312 3156560
E-mail:
gokcecagla.arikan@tarimorman.gov.tr

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Abstract

This study examines the transition from surface to drip irrigation in Sector 23 of the Acequia Real del Júcar (ARJ) irrigation district in Spain, through a performance evaluation based on field experiments, on-site observations, and stakeholder perspectives. Spatial observations in 428 plots, representing 51% of the area, revealed that 73% used drip irrigation, 8% used surface irrigation, and 12% was fallow or abandoned. Surface irrigation showed high application efficiency but only met 65.6% of crop water needs, while drip irrigation, with good distribution uniformity, satisfied only 57% and 33.9% of crop needs due to issues such as emitter clogging. Drip systems required higher maintenance (93%) compared to surface systems (14%), which had higher abandonment rates. Main crops cultivated included oranges and persimmons. Herbicide use was common in drip-irrigated fields, while mowing and plowing were more common in surface-irrigated fields. Findings based on farmer and manager perspectives emphasize that, beyond technical efficiency, user behavior and perceptions play a significant role in irrigation system success. These findings provide practical, spatially grounded insights for improving irrigation strategies and irrigation modernization should be evaluated not only in terms of technical efficiency, but also in relation to maintenance requirements, agricultural management practices, and land use decisions. The results can guide policy and investment decisions aimed at enhancing sustainability in agricultural water management.

Introduction

The Acequia Real Del Júcar (ARJ) (2022), an Irrigation Scheme in the Valencia region of Spain serves as the foundation for this project.

Between 1950 and 1986, Spain's agricultural policy prioritized the expansion of irrigation zones, a strategy that, despite yielding economic benefits, has placed significant pressure on the country's water resources, leading to shortages (DGA, 2010; Sanchis-Ibor et al., 2017). To mitigate water losses and improve water service quality and agricultural productivity, pressure pipe systems are progressively replacing surface irrigation, which is perceived as inefficient (Playán and Mateos, 2006). In response to the Júcar River Basin Authority's decision to reduce water rights and allocations from the Tous Dam, the Acequia Real del Júcar (ARJ) must reconsider its water distribution strategy (V. Llopis Córdoba, personal communication, 12 May 2022).

The ARJ has set an objective to fully transition to drip irrigation by 2025. However, since the project's initiation in 2005, only 17 out of 40 sectors have been converted, highlighting a substantial disparity between projected and actual progress (V. Llopis Córdoba, personal communication, 12 May 2022). The reasons for this delay remain uncertain, though it is suggested that farmers feel coerced into abandoning traditional irrigation practices and perceive the benefits of drip irrigation as limited. The transition necessitates financial contributions not only from governmental institutions but also from farmers themselves, posing an additional challenge (Ortega-Reig et al., 2017). While the modernisation of ARJ is expected to enhance water conservation, irrigation efficiency, agricultural productivity, and reduce labor and fertilizer costs, a comprehensive quantification of these benefits, as well as a comparative analysis between drip and surface irrigation, remains absent.

The slow pace of the transition to drip irrigation is impeding the region’s overall irrigation modernisation efforts. The diverse perspectives of stakeholders regarding irrigation performance and water conservation further complicate the assessment of this shift. Additionally, limited research exists on the perceptions of water conservation and irrigation efficiency among irrigation managers and users. Initial interviews indicate notable differences between sectors using surface and drip irrigation. Economic challenges, including declining crop prices—comparable to those of three decades ago—along with the financial burden of labor and fertilizers, hinder farmers' ability to sustain irrigation. Furthermore, the relatively small landholding size, averaging 1.5 hanegadas (approximately 1,246.5 square meters), exacerbates the difficulty of achieving viable agricultural productivity, thereby threatening farmers’ economic sustainability (Smart Water Magazine, 2022).

Concerns have also been raised regarding the increasing proportion of abandoned farmland and the younger generation's declining interest in agricultural activities. While these challenges are primarily associated with surface irrigation, the modernisation process through drip irrigation has progressed across 40% of the area, potentially enabling farmers to reallocate their resources to enhance yields (Darouich et al., 2014; Pereira et al., 2012).

To evaluate the transition from surface to drip irrigation, this study aimed to collect relevant data, selecting Sector 23, located centrally within the ARJ irrigation district, as the focus area. Currently, the Acequia Real del Júcar lacks an up-to-date assessment of irrigation performance and agricultural practices that differentiate between drip and surface irrigation. This project seeks to address this gap by analyzing existing irrigation performance levels and compiling data from management, irrigation users, and field observations. The study outputs include a performance evaluation and comparison of drip and surface irrigation systems, a spatial overview of irrigation and agricultural practices in Sector 23, and an analysis of irrigation managers’ and users' perspectives on different irrigation methods. These findings will contribute to a more comprehensive understanding of the ongoing transition and its implications for the region.

Materials and Methods

Study Area

The Acequia Real del Júcar (ARJ) region is situated in southeastern Spain, between Alicante to the north and Valencia to the south, within the lower Júcar region of the Júcar River Basin (Figure 1).

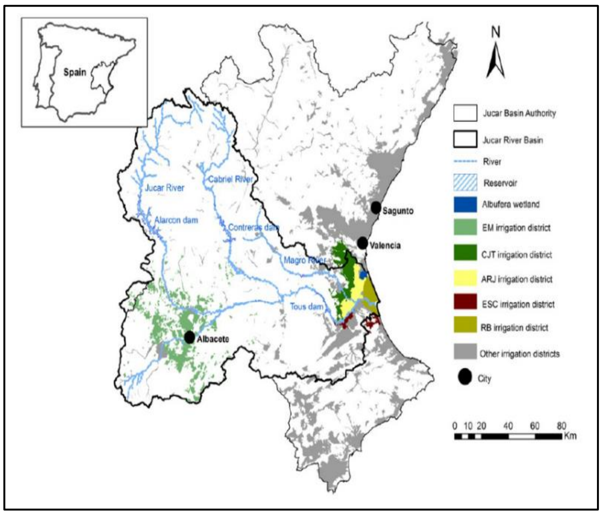

Figure 1. Overview of the Júcar river basin District with the location of the Acequia Real del Júcar in yellow (Kahil et al., 2016)

This basin encompasses three primary irrigation zones: the upper Júcar, lower Júcar, and the Turia Basin (Kahil et al., 2016). The region experiences a semi-arid Mediterranean climate, with an annual precipitation range of 300–600 mm. Summers are characterized by hot and dry conditions, while winters are mild, with an average annual temperature of approximately 18°C (Kahil et al., 2014; Kahil et al., 2016). A significant reduction in environmental flows has severely impacted downstream water users, with water availability in the ARJ region declining by approximately 70% over the past four decades, resulting in substantial environmental degradation of water-dependent ecosystems (García-Mollá et al., 2013).

Although the ARJ region has traditionally been known for citrus production, declining orange prices have led farmers to diversify their crops. They now cultivate apricots, dates, watermelons, and winter vegetables such as onions, potatoes, garlic, and lettuce

(Kahil et al., 2016; Poblador et al., 2021). Additionally, water-intensive crops such as avocados have recently been introduced (Sommaruga and Eldridge, 2021).

As of 2005, surface irrigation was the predominant irrigation method, covering 19,985 hectares. However, by 2025, it is expected that all surface irrigation systems will be replaced by drip irrigation (V. Llopis Córdoba, personal communication, 12 May 2022). Water for drip irrigation is supplied through the Júcar-Turia Transfer pipeline, which conveys water from the Tous Dam across the Júcar River to the Turia River near Valencia. This pipeline, running parallel to the main canal, delivers water to both the traditional acequia surface irrigation network and the pressurized drip irrigation system. Consequently, surface irrigation channels receive water from both the pipeline and the main canal.

Sector 23, located at the core of the ARJ irrigation network, is primarily dedicated to citrus cultivation, where both surface and drip irrigation techniques are employed. Figure 2 provides an overview of the ARJ irrigation scheme, illustrating the case study area, key sectors, and the progress of irrigation modernization.

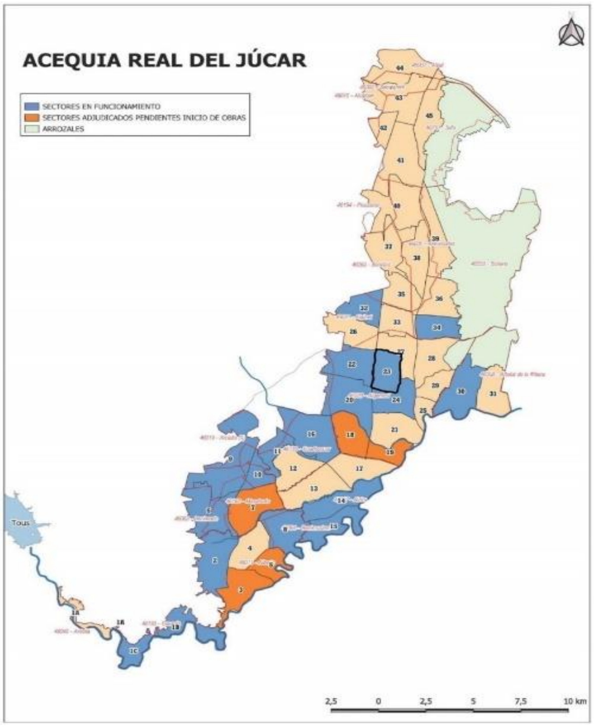

Figure 2. The Acequia Real del Jucar sectors. With traditional surface irrigation sectors (beige), modernized drip irrigation sectors (blue), partly modernized drip irrigation sectors (orange), rice surface irrigation sectors (green) and the selected sector of our project (black). (Acequia Real Del Júcar, n.d.)

Data Collection

Figure 3 represents the research methodologies used in data collection, their aims and, accordingly, the output.

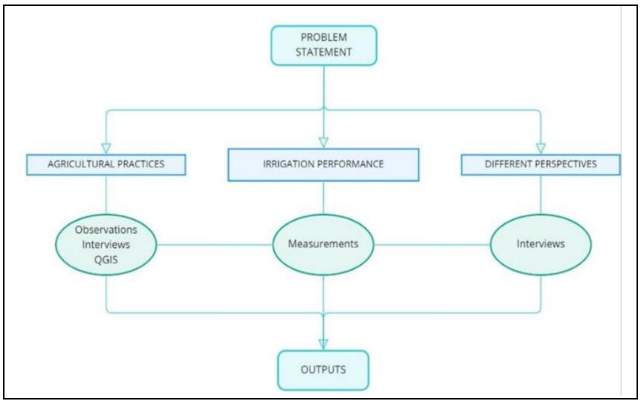

Figure 3. Graphical representation of the methodology and outputs

Two areas irrigated by drip irrigation in Sector 23 and two areas irrigated by surface irrigation were selected in the nearby of Sector 23, for comparing and evaluating their irrigation capabilities (Figures 4 and 5). These decisions were influenced by the permits and availability of farmers. Research components included water height in surface irrigation areas, irrigation time, emitter discharge, and canal flow. In summary, the manner in which irrigation is supplied affects its performance. Whether the crop's water needs were satisfied and whether the irrigation was uniform were determined in this study.

Figure 4. Water delivery canals and location of surface irrigation fields

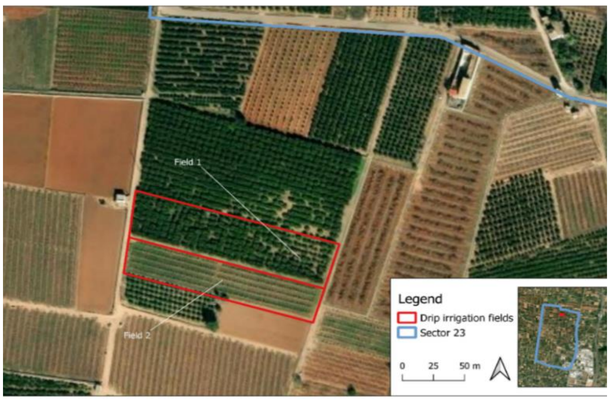

Figure 5. Location of drip irrigation fields

The effectiveness of drip irrigation is mostly determined by the agronomic and hydraulic design, the calibre of the materials utilised, the irrigation process, and the upkeep of the infrastructure (Schilardi and Morábıto, 2011). The application efficiency (AE) and distribution uniformity of the applied water (DU) are the primary criteria used to evaluate drip irrigation (Pereira, 1999). Low uniformity increases the risk of agricultural water deficit in the less irrigated fields and results in water losses from percolation in the most irrigated areas (Bohórquez and Ruiz, 2011).

Distribution uniformity (DU)

Merrian and Keller (1978) devised a method that involves monitoring the applied discharge for n repetitions and comparing the average discharge with respect to the lowest quarter section of the applied discharge in order to calculate distribution uniformity in drip irrigation. As the following expression:

$$DU = \frac{q_{25\%}}{q_{avg}} * 100 \quad \text{........................} \ (1)$$

Where:

DU → Distribution uniformity (%)
$q_{25\%}$ → Average of the lowest discharge quarter (L/h)
q_{avg} → Average discharge (L/h)

Using graduated cylinders and a chronometer, more than ten emitter discharge measurements were made per field in order to assess the drip irrigation system's distribution homogeneity. Within sector 23, data collection is intended to take place in at least two distinct fields. The range values used to classify the distribution uniformity in drip irrigation are shown in Table 1.

Table 1. Performance indicators for drip irrigation (Merrian and Keller, 1978).

Classification	Distribution uniformity (%)
Excellent	>90
Good	80-90
Regular	70-80
Poor	60-70
Inadequate	<60

Application efficiency (AE)

The crop water requirement in relation to the daily applied water was taken into account while calculating the drip irrigation application efficiency. Could be stated in terms of volume or depth of water (Howell, 2003; Pereira, 1999). Application efficiency was calculated by using Equation 2;

$$A_e = \frac{CWR}{W_a}\ x\ 100 \text{.............................} \ (2)$$

Where:

AE → Application efficiency (%)
CWR → Crop water requirement per irrigation event (mm or m^3)
W_a → Water applied per irrigation event (mm or m^3)

Conveyance Efficiency

Equation below illustrates how the conveyance efficiency of drip and surface irrigation took into account the inlet water discharge to the field as well as the inlet water discharge from a specified checkpoint (García-Petillo, 2008):

$$C_e = \frac{Q_f}{Q_{cp}} * 100 \text{.............................} \ (3)$$

Where:

C_e → Conveyance efficiency (%)
Q_f → Inlet discharge to the field (m^3 /s)
Q_{cp} → Inlet discharge from the checkpoint (m^3 /s)

The application and conveyance efficiencies determine the irrigation efficiency in both drip and surface irrigation. This equation was used to generate this parameter (Brouwer et al., 1989):

$$IE = \frac{A_e * C_e}{100} \text{ ....} \ (4)$$

Where:

IE → Scheme irrigation efficiency in drip and surface irrigation (%)
A_e → Application efficiency (%)
C_e → Conveyance efficiency (%)

In the case where application efficiency was above 100%, an adequacy was defined (RWS), using the following equation:

$$RWS\ (\%) = \frac{Water\ depth\ applied}{Crop\ water\ requeriment\ in\ depth\ water} * 100 \text{ ..} \ (5)$$

Observations conducted in Sector 23 were systematically assessed using structured observation forms. The evaluation focused on various factors, including crop types, land conditions, irrigation techniques, and weed management strategies. Prior to data collection, a standardized methodology was established through a structured observation sheet developed on Google Forms. These structured observations facilitated the creation of a spatial overview of the distribution and application of surface and drip irrigation within the sector. Strict criteria were defined for agricultural and irrigation practices to ensure objectivity in deriving qualitative results. Irrigation practices were categorized into three types: drip, surface, and non-irrigation. Additionally, field and crop maintenance were classified into three levels: low, medium, and high. Weed removal methods were recorded based on specific indicators—herbicide use was noted when weeds were absent, with no visible signs of mowing or plowing. Fields where soil had been loosened and displaced through plowing were identified separately, while mowed fields were characterized by visibly cut weeds. Furthermore, the state of the fields was classified into four primary categories: in use, abandoned, fallow, and unknown.

In addition to field observations, semi-structured interviews were conducted to gather insights from participants regarding their backgrounds and interests in agriculture. The primary objective of these interviews was to understand participants' perspectives on surface and drip irrigation. Moreover, the interviews served as a tool to review and refine the assessment metrics, ensuring a comprehensive evaluation of irrigation practices in Sector 23.

Results and Discussion

Field Observations during Data Collection

Surface and drip irrigation trials were conducted to assess irrigation performance in the designated measurement area and adjacent irrigated farms. During surface irrigation, it was observed that numerous gate entries along the canal were obstructed with concrete blocks intended to regulate water flow. However, leakage occurred through these blocks, leading to soil collapse near field entrances due to continuous water inflow. This issue was managed by filling the affected areas with concrete debris. Additionally, field heterogeneity was identified as variations in the dimensions of basin gutters (height, length, and width) that influenced irrigation performance. The irrigation strategy, which involved sequentially opening field gates during irrigation, was another factor affecting efficiency. Furthermore, the presence of weeds and leaf debris interfered with water distribution.

In the drip irrigation trials, multiple operational issues were identified, primarily related to the condition and maintenance of the system. Drip lines were frequently found folded and twisted, reducing system efficiency, while air blockages were observed, particularly toward the end of the irrigation cycle. It was reported that the system had not been maintained since its installation three years prior, despite routine maintenance being crucial for optimal performance. Maintenance should prioritize primary system components, including mains, subgrids, laterals, and emitters, alongside regular cleaning of filters to prevent clogging. A notable observation was the application of irrigation water containing salts along with fertilizers in sector 23, which poses a risk of clogging in emitters and pipes, thereby reducing system efficiency and longevity. Despite these risks, no acid treatment was applied, as the salts were not perceived as a significant issue. However, literature suggests that chemical treatment and enhanced filtration can mitigate clogging problems (Bounoua et al., 2016; Jarwar et al., 2019).

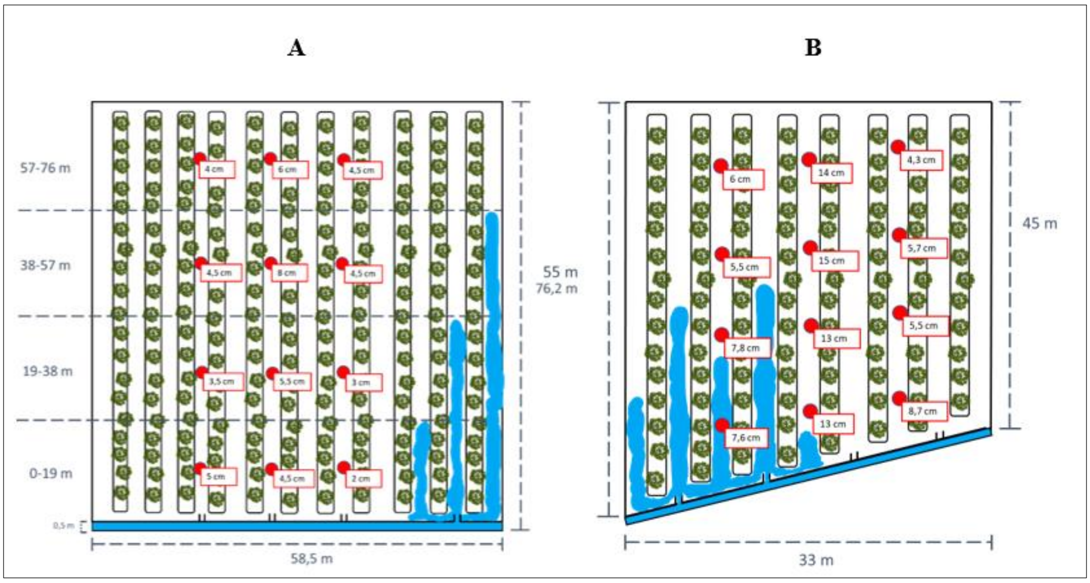

Figure 4. Graphical representation of surface irrigation in the first field (A) and second field (B) (red points represent water depths after irrigation cut-off)

Irrigation Performance Measurements

A graphical representation of the areas irrigated by surface irrigation is shown in Figure 4. The assessment of irrigation performance included the evaluation of application and conveyance efficiency across surface irrigation systems. In the first surface irrigation field, 226.7 m³ of water was applied, resulting in an average application depth of 50.9 mm. However, the crop's water requirement was calculated as 345.61 m³, corresponding to an average depth of 77.53 mm. Accordingly, the application efficiency was calculated as 65.6%, indicating that only 65.6% of the required water was applied, and the crop's irrigation requirement was not fully met, pointing to a water deficit. In the second field, 136 m³ of water was applied with an average depth of 82.4 mm, while the crop's requirement was 127.9 m³ (77.53 mm). The application efficiency in this case was 94.1%, also suggesting a slight water deficit, although closer to the crop's needs compared to the first field. In both cases, the irrigation process spanned 21 days (Table 2).

Table 2. Application efficiency in surface irrigation

Parameter		Field 1	Field 2
Water applied to field	Volume (m^3)	226.7	136
	Depth average (mm)	50.9	82.4
Water required for crop	Volume (m^3)	345.61	127.9
	Depth average (mm)	77.53	77.53
Application Efficiency (%)		152.45 (Only 65.6% of the required water was applied)	94.1

Conveyance efficiency was measured with reference to a checkpoint located 328.2 meters from the first field and 98.3 meters from the second. The conveyance efficiency was calculated as 89.57% for the first field and 97.9% for the second (Table 3).

Table 3. Conveyance efficiency in surface irrigation

Parameter	Field 1	Field 2
Length canal in field one related to checkpoint (m)	328.2	98.3
Discharge delivers in the beginning of the field (m^3/s)	0.089	0.111
Discharge delivers in the checkpoint (m^3/s)	0.099	0.113
Conveyance efficiency (%)	89.57	97.9

According to the ARJ Irrigation Control Centre (ICC), the high-pressure pipeline supplying water to the drip irrigation system operates at a reported 100% conveyance efficiency, implying that all supplied water reaches its designated fields without losses. However, given the inherent losses in water delivery systems, this claim remains subject to scrutiny. Since upstream flow dynamics influence conveyance efficiency, measurements were taken at a downstream checkpoint where no fields were being irrigated to ensure stable conditions and obtain reliable data. Potential sources of water loss include leakage through canal linings and malfunctioning gates. Regular manual maintenance and timely repairs of minor canal structures are critical in mitigating these losses (Jadhav et al., 2014). Considering both application and conveyance efficiency, overall irrigation efficiency was estimated at 89.6% in the first field and 92.1% in the second (Table 4). The assumption of 100% application efficiency in the first field reflects the fact that the crop's irrigation requirement was not fully met within the system, rather than indicating an absence of water losses.

Table 4. Water delivery canals in surface irrigation zone

Parameter	Field 1	Field 2
Irrigation efficiency per system (%)	89.6	92.1

In the context of drip irrigation, the discharge per emitter was measured in the field and defined using data from the Irrigation Control Centre (ICC) of the ARJ. In Field 1, the measured discharge was found to be lower than the reported discharge by the ICC, with a discrepancy of approximately 0.6 L/hr (average of 24 emitters). In Field 2, the measured discharge was found to be approximately equivalent to the reported discharge by the ICC, with a discrepancy of approximately 0.1 L/hr (average of 15 emitters) (Table 5). Table 5 presents general irrigation information from ICC. The first field is irrigated twice per day from Monday to Saturday, while the second field is irrigated once each Monday, Wednesday, Friday, and Saturday.

Table 5. Irrigation data

Number of irrigations	Parameter	Field 1	Field 2
1st	Discharge applied (m^3/han/hr)	0.99	0.8
	Volume applied (m^3)	10.1	4.9
	Irrigation time (min)	74	75
2nd	Discharge applied (m^3/han/hr)	1.11	-
	Volume applied (m^3)	10.8	-
	Irrigation time (min)	70	-

In the first field, discharge per emitter is 1.69 L/hr according to the ICC-ARJ; 1.085 L/hr according to measurements (average). In the second field, discharge per emitter is 1.3 L/hr according to ICC-ARJ; 1.28 L/hr according to measurements (average)

It is plausible that the discrepancy in discharge is attributable to the accumulation of salt and organic matter within the emitters, in addition to entrapped air issues. The configuration and condition of the drip lines in the second field were superior to those in the first field. Additionally, the second field has younger trees, which suggests that the irrigation system may be more recent than that of field one.

The application efficiency in both drip fields was above 100%, in accordance with the established definition of application efficiency, which is constrained to a maximum value of 100%. Consequently, the relative water supply parameters were calculated, indicating that the applied water only fulfilled 57% and 33.9% of the crop water requirements in the first and second field, respectively (Table 6).

Table 6. Application efficiency in drip irrigation

Parameter		Field 1	Field 2
Water applied to field	Volume (m^3)	0.031	0.0128
	Depth average (mm)	1.89	1.21
Water required for crops	Volume (m^3)	0.055	0.038
	Depth average (mm)	3.32	3.58
Application Efficiency (%)		175.46 (Only 57% of the required water was applied)	295.2 (Only 33.9% of the required water was applied)

The distribution uniformity (DU) in the first field was found to be 81%, while in the second it was 90.1%. According to the classification system proposed by Merrian and Keller (1978), these results could be classified as "good" and "excellent," respectively (Table 7). It is important to note that, in light of the discrepancies between the discharge measurements and the reported data by the ICC, the distribution uniformity (DU) in the first field is relatively close to the classification of "regular" (70-80%), while the second is close to "good" (80-90%).

Table 7. Distribution uniformity in drip irrigation

Parameter	Field 1	Field 2
Average discharge (mm/min)	31.58	37.40
Average discharge of the lower quarter ($q_{25\%}$) (mm/min)	25.58	34
Distribution Uniformity (DU) (%)	81	90.1

The irrigation efficiency in both drip irrigation fields is computed as 100% because application efficiency exceeds 100%, and conveyance efficiency is assumed to be 100%. It is important to note that this does not reflect reality.

The noticeable entrapped air problem in the drip lines (evidenced by the continued release of air from the pipe even when the irrigation was nearing completion) prompted the development of an entrapped air revision. This revision aimed to identify the specific pipe lengths where the problem was most prevalent. In a previous study, Quintana-Molina et al. (2021) proposed an equation that defines the water velocity in small pipeline diameters with the objective of removing entrapped air. The equation has been validated for diameters between 12.7 and 19.05 mm and downward angles between 0° and 60°.

It was determined that air valves were not installed in the areas measured in sector 23. The rate of water discharge is observed to decrease along the drip line, which is accompanied by a corresponding reduction in the average water velocity. In the event that the water velocity is unable to displace portions of entrapped air through hydraulic means (i.e., by the water flow), it is necessary to install air expulsion-intake valves (Jarwar, 2019; Sanders, 1992). During the field experiments, it was observed that the drip lines exhibited a maximum downward angle of 5 degrees. The minimum water velocity required for the removal of air in this pipe angle is 0.183 m/s. As illustrated in Table 8, between three-quarters and the conclusion of the drip line, instances of entrapped air may arise in both drip irrigation fields. This is due to the fact that the velocity of the water within the pipeline is less than the velocity required for the removal of entrapped air through hydraulic means.

Table 8. Water velocity in different pipeline points

Point of reference from pipeline beginning	Drip irrigation field 1		Drip irrigation field 2	
	Discharge per irrigation drip line (m^3/s)	Water velocity (m/s)	Discharge per irrigation drip line (m^3/s)	Water velocity (m/s)
Beginning	1.42E-04	0.7071	1.09E-04	0.5416
Middle	7.11E-05	0.3536	5.44E-05	0.2708
Three quarters	3.55E-05	0.1768	2.72E-05	0.1354
Seven eighths	1.78E-05	0.0884	1.36E-05	0.0677

The findings from the field experiments are subject to several limitations, primarily due to the small sample size, which reduces the reliability of performance evaluations. To enhance representativeness, data collection should be expanded, and studies should be conducted in areas beyond Sector 23. During the four-week testing period, several constraints were identified. Initially, only two fields—each employing a different irrigation method—were considered in this study. However, comparing the performance of surface and drip irrigation is inherently challenging, as farm-specific conditions vary and system performance fluctuates over time, necessitating continuous evaluation (Roth et al., 1995). In general, comparisons between surface and drip irrigation should be framed within the broader context of irrigation planning (Darouich et al., 2014).

Furthermore, agricultural practices and irrigation methods differ between surface and drip systems. Field-level actions and procedures undertaken by farmers are integral to these applications. Soil tillage practices, including the use of machinery, influence soil conditions, particularly in the presence of soil degradation and erosion. Fertilizer application affects both crop quality and nutrient distribution. Additionally, weed and pest control techniques involve the spraying of crops and soil, often requiring the application of herbicides and pesticides, which are linked to land use management (Pereira et al., 2002).

Overall, irrigation technology and agricultural practices significantly impact the type and amount of labor required in farming operations (Kaini et al., 2020). Therefore, any assessment of irrigation efficiency should also consider the broader agricultural and socioeconomic factors that influence irrigation system performance and sustainability.

Spatial Overview of Irrigation and Agricultural Practices

The transect observations encompassed 428 fields, representing approximately 51% of all parcels in the sector. These data were mapped using GIS to highlight the spatial distribution of agricultural and irrigation features. The analysis excluded residential areas, which are not typical for irrigation systems. The irrigation methods revealed that surface channel irrigation was used on only 8% of fields, while drip irrigation covered the majority (73%). Fields under drip irrigation exhibited dry, solid topsoil, and surrounding waterways appeared deserted. Approximately 12% of the area was non-irrigable due to fallow and abandoned fields. In terms of field maintenance, 42% of fields were categorized as high maintenance, 36% as medium, and 14% as low maintenance. Drip irrigation fields mainly showed medium (42%) and high (51%) maintenance levels, whereas surface irrigation fields

Figure 5. Observational classifications of sector 23 with 5A Irrigation type, 5B Maintenance level, 5C Weed removal strategy, and 5D Crop types

exhibited more frequent low (14%) maintenance, with a smaller proportion requiring high maintenance (31%). Fallow and abandoned fields were classified as high and low maintenance, respectively, due to the absence of irrigation.

The weed-removal strategy in the area primarily involves the application of herbicides, covering over 50% of the land. Farmers were also observed using herbicide-based pesticides, such as glyphosate, for weed control. Mowing and plowing accounted for 10-13% of the weeding methods. Due to the dense crop configurations and irregular tree lines in most orchards, automated weed removal is challenging. Among fields with drip irrigation, 60% were treated with herbicides more frequently than mowed (15%) or plowed (8%). For surface irrigation, spraying was the most common method (38%), with mowing and plowing being less frequent. Additionally, 32% of respondents indicated farming could occur without irrigation, while 3% deemed mowing as insignificant. The status of 39% of the practices remains unknown, and 25% involve herbicide usage.

Table 9. Weed removal strategy per irrigation type

Weed removal strategy	Drip amount	%	Surface amount	%	No Irrigation amount	%
Herbicides	186	59,8	12	37,5	8	25,8
Ploughed	24	7,7	7	21,9	10	32,3
Mowed	47	15,1	6	18,8	1	3,2
Unknown	54	17,4	7	21,9	12	38,7
Total	311		32		31	

Figure 5D displays the crop diversity in the region, with kiwifruit (17%) and oranges (59%) being the most common crops. Other crops, such as peaches, nectarines, peppers, tomatoes, and potatoes, accounted for 1% of the fields. Additionally, some fields were in early germination stages, cultivated in greenhouses, or covered with plastic. Approximately 6% of the areas were classified as unidentified. Table 10 indicates no statistically significant difference between drip and surface irrigation concerning crop types. Drip irrigation fields showed a slightly higher prevalence of kaki and oranges, while surface irrigation fields favored vegetables, which accounted for 9%. The yield rate was 36% higher in areas with abandoned and fallow fields.

The field condition is illustrated in Figure 6. A significant proportion of fields (77%) have been observed to be actively cultivated and classified as ready for use. Abandoned land comprised 8.5% of the total area, while 4% was left fallow. The remaining locations are either residential areas or of unknown designation. A comparison of the field condition with the type of irrigation (4A) (Table 11) reveals that drip irrigation is employed in the vast majority of fields

Table 10. Crop type per irrigation type

Crops	Drip amount	%	Surface amount	%	No irrigation amount	%
Orange	214	69,0	19	59,4	7	21,2
Kaki	64	20,6	5	15,6	1	3,0
Citrus	13	4,2	1	3,1	0	0,0
Peach & Nectarine	2	0,6	0	0,0	1	3,0
Vegetables	3	1,0	3	9,4	0	0,0
Others	2	0,6	1	3,1	1	3,0
Multiple crops	2	0,6	0	0,0	0	0,0
No crop	0	0,0	0	0,0	12	36,4
Unidentifiable	10	3,2	3	9,4	11	33,3
Total	310		32		33	

Table 11. Field status per irrigation type

Field Status	Drip Amount	%	Surface Amount	%	No Irrigation	%
In Use	297	95,5	25	78,1	2	4,5
Abandoned	7	2,3	3	9,4	26	59,1
Fallow	0	0,0	2	6,3	14	31,8
Unknown	7	2,3	2	6,3	2	4,5
Total	304		32		44	

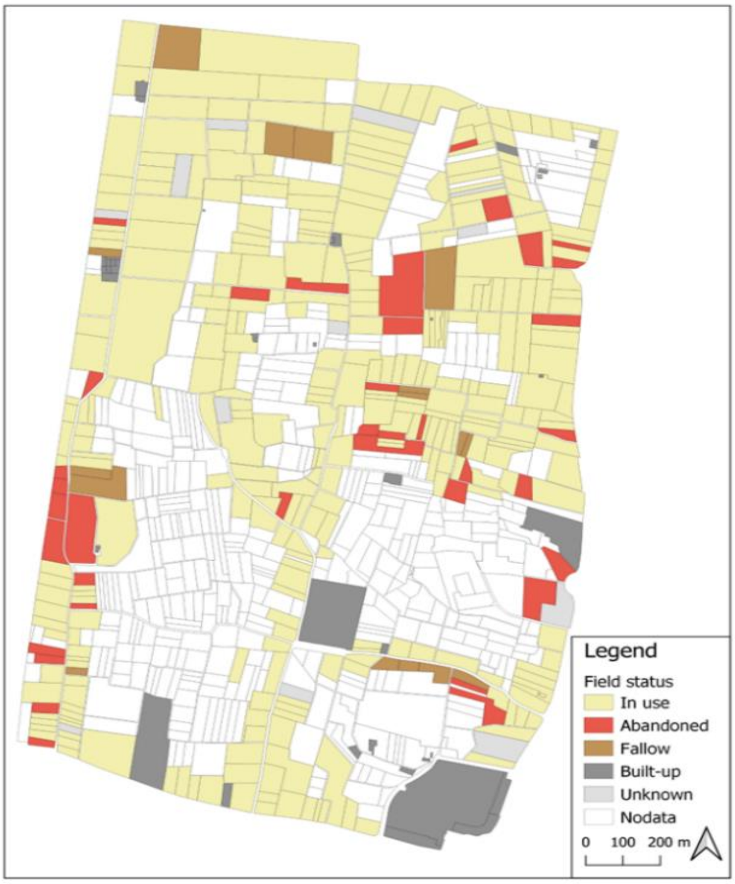

Figure 6. Observational classification of sector 23 with field status.

(96%). Surface irrigation is employed in 78% of cases, with 9% of fields having been abandoned and 6% remaining fallow. Of the non-irrigated fields, 59% were most often abandoned, while 32% were left fallow.

Perspectives

An analysis of stakeholders' views on surface and drip irrigation was conducted through structured interviews with farmers and irrigation managers. The goal was to gather insights from individuals directly involved in field operations within the ARJ. Interviews, lasting between 30 to 60 minutes, included general questions on the respondents' roles and experiences, followed by inquiries on water conservation, irrigation practices, and system performance. People's perspectives are obtained throughout the observation process even though it is preceded by a discussion. There were issues with the observation form's closed questions, which revealed that the fields varied from one another and that a plot occasionally included more than one crop or growth stage. Asking more targeted questions will enable a more focused and thorough study (Knott et al., 2022). Men over 45 and one woman made up the majority of the interviewees' diversity. This may restrict how comprehensive the viewpoints are.

Farmers' responses on water savings from modern irrigation systems were mixed, with some uncertainty about the ultimate use of conserved water, while others suggested it was redirected to regions like Andalucia or Albufera. A few farmers highlighted financial savings from drip irrigation, though concerns about the system's cost were noted, as drip irrigation is three times more expensive than surface irrigation. Additionally, some farmers were unaware of the exact composition of fertilizers applied through the irrigation systems, and while a drip farmer mentioned a reduction in weeds, others expressed doubts about yield improvements. Furthermore, during the time when water requirements were measured, the heatwave changed the typical weather and increased the crop water requirements. Farmers have discovered that drip irrigation increases yields and makes management easier. Farmers' first understanding runs counter to these opinions and needs more investigation. In the future, it will be important to find out why, in the event that the crop water requirement is not fulfilled, farmers' discontent with the trickle is still ongoing. Dripping is more convenient to farmers since it requires less effort (Jarwar, 2019). This could be the primary driver behind farmers choosing to invest in drip rather than crop water requirement. It was evident from the discussions that farmers are eager to modernize. But it was evident from the way the difficulties were phrased that investments needed to be made, which might account for the modernization's delay.

Interviews with surface irrigation regulators revealed that irrigation practices varied based on field characteristics such as weed density, slope, and tree age, with customized irrigation plans developed for each field. In contrast, drip irrigation doses are determined based on soil and tree leaf analysis, with adjustments made every three months. Maintenance practices differed for the two systems: drip irrigation requires regular checks and fixes by the irrigation engineer, while surface irrigation maintenance is more hands-on, with farmers paying for services related to canal cleaning. Overall, while both irrigation types have their advantages, the implementation and maintenance processes reflect different levels of responsibility and operational dynamics.

Conclusion

In order to contribute to the Acequia Real del Jucar region's goal of irrigation modernization, irrigation system sites, referred to as sector 23, were subjected to a performance review informed by field experiments, field observations, and user perspectives. The evaluation of irrigation performance during the transition from surface to drip irrigation in Sector 23 of the ARJ irrigation district revealed notable differences in efficiency across systems and fields. In surface irrigation, application efficiency was calculated as 65.6% in the first field and 94.1% in the second, both indicating water deficits, with the first field showing a greater shortfall. Conveyance efficiency was 89.57% and 97.9% for the first and second fields, respectively. Despite the Irrigation Control Centre's (ICC) claim of 100% conveyance efficiency in drip systems, field-based observations suggest potential losses due to canal leakage and structural deficiencies. Overall irrigation efficiency was estimated at 89.6% in Field 1 and 92.1% in Field 2. In the drip irrigation context, discrepancies between reported and measured emitter discharges were observed, 0.6 L/hr in Field 1 and 0.1 L/hr in Field 2, highlighting the importance of field validation. Additionally, irrigation schedules differed between the fields, with Field 1 receiving water twice daily on weekdays and Field 2 irrigated four times weekly. These findings underscore the critical role of field-based performance monitoring, maintenance, and scheduling in optimizing irrigation efficiency during system transitions.

A spatial assessment of irrigation and agricultural practices in Sector 23 was conducted through structured observations of 428 fields, representing 51% of the total area. Drip irrigation was the predominant method, applied in 73% of fields, while surface irrigation was limited to 8%. The majority (77%) of fields were actively cultivated, whereas 12% remained abandoned or fallow. Drip-irrigated fields required moderate (42%) to high (51%) maintenance, while surface irrigation fields had a lower maintenance classification (14%). Citrus orchards, particularly orange (59%) and persimmon (17%), were the most commonly cultivated crops, with slightly higher kaki and orange prevalence in drip-irrigated fields. Observations revealed significant differences in agricultural practices between irrigation methods. Drip irrigation fields were well-maintained, with frequent herbicide application, whereas surface irrigation fields exhibited higher abandonment rates and lower maintenance. Non-irrigated fields, including rainfed and degraded areas with unused canals, also had elevated abandonment rates. Weed management practices varied, with herbicide application more common in drip-irrigated fields, while mowing and plowing were preferred in surface irrigation. Notably, vegetable cultivation was more prevalent in surface-irrigated fields than in drip-irrigated ones.

This study examined the performance differences between surface and drip irrigation systems in Sector 23, incorporating both field experiments and stakeholder perspectives. Results indicated that while drip irrigation was perceived as more efficient in water conservation and field management, it required higher upfront costs and more centralized maintenance compared to surface irrigation, which relies more on direct, field-level management. Farmers favored drip irrigation for its ability to reduce labor intensity, improve crop yield, and mitigate water scarcity. However, challenges such as emitter clogging and air entrapment in drip lines highlighted the need for regular maintenance and water quality management. The study also emphasized the importance of installing water flow measurement stations in surface irrigation systems and recalculating transport efficiency in high-pressure pipelines. Furthermore, it is crucial to address the declining interest in agriculture among youth and promote sustainable practices to enhance irrigation system efficiency. Finally, this study demonstrates that the success of irrigation modernization depends not only on technical efficiency but also on user behavior, maintenance strategies, agricultural practices, and land use decisions, offering insights for developing sustainable irrigation strategies, particularly in water-scarce regions.

Author Contribution

G.C.A: collecting data, conceptualization writing draft report and writing article, analysed the results; **E.Q.M:** collecting data, conducting fieldwork, project administration, writing draft report; **E.V:** carrying out fieldwork, performing and evaluating spatial overview, writing draft report; **H.C.M:** methodology, conducting structured interviews, writing draft report; **E.T:** carrying out observations, data collection and writing draft report, resources.

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Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that might appear to influence the work reported in this paper.

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RESEARCH PAPER

Assessment and classification of surface soil erosion impact around Dutse Jigawa State Nigeria

Suleiman Usman[1]*, Yusuf Aliyu Firi[1], Bashir Uba Sani[1]

[1] Department of Soil Science, Faculty of Agriculture, Federal University Dutse, Nigeria

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***Corresponding Author**
Tel.: +2347034233241
E-mail: labboallugu@yahoo.com

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Abstract

Surface soil condition from erosion-affected sites of Dutse is physically damaged by gully erosion. Book for Describing and Sampling Soils version 3.0 was used to evaluate soil texture, soil structure, soil consistency, and vegetation pattern of the 9 different study sites. The impact of soil erosion was measured on gully channels and calculated based on USDA soil erosion method. Soil quality (P-Sq) and land suitability (P-Ls) classes were evaluated by Visual Soil Erosion Approach (VSEA). Eroded soil volumes of 42.2 m^3 and 33.5 m^3 at Fagoji (FGJ) and Gidan Sarkin Askira (GSA) compared to those recorded at KRG sites (23.9 m^3). There was no reasonable variation between the sites for the condition of soil in terms of soil texture, soil structure, soil consistency and vegetation. However, a correlation analysis between the sites for the calculated values of depth and width observed that five sites (FGJ2, FGJ3, KRG1, KRG2 and GSA3) are significant (P < 5%) whereas the other four sites (FGJ1, KRG3, GSA1 and GSA2) were not significant (P = 5%). Soil quality and land suitability classes were evaluated as Sq2, Sq3 and Ls2, Ls3 which can be managed under careful soil conservation application whereas Sq4, Ls4 and Sq5, Ls5 are lands not suitable for agronomic production. These land conditions of the study sites were attributed to weak soil structural condition, poor vegetation and inadequate soil management. This study suggested the use of advanced soil conservation approaches such as orchard plantation, water harvesting system and drainage application in the affected sites.

Introduction

Surface soil is a shield layer that provides protection to soil materials, soil quality and soil fertility to support plants, organisms and underground soil and water systems (Usman, 2016). Soil erosion has become a serious surface soil problem and has affected the potential of soil quality and soil fertility around Dutse, Jigawa State (Usman et al., 2019). The impact of soil erosion was considered one of the most important factors threatening the sustainability of food security in this part of sub-Saharan Africa (Usman et al., 2017). Soil erosion affects the physical, biological and chemical components of soil, biota and biodiversity (Al-Shoumik et al., 2023). Soil erosion damages surface soil condition and forced the surface soil particles to detach from one place to another (Gebrie et al., 2023). This detachment of soil particles was also regarded as one of the violent environmental problems, which reduce the potential of soil to support plant and ensure food security in sub-Saharan Africa (Andualem et al., 2023). Soil erosion in this regard, removes the soil materials from the top surface soil layer (sheet), extending if not

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control to small channels (rills), and to deeper channels (gullies) (Andualem et al., 2023). This removal of surface soil materials take place in the form of depression by rainfall impact (splash erosion) and cause the sheet, rill and gully erosion or even overland flow sometimes (Baade et al., 2024). These forms of soil erosion, if they occurred in a given environment, the metaphors of how concentrated they are, depends largely on the nature and condition of the overall soil properties (texture, structure, consistency, drainage, organic matter content etc.), slope, vegetation cover of and land use activities (Usman et al., 2024a). Land areas subjected to continuous cultivation without proper soil management, lack of tree plantation and mismanagement of vegetation shrubs and plants, are considered highly prone to soil erosion (Usman, 2016). Under these conditions, it is noticeable that soil materials can be washed away easily by water and leaving the entire surface soil affected by various forms of soil erosion (Evans, 2013). This soil erosion impact has been described as both on-site (at the place where the soil is detached) and off-site (wherever the eroded soil gets deposited) (Usman et al., 2024b). The problem is more serious in poor vegetation areas where erosion is intense because of extreme climate conditions and poor management applications (FAO, 2023). This process of soil erosion is caused by combination of natural erosive agents, which include rainfall, wind, waves and bioturbation including human-induced factors such as over-ploughing, overgrazing, building, deforestation, forest fires and off-road vehicles (Pandey et al., 2016). According Usman et al. (2019), these erosive agents appeared to have physically caused more serious surface soil damages and bigger gully channels in some areas around Dutse. These gully channels around Dutse areas, are hastened by agricultural land use and climatic change impact, and often have been forming for many years (Usman et al., 2024a). In these areas, surface soil particles are lost by water from agricultural lands because of poor vegetation cover and improper soil management application (Usman et al., 2017). Therefore, knowing the extent of gully erosion development through assessment will help provide some solution towards a better management (Ezeh et al., 2024).

The physical and economic impact of soil erosion was considered as important driving force threatening ecological resilience, resulting in reduced land quality and productivity, increased natural disasters, and decline food security and economic development (Yang et al., 2023). Reduction in agricultural land size and soil functional service to support the production of cereals and legumes, were noted to have been occurred as a result of soil erosion impact around Dutse (Usman et al., 2019). Understanding the status of soil erosion affected sites in Dutse is therefore essential when addressing the ways to manage soil quality and increase the production of cereals and legumes in the region. Soil erosion such as gully, is destructive and cannot be managed by ploughing because of its depth, size and nature (Usman, 2007). In Dutse however, there is little information regarding the extent of soil erosion on both physical and quantitative impact. This study will provide a contribution to the management of soil and water for crop production and environmental security in the study area (Usman, 2024). Therefore, the study was aimed to assess and classify the impact of soil erosion on surface soil quality. The scope of its objectives was addressing the extent of soil erosion on physical and quantitative measures in the study area.

Materials and methods

Study area

Dutse is a capital city of Jigawa State located geographically in the north-west Nigeria. The average monthly temperature is between 30°C and 45°C and annual average rainfall is 743 mm. Elevation from sea level is between 349 m and 462 m and GPS coordinates ranging from 11.7160°N and 9.3557°E. The total population size of the human living in Dutse was estimated to account for 246,143 according to National Population Census of Nigeria (NPCN-JG, 2007). The common agricultural land use activities include monocropping, mixed farming, crop rotation, irrigation, rearing animals and fish farming. The major crops grown in Dutse and villages around are pearl millet, groundnut, maize, soybean, rice, wheat, sorghum, cowpea, sesame and date palm. The vegetation has been described as scattered trees and shrubs, which

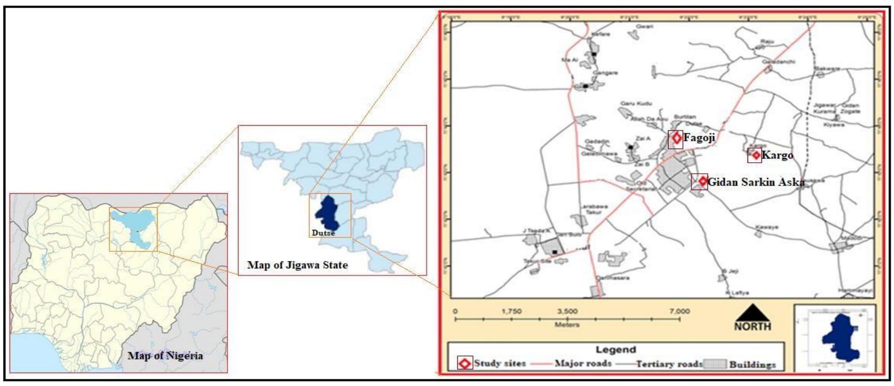

Figure 1. Map of the study area indicating the actual study sites in Dutse, Jigawa State Nigeria

include Acacia, Baobab, Neem and Palm (Dabino). However, three different study areas were selected around Dutse namely – Fagoji, Kargo, and Gidan Sarkin Aska (Figure 2).

Surface soil condition and site selection

The surface soil condition of the study site has been physically damaged by soil erosion (Figure 2). Bigger channels of gully erosion have created surface soil imbalances, which have affected the vegetation cover and plant biomass of the study sites (Figure 2). Study sites were selected based on these surface soil conditions as recommended by Evans (2013). The selection process considered the gully occurrence in the affected sites by focusing on the physical nature, size and geomorphogical feautures its channels. Both the large (bigger in size and shape) and active gullies (characterised by eroding headwalls without vegetation cover and sediment-deposited fan) are believed to have generated significant amounts of sediment and have caused serious damage to surface soil condition of the selected study sites (Figure 2).

Figure 2. Typical example of the surface soil condition of the study area

The 3 selected areas around Dutse [Fagoji, Kargo and Gidan Sarkin Aska (Figure 2)] were corded as Fagoji (FGJ), Kargo (KRG), and Gidan Sarkin Aska (GSA). However, at each of the study area, 3 different sites were also assessed and evaluated. A total of 9 different sites were covered in the study region: FGJ1, 2 and 3; KRG 1, 2 and 3; and GSA1, 2 and 3 accordingly. The overall assessment was established across these selected sites by considering the different land use practices, vegetation cover and surface soil condition. The local slope gradient of the selected areas varied from length, depth and width, which was of the typical land topography of the study sites. Physically, these sites consist of few trees and shrubs, and mostly dominated by silt and fine sand.

Soil sampling and analysis

Four different composite soil samples were collected using soil auger from the field at each of the study sites. Two of these soil samples were taken from the upper part of the gully site whereas the other two were taken from the lower part of the gully channel. A total of nine (9) different composite soil samples collected from 90 different points (30 x 3 = 90) were taken to the lab for soil textural analysis. This soil textural analysis was performed based on simple jar test which provided a typical separation of percentage sand, silt and clay (Usman, 2013). Book for Describing and Sampling Soils version 3.0 (Schoeneberger *et al.*, 2012) was used to evaluate soil structure, soil consistency and vegetation.

Measurement of the gully erosion

This study adapts the concept of direct measurement of soil erosion at *in situ* level introduced by United State Department of Agriculture (USDA, 2012). Range poles were used to earmark the affected areas and also to identify point-by-point for measurement of the affected area. These range poles were inserted into the soil along the slope transects

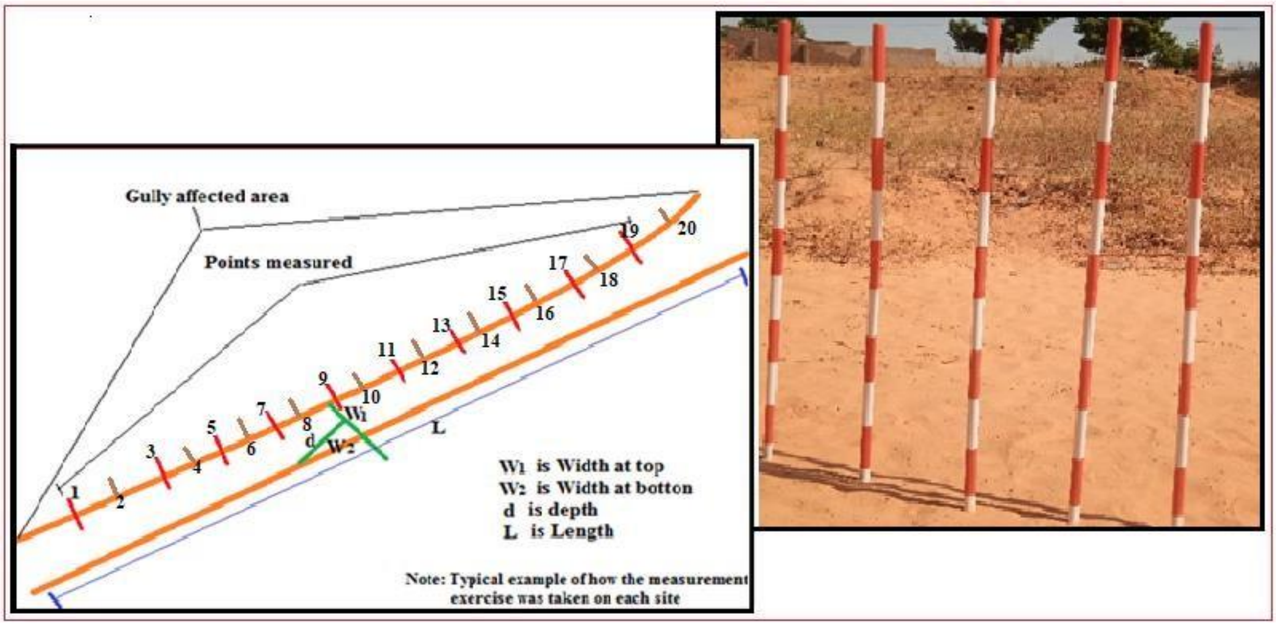

Figure 3. Example of the field layout for measurement exercise

with 3 m to 5 m intervals across the slope. However, for each transect, five poles were spaced at 5 m intervals across the entire gully channel. The lengths of the poles that were left exposed above the soil surface were used as reference point for the measurement exercise. This measurement took place in the field and covered 20 different measurements transects or points on each of the gully area (Figure 3). Selection of these measurement points was based on random sampling within the affected area. It covers the top width (W_1), width at bottom (W_2), depth (d) and length (L).

Likewise, soil quality (P-Sq) and land suitability (P-Ls) classes were evaluated by Visual Soil Erosion Approach (VSEA) introduced by Usman et al. (2024) for agronomic and management application (Table 1).

The overall results were used to determine the volume of soil loss at each study site, and calculated according to USDA (2012) formula:

$$V = L \times \frac{W1+W2}{2 \times d}$$

Table 1. Soil quality (P-Sq) and land suitability (P-Ls) description guide (Usman *et al.,* 2024)

a) P-Sq[1]	Sq1	Very small-size channel of sheet erosion: 0 – 5 cm width and depth
	Sq2	Small-size channel of sheet erosion: 6 – 10 cm width and depth
	Sq3	Small-size channel of rill erosion: 11 – 20 cm width and depth
	Sq4	Large-size channel of rill erosion: 21 – 30 cm width and depth
	Sq5	Gully surface erosion: >30 cm width and depth
b) P-Ls[2]	Ls1	Good land: few indications of very small-size channels of sheet in the study sites at that time of assessment in the field
	Ls2	Moderately good land: few small-size channels of sheet erosion in the study sites at that time of assessment in the filed
	Ls3	Poor land: 20% of the site is affected by small channels of rill in study sites
	Ls4	Very poor land: >20% of the site is affected by large channels of rill in the study sites at that time of assessment in the field
	Ls5	Bad land: significant portion of the land is affected by gullies in study sites

[1, 2] P-Sq and P-Ls classes are described based on VSEA. The measurement was carried out in the field

Where:

V = volume of soil loss
L = length
W_1 = the average top width measured from the gully channel
W_2 = the average bottom width measured in the gully channel
d = the average depth of gully erosion

Statistical Analysis

All the data was run for statistical analysis using excel to compare the sum, average, minimum and maximum values of depth, width at top and width at bottom between the therww (3) study sites.

Results

Soil physical properties, vegetation, management and drainage condition

Table 2 presents the results of particle analysis, textural class, soil structural class and vegetation. Across all the study sites, percentage sand particles were found to be the dominant texture fraction. Soil structural class appeared to be weak and structureless whereas vegetation cover was evaluated as poor and very poor. Initial background of the surface soil condition prior to this assessment has also confirmed that the vegetation cover is poor (Figure 2). A significant decline of surface soil quality was noted from the results of soil structural classes across all the study sites (Table 2).

Table 2. Soil texture, structure and vegetation condition of the study sites

Site	% Sand	% Silt	% Clay	Texture Class	Soil Structural Class	Vegetation
FGJ1	82	8	10	Sandy Loam	Weak	Poor
FGJ2	84	6	10	Sandy Loam	Weak	Poor
FGJ3	80	6	15	Fine sand	Structure-less	Very-Poor
KRG1	80	8	12	Sandy	Structure-less	Poor
KRG2	81	5	15	Sandy	Structure-less	Poor
KRG3	81	7	12	Sandy	Structure-less	Poor
GSA1	81	8	11	Sandy loam	Structure-less	Very-poor
GSA2	82	8	10	Sandy	Weak	Very-poor
GSA3	85	5	10	Sandy	Weak	Very-Poor

Table 3 explained the management and drainage condition of the study sites. There are indications of farmers' efforts through manure and compost application to help improve the condition of the soil (Table 3). However, both the soil and crop management applications, which also reported the use of cow dung, house refuse and inorganic fertilizers under mixed and mono-cropping systems, are not sufficient probably due to drainage conditions of the sites (Table 3). The drainage pattern either drained, well-drained or excessively drained are likely to cause surface soil deterioration leading to surface soil damage and occurrence of soil erosion.

Table 3: Management practices and drainage condition of the study sites

Sites	Management practices (soil)	Management practice (crop)	Drainage class
FGJ1	Manure, inorganic fertilizer	Mixed-cropping	Well Drained
FGJ2	Cow dung, inorganic fertilizer	Mono-cropping	Drained
FGJ3	Compost manure	Mixed-cropping	Excessively Drained
KRG1	Manure, cow dung	Mono-crop	Well-drained
KRG2	Inorganic fertilizer	Mono-crop	Drained
KRG3	Inorganic fertilizer	Mono-crop	Excessively Drained
GSA1	Inorganic fertilizer	Mono-crop	Well Drained
GSA2	House refuse, cow dung	Mixed-cropping	Drained
GSA3	Inorganic fertilizer	Mono-crop	Excessively Drained

Length, width and depth of gully erosion

Table 4 presents the data recorded for length, width and depth of gully erosion whereas the averages for these parameters are presented in Table 5. The observation was based on the measurement exercise in the field. The highest depth was recorded around Gidan Sarkin Aska (GSK) sites compared to those recorded around Fagoji (FGJ) and Kargo (KRG). However, higher width was recorded at KRG sites, which appeared to be bigger than those recorded at FGJ and GSA, respectively. The total length measured at FGJ1 and GSA3 were higher than all the sites across the study area. The expanding of gully erosion across these study sites are defined by these parameters, and appeared to have been destroying the aggregate structure and reduce the surface soil quality as reported in Table 2 and 3. Width expanded with the damage of soil structure and can be noticed by distance across the gully channels, which is physically damaging the end-to-end portions of the gully in the study sites. The correlation analysis shows that sites at FGJ2, FGJ3, KRG1, KRG2 and GSA3 are significant (P < 5%). However, sites around FGJ1, KRG3, GSA1 and GSA2 were not significant (P = 5%).

Table 4. Depth, width at top and bottom and length of gully erosion in the study sites

Site	Depth (m)	Width top (m)	Width bottom (m)	Length (m)
FGJ1	19.2	14.0	12.1	45.50
FGJ2	16.1	56.3	53.6	25.5
FGJ3	52.1	50.1	42.2	39.0
KRG1	8.9	71.3	57.1	32.0
KRG2	15.0	89.4	81.4	35.0
KRG3	11.5	87.6	89.3	26.0
GSA1	77.1	52.5	43.5	35.5
GSA2	74.6	28.9	22.4	27.0
GSA3	80.3	61.0	52.2	43.3

Table 5. Correlation analysis of the gully parameters in the study sites

Site	Depth (m)	Width top (m)	Width bottom (m)
FGJ1	-0.97079^{NS}	-0.93606 ^{NS}	-0.95706 ^{NS}
FGJ2	0.666784*	0.749371*	0.704476*
FGJ3	-0.67054*	-0.57917*	-0.63123*
KRG1	-0.90355*	-0.84723*	-0.88015*
KRG2	0.980868*	0.993137*	0.998659*
KRG3	0.998779 ^{NS}	0.988647 ^{NS}	0.99786 ^{NS}
GSA1	-0.97072 ^{NS}	-0.93597 ^{NS}	-0.95699 ^{NS}
GSA2	-0.99539 ^{NS}	-0.97734 ^{NS}	-0.98909 ^{NS}
GSA3	-0.95767*	-0.91743*	-0.94148*

Note: NS Signifies not significant at P = 5%
* Signifies significant at P < 5%

Volume of soil loss, sum, maximum and minimum

The basic geometric components of the width and depth, and the volume of soil loss across all the study sites are presented in Table 5. Sites GSA1, GSA3 and FGJ1 recorded the highest volume of soil loss whereas sites FGJ2 and GSA2 recorded the lowest volume. This soil loss was calculated from the width, depth and length of gully erosion at each of the study sites. This soil loss increased in response to the rise in these three parameters. Sites recorded the higher width, depth and length are noted to have an increased in soil loss. This means that the volume of soil loss at each of the study sites depend entirely on the sum, average, maximum and minimum values of the parameters measured (Table 6).

Table 6. Sum, maximum and minimum values of depth and width in the study sites

Factor	Value	FGJ1	FGJ2	FGJ3	KRG1	KRG2	KRG3	GSA1	GSA2	GSA3
Depth (d m)	Sum of d	19.2	16.1	52.1	88.9	11.5	15.0	77.1	74.3	80.3
	Average d	9.6	80.5	26.0	8.9	57.0	79.0	17.0	37.15	40.5
	Maximum d	9.3	9.5	4.9	11.2	9.4	9.5	8.0	6.0	5.5
	Minimum d	3.1	2.3	1.1	1.8	1.0	3.9	1.6	2.0	2.6
Width top (W_1 m)	Sum of W_1	14.0	56.3	50.1	71.3	87.6	89.4	52.5	28.9	61.0
	Average W_1	69.5	28.1	25.0	71.3	43.7	44.7	52.5	14.4	30.4
	Maximum W_1	9.5	4.0	3.6	7.3	55.0	57.1	3.0	6.7	45.0
	Minimum W_1	3.4	1.5	6.0	3.0	37.0	32.0	2.2	3.5	3.8
Width bottom (W_2 m)	Sum of W_2	12.1	25.5	42.2	57.1	89.3	81.4	43.5	22.4	52.2
	Average W_2	61.8	26.8	21.3	57.1	44.6	40.9		11.1	26.4
	Maximum W_2	8.6	4.3	3.2	9.0	60.0	51.2		6.2	43.7
	Minimum W_2	3.1	1.5	4.0	3.7	3.4	2.9	1.5	1.7	3.9
Soil loss (m^3)		30.8	9.1	42.2	23.9	20.5	19.5		11.5	30.5

Table 7. Soil loss, soil quality and land suitability classes in the study sites

Site	Soil loss (m^3)	Soil quality class (P-Sq)	Land suitability class (P-Ls)	Label of the surface condition
FGJ1	30.8	Sq4	Ls4	Notably damaged
FGJ2	9.10	Sq2	Ls2	Small portion damaged
FGJ3	42.2	Sq5	Ls5	Bad land
KRG1	23.9	Sq4	Ls4	Notably damaged
KRG2	20.5	Sq3	Ls3	Partly damaged
KRG3	19.5	Sq3	Ls4	Notably damaged
GSA1	33.5	Sq5	Ls5	Partly damaged
GSA2	11.5	Sq3	Ls3	Partially damaged
GSA3	30.5	Sq4	Ls4	Notably damaged

Soil loss, soil quality and land suitability classes

Table 7 shows the soil quality and land suitability condition for agricultural and management application. Compared with the volume of soil loss across the study sites, 3 major classes of soil quality and land suitability were evaluated (Table 7). Except for Sq2, Sq3 and Ls2, Ls3 which can be managed under careful soil conservation application, the other sites appeared to be partially damaged and bad condition. These Sq4, Ls4 and Sq5, Ls5 are lands not suitable for agronomic production. Significant portion of the land was destroyed and management application required is likely to be more costly.

Discussion

This study aligns with previous studies in Nigeria and Africa that assessed the impacts of soil erosion from agricultural soils (Usman et al., 2017; Onyelowe, et al., 2018; Ezeh et al., 2024). It is also tallied with other similar studies (Stott, 1997; Shi et al., 2011) that measured soil losses and made comparisons between the affected sites. Eroded soil volumes of 42.2 m^3, 33.5 and 23.9 m^3 at FGJ and GSA interpreted within the same range of 21.47 m^3 and 45 m^3 recorded by Usman et al. (2019) in Dutse. This physical and quantitative impact of the gully erosion across the study sites positioned the surface soil properties at a very high risk of damage as already had destroyed the soil functional services of the area (Evans, 2013). This also has caused a serious surface soil deterioration that could probably affect the physical, biological and chemical properties of the in the study sites (Al-Shoumik et al., 2023). The detachment of soil particles around the sites recorded the highest volume of soil loss as observed around FGJ and GSA is a serious threat to soil biological biodiversity and soil productivity (Usman et al., 2016). At very high rainfall intensity, this detachment of soil particles across the study sites could lead to greater deterioration of soil particles and surface soil damage (Gebrie et al., 2023). In this regard, the impact of gully erosion around Dutse is likely to reduce the potential of soil to support crop production and ensure food security (Andualem et al., 2023). Therefore, increase of width, depth and length of gully erosion in the study sites around Dutse is possible to cause frequent landslides and advanced soil loss in all the sites (Andualem et al., 2023). The limited plant biomass and poor vegetation cover in the study sites are factors, which could also lead expanding of gully erosion and removal of surface soil materials long time ago (Baade et al., 2024). The metaphors of this incident could had resulted to total decline of the overall soil properties including the organic matter and organic carbon content of the study sites slope (Usman et al., 2024a).

The physical damaged caused by the expanding of gully channels from end-to-end portions of the affected area at each of the study site, is an indication of impossibility for agricultural cultivation (e.g. Figure 2). The configuration of these gully channels across the study sites is believed to have been increased due to natural condition of the drainage patterns, which were described as drained, well drained and excessively drained (Table 2). This had probably given direction for gully erosion to expand by progressive head cutting collapsed and damaged the surface soil of the study sites (Figure 2). The percentage width and depth that were calculated on the volume of soil loss across the study sites (Figure 4), can be linked to the overall surface soil conditions, management application, vegetation forms and drainage classes, which were characterized as weak, structureless and poor (Table 2). Soil condition with this specification, was considered vulnerable to soil erosion assault, and could lead to total surface soil damage (Usman, 2024).

Obviously, the 3 sites were characterized by dominant sand particles, which can be explained as instable due to the nature and condition of the surfaces that appeared to be homogeneous in nature (Table 1). Usually, soils with these textural particles may probably experience slow erosion processes, which over time may create deep-cut and wider channels leading to surface damage and landslides (Baade et al., 2024). This is likely to be applicable to most of the study sites as

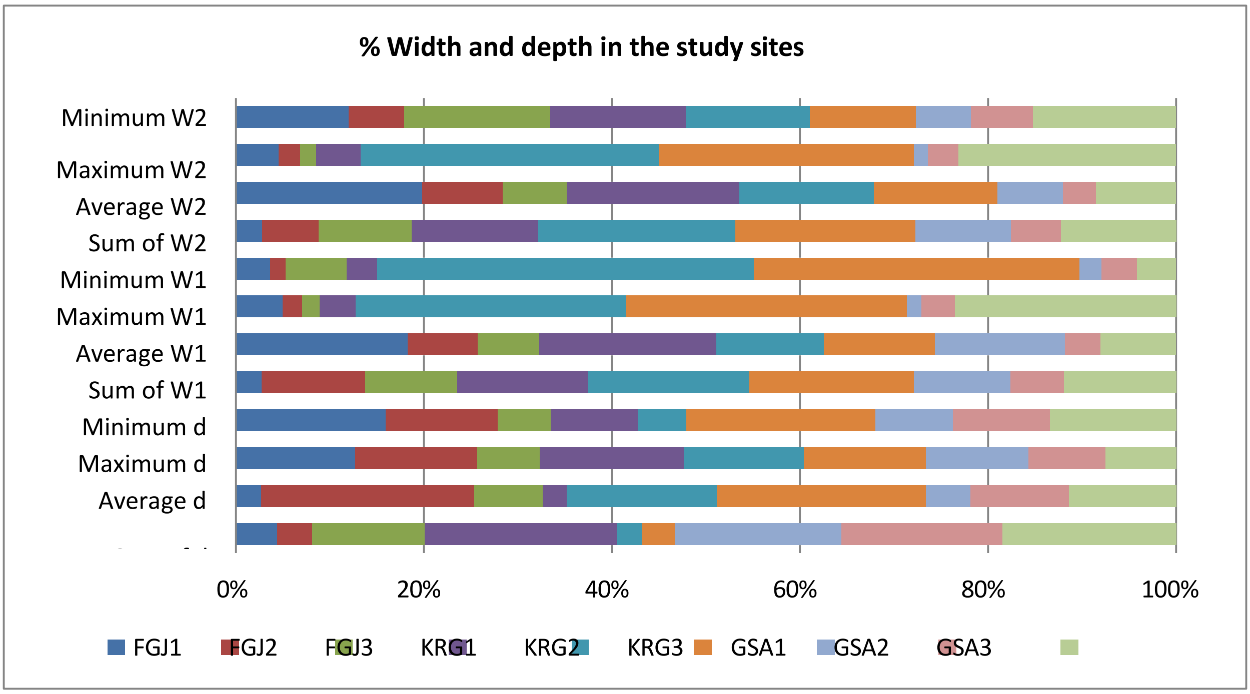

Figure 4. Percentage depth and widths across the study sites

indicated by the correlation analysis (Table 4). The result shows that gully erosion has an advance soil impact over any other type of soil erosion, and can be verified from the fact that the amount of soil loss from the various depths and widths recorded across the study sites (Table 3, 5). Perhaps, this had destroyed significantly the soil functional services, which are playing major roles for ensuring food security and biological biodiversity in the study area (Usman et al., 2016; Usman et al., 2019).

Conclusion

Initial surface soil and vegetation condition were affected by gully erosion many unknown years ago. The study has shown that the gully erosion increased as width, depth and length expanded. The characteristics of soil textures and soil structural formation plus vegetation condition across the study sites have also contributed to the increased of gully erosion. Most of the soils are structureless and vegetation, are poor; these yielded many imbalances, which have contributed to the soil damages in the study area. Differences of the volume of soil loss in the study sites are not much and many sites are related to others in term of depth, width and length. However, the evaluation of soil quality and land suitability classes indicated that the soil condition was deteriorated and the use of land for crop production will require management effort. Planting shelterbelt and forest regeneration along the affected sites are recommended for long term sustainability of the agricultural soil in the study region. Thus, the use of VSEA for other similar soils/environment affected by erosion requires through assessment and evaluation of the major components of environment (e.g. soil properties, plant biomass, vegetation, socio- economic factors such as poverty, deforestation etc.) in the study area. This will validate the efficiency and an adaptability of VSEA to other similar soils/environment across the African drylands, further.

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Ethical Statement

This work is mainly on soil and soil resources and does not involve any information on humans or animals; thus, an ethical statement is not applicable to the context of the manuscript.

Credit authorship contribution statement

Suleiman Usman designed the study, calculated the data and analysed the results. Suleiman Usman, Yusuf Aliyu Firi collected the data in the field. Bashir Uba Sani helps in field design.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that might appear to influence the work reported in this paper.

Data availability

The results of this study were obtained from field assessment conducted in Dutse, Jigawa State Nigeria. The work was part of the Institutional Based Research (IBR) supported by TetFund research programmes. All the data are available in the Department of Soil Science, Faculty of Agriculture, Federal University Dutse, and also, can be obtained from the depository of Tetfund IBR reports in Abuja, Nigeria.

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RESEARCH PAPER

Reducing the average P factor value in sloping land through scenarios that ıncorporate terracing and contour farming practices

Halil Aytop[1]*

[1] Eastern Mediterranean Transitional Zone Agricultural Research Institute (TAGEM/MoAF), 46146, Kahramanmaras, Türkiye

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***Corresponding Author**
Tel.: +90533 312 11 69
E-mail: halilaytop@gmail.com

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Abstract

The soil protection (P) factor, one of the components of the Revised Universal Soil Loss Equation (RUSLE) Model, is critical in influencing erosion. It significantly reduces soil erosion by minimizing surface runoff on sloping terrains. The P factor is unitless. In this article, 4 scenarios involving soil conservation practices tailored to the slope percentages of the study area, which features a sloping landscape, were developed. Terracing and contour farming were proposed as soil conservation strategies. Areas with slopes ranging from 6% to 12% were regarded as suitable for contour farming, while those with slopes between 12% and 30% were considered ideal for terracing practices. The study revealed that scenario 4 lowered the average P factor value of the study area from 1 to 0.58. This outcome indicated that the scenarios devised could decrease the average P factor value in the study area by 42%. It is believed that the approach employed in this study can effectively reduce the average P factor value in sloping regions facing erosion issues.

Introduction

Erosion is highlighted as one of the main factors threatening soils, which are regarded as natural and irreplaceable resources. Water-induced erosion occurs when the upper layer of soil, the most fertile part, washes into surface flows. This leads to land degradation accompanied by the loss of organic matter and nutrients, as well as mineral materials in the topsoil (Wischmeier and Smith, 1978). Overgrazing, deforestation, and agricultural practices in unsuitable areas exacerbate the erosion problem. Productivity issues arise in lands where the adverse effects of erosion are observed. The productivity loss caused by water-induced erosion has been identified as 0.92% in Türkiye (Aytop and Pınar, 2024), which is approximately 1.84 times higher than that in the agricultural lands of European Union (EU) countries. Agricultural areas are more susceptible to soil erosion than any other land-use type (García-Ruiz et al., 2015). Agricultural activities on sloping terrain further worsen erosion. Measurement and assessment of erosion's effects are considered necessary to combat it in these areas (Tian et al., 2021). The Revised Universal Soil Loss Equation (RUSLE) is commonly employed to determine the spatial distribution and effects of erosion (Artun and Koca, 2018; Aytop and Şenol 2022; Ebabu et al., 2022). In the RUSLE model, factors such as rainfall erosivity (R), soil erodibility (K), vegetation cover (C), slope length and steepness (LS), and soil conservation practices (P) are identified and multiplied to estimate soil erosion caused by water (Renard et al., 1997). Consequently, the annual soil loss rate of the measured area due to erosion is calculated in t/ha.

Among the RUSLE factors, the P (support practice) and C (cover-management) factors are the most dynamic and influential contributors to soil erosion (Kebede et al., 2021; Aytop and Şenol, 2022; Pınar and Erpul, 2023). The values of these factors can vary depending on changes in vegetation cover or the implementation of soil conservation practices (Renard et al., 1997). In particular, areas lacking such conservation measures experience accelerated topsoil loss and a rapid decline in land productivity (Panagos et al., 2015; Aytop and Pınar, 2024). A decrease in the P factor value corresponds directly to a reduction in the soil erosion rate.

Various soil conservation practices are employed to mitigate soil erosion in sloping regions (Madenoğlu et al., 2024). Among these, terracing and contour farming are commonly implemented in areas prone to erosion (Didoné et al., 2021). The aim of this study is to apply these soil conservation practices—terracing and contour farming—in slope-appropriate areas of the lands belonging to Beşenli Village, located in the Dulkadiroğlu District of Kahramanmaraş Province, Türkiye, which is characterized by sloping topography. Additionally, the study analyzes the effectiveness of the proposed scenarios in reducing the average P factor value across the study area.

Materials and Methods

Study area

The study area (37.661260° Latitude and 37.253564° Longitude) covers a part of the agricultural and forest lands of Beşenli Village, located within the borders of the Dulkadiroğlu District of Kahramanmaraş Province (Figure 1). In Kahramanmaraş, where the degraded Mediterranean climate is observed, the long term average temperature for many years (1930-2024) is 16.8 °C, and the average precipitation is 721.6 mm (Anonymous, 2025). The total area of the study area is 75.70 ha.

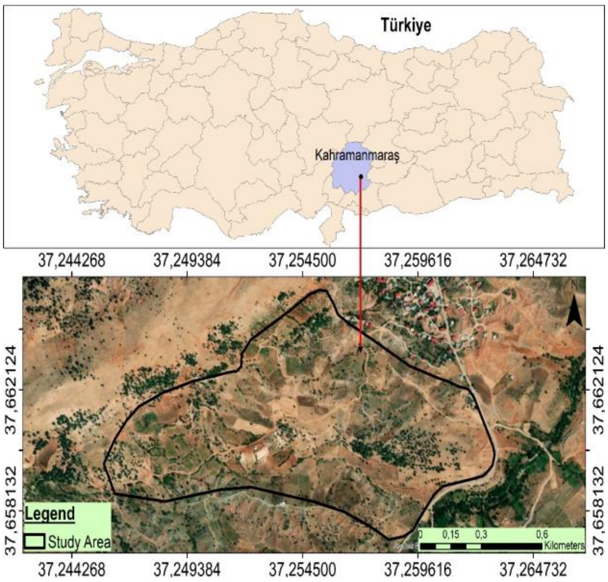

Figure 1. Location map of study area

The study area is located approximately 50 km from the city center of Kahramanmaraş. Elevation within the area ranges from 1,176 to 1,353 meters above sea level (Figure 2). The highest elevations are found in the western part of the area, gradually decreasing toward the east. Three main land use types are observed in the study area: fruit orchards (primarily walnut), annual agricultural crops, and forested areas.

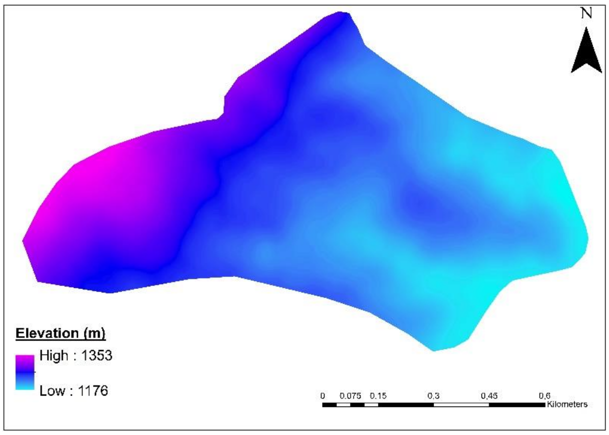

Figure 2. Elevation map of the study area

The study area has a sloping topography. Only 3.57% of the total area has a slight slope, while the remaining 96.43% consists of steep, very steep, and moderately steep slopes. The western and northwestern parts of the area have slopes exceeding 20%. Areas with lower slope percentages are generally located in the northeastern and central parts of the study area (Figure 3).

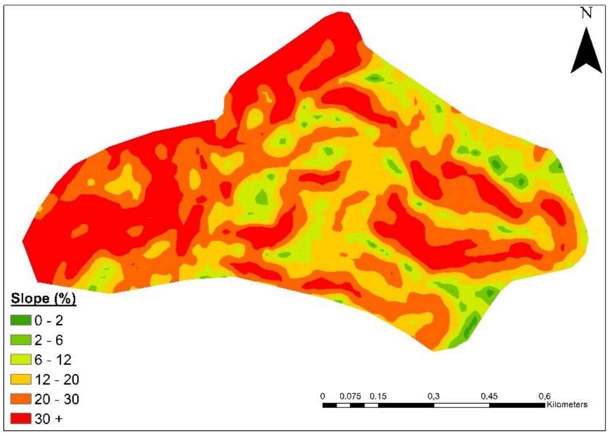

Figure 3. Slope map of the study area

Studies to create P factor scenarios

The P factor is one of the key components of RUSLE, an empirical model used to estimate water-induced soil erosion, and it is unitless. Particularly in sloping areas, a lower P factor value indicates a greater reduction in soil erosion. In this study, the P factor was assigned values of 1.0 for areas without any soil conservation measures (Renard et al., 1997), 0.5 for areas with contour farming, and 0.2 for areas with terracing (Wischmeier and Smith, 1978).

Two soil conservation measures—contour farming and terracing—were selected to develop the P factor scenarios in the study area. The areas where these practices would be applied were identified based on the slope percentages within the study area (Aytop and Şenol, 2022; Saygın et al., 2025). According to the Food and Agriculture Organization (FAO), slopes between 6–10% are suitable for contour farming (FAO, 2003), while slopes between 12–20% are ideal for terracing (FAO, 2000).

Four scenarios were created for the study area. In the first scenario, the P factor value for the study area was assigned as one and it was assumed that no soil protection measures were taken. In the second scenario, only contour agriculture was applied as a soil conservation measure in areas where the slope was between 6-12%; in the third scenario, only terracing was used in areas where the slope was between 12-30%; in the fourth scenario, both contour farming and terracing were applied in areas where the slope was suitable.

Data collection and analysis

The boundary of the study area was delineated using Google Earth. A digital elevation model (DEM) with a resolution of 12.5 × 12.5 meters was downloaded from the Earth Explorer website (https://earthexplorer.usgs.gov) to generate slope and elevation maps of the study area. The DEM was clipped to the boundaries of the study area. ArcGIS 10.7 software was used for all these processes, including the creation of P factor scenario maps.

Results and Discussion

Scenarios were created according to the slope percentages of the study area (Aytop and Şenol; 2022; Saygın et al., 2025). P factor practices were applied to the scenarios at different rates to see the soil conservation practices' individual and combined effects (Tablo 1). Contour farming practices were selected for areas with a slope between 6-12%, and terracing practices were selected for areas with a slope between 12-30%. In the regions where the slope is between 0-6% and 30% and above, no P factor practices were applied. According to these practices, the highest contour agriculture practices are seen in scenario 2 and scenario 4 with 10.38%. In the first and third scenarios, no contour farming was applied. Terracing covers an area of approximately 58 per cent in Scenarios 3 and 4, but not in Scenarios 1 and 3. Scenario 4 was the scenario where all P factor practices were included (Tablo 1). Terracing generally covers more area in the scenarios than contour agriculture. This was because the slope between 12-30%, suitable for terracing, represented 58.50% of the study area.

Effect of scenarios on P factor mean

Figure 4 shows the P factor maps of the scenarios for the study area. The literature review provided the P factor values for soil protection measures. Terracing had the lowest P factor value, at 0.2. The P factor values for the areas with contour agriculture were 0.5. Areas that do not include soil protection measures have a value of 1.

Of the P factor scenarios, Scenario 4 has the smallest average P factor value, 0.58. Scenario 3 has a value of 0.68, while scenario 2 has a value of 0.90. The

Tablo 1. P factor scenarios and their contents

Scenarios	P factor practices	Area (ha)	% Ratio
1st Scenario	No soil conservation practice	75.70	100
	Contour farming practice	0	0
	Terracing practice	0	0
2nd Scenario	No soil conservation practice	67.84	89.62
	Contour farming practice	7.86	10.38
	Terracing practice	0	0
3rd Scenario	No soil conservation practice	31.42	41.51
	Contour farming practice	0	0
	Terracing practice	44.28	58.49
4th Scenario	No soil conservation practice	23.56	31.12
	Contour farming practice	7.86	10.38
	Terracing practice	44.28	58.50
	Total	75.70	100

highest average P factor value was obtained in Scenario 1, where no soil protection measures were applied. Assuming that other factors calculated in RUSLE are constant, Scenario 4, which has the lowest average P factor value, will have the least erosion compared to other scenarios. Many studies report that the areas with the lowest P factor value have less erosion than others (Arnáez et al., 2015; Panagos et al., 2015; Sud et al., 2024).

In the scenarios, contour farming covered less area than terracing practices (Figure 4). This is because most of the study area has high slopes (> 12%), which reveals that the area is more suitable for terracing (FAO, 2000; FAO, 2003). Contour farming is also less effective than terracing in reducing the average P factor in the study area. This can be explained by the fact that contour agriculture's P factor value is higher than terracing's, in addition to the area it covers. The P factor values derived from earlier field studies contributed to enhancing the effectiveness of terracing in the current investigation.

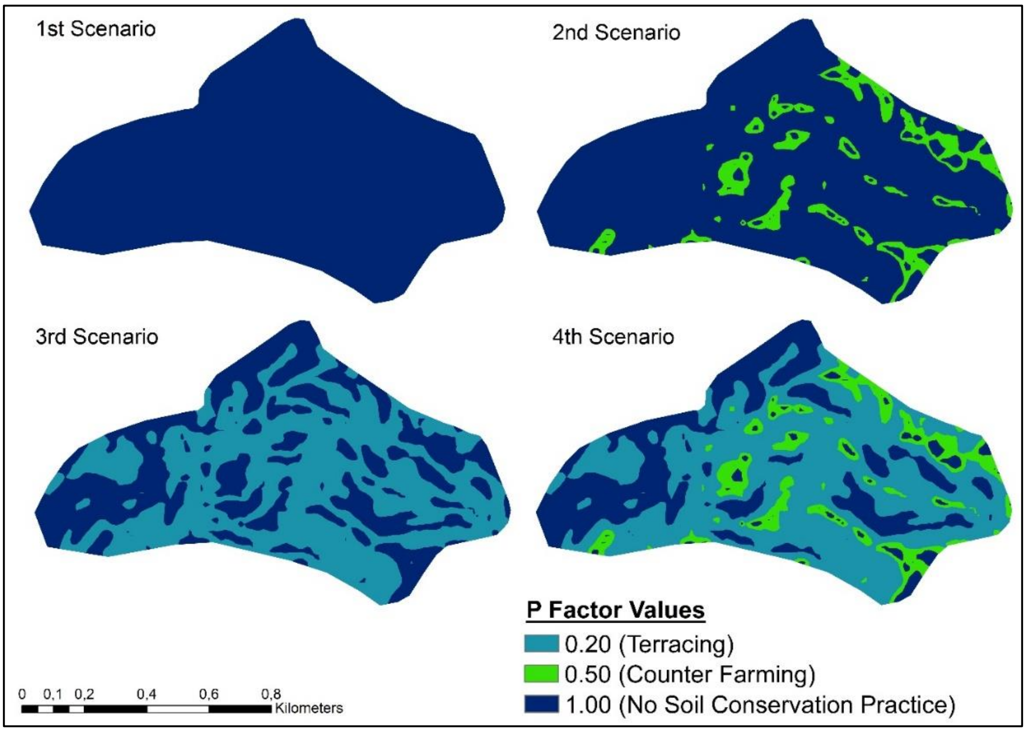

Figure 4. Scenario-Based P Factor Mapping for the Study Area

The average P factor in the agricultural lands of EU countries is estimated to be 0.95 (Panagos et al., 2015). The current paper's method reduced the average P factor to 0.58 in this area with a sloping topography, which shows that the applied model is successful. Scenario 4 involves terracing areas covering a larger area. Since terracing has a lower P factor value than contour agriculture, it is expected that Scenario 4 has the lowest average P factor value. Terraces characterized by low P-factor values enhance water infiltration and mitigate surface runoff (Arnáez et al., 2015), leading to micro or slight erosion within these regions (Liu et al., 2021). Moreover, it has been documented that soil conservation practices effectively diminish nutrient losses (La et al., 2023).

The costs of terracing practices can be high. However, the economic costs caused by soil erosion can also reach very high levels. The total cost of soil erosion for the world is estimated to be 400 billion dollars (FAO, 2016), including off-site impacts caused by erosion. In addition, the decrease in soil quality due to erosion may cause land degradation. This further increases the costs (Adhikari and Nadella, 2011).

Conclusions

This paper presents scenario applications for reducing the average P factor in the study area, which has sloping land. To achieve this, scenarios incorporating soil conservation practices (such as terracing and contour agriculture) were developed, taking into account the slope percentages. Scenario 4, featuring more intensive terracing practices, yielded the lowest P factor value. Consequently, the average P factor of the study area decreased from 1 to 0.58.

The approach presented in this study may offer a feasible model for reducing P factor values in sloping areas. However, challenges may arise when implementing these scenarios under field conditions. One major issue is the high initial cost of terracing. To address this, more economically viable land-use types—such as fruit cultivation—could be considered in terraced areas. Additionally, it is essential to gain local community support for soil conservation initiatives in erosion-prone regions. This can be facilitated through the involvement and backing of regional authorities and government agencies.

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Conflicts of Interest

The author declares no conflict of interest.

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RESEARCH PAPER

Effects of subsurface drip irrigation and water stress on sesame seed color characteristics

Filiz Akın[1]*, Çetin Sayılğan[1], Fatih Alpay Vuran[1], Ömer Özbek[1], Bilal Cemek[2]

[1] Bati Akdeniz Agricultural Research Institute, Antalya, Türkiye
[2] Ondokuz Mayıs University, Faculty of Agriculture, Department of Agricultural Structures and Irrigation, Samsun, Türkiye

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***Corresponding Author**
Tel.: +90 2423216797
E-mail:
filiz.kara@tarimorman.gov.tr

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Abstract

Sesame seed color is an important criterion used in selection for marketing and variety development of the product. Although several studies have related seed color to biochemical composition, the effect of irrigation strategies on sesame seed color has not been investigated yet. The present study aimed to evaluate the effects of four irrigation levels (I1: 100%, I2: 70%, I3: 40% and I4: rainfed) applied by subsurface drip irrigation system at three different lateral depths (D1: 20 cm, D2: 30 cm and D3: 40 cm) on sesame seed color. The results show that sesame seeds grown under different irrigation levels showed significant differences in a*(red-green) and b* (yellow-blue) color parameters. Water level as the lateral depth of irrigation water increased, the color of sesame seeds lightened. Intensification was observed in the density and overall average color values at 30 cm lateral depth irrigation. Although the values and density are more scattered in the irrigations at 20 and 40 cm depth, an increase is observed in the L* color values obtained in the irrigations at 40 cm depth. In general, an increase was detected in the L* value with the lateral depth. When all the results were evaluated, it was determined that the lateral depth recommended in the study should be 40 cm and the irrigation level should be 70%.

Introduction

The annual global production of vegetable oils in Türkiye is approximately 1.2 billion tons, of which approximately 6.2 million tons consist of sesame (Sesamum indicum L.). Among oilseeds, sesame holds a prominent position in international trade, with an import volume of 2.5 million tons valued at 3.6 billion dollars and an export volume of 2.1 million tons valued at 3 billion dollars (FAO, 2023).

Seed color plays a critical role in consumer preference, marketability, and breeding programs. Various studies have demonstrated strong correlations between seed color and biochemical composition, with darker seeds typically exhibiting higher protein content and lighter seeds containing increased levels of palmitic and linoleic acids (Baydar et al., 1999; Beatrice et al., 2006). While previous research has extensively analyzed genetic and environmental influences on sesame seed color, little attention has been given to the effects of irrigation practices. The color of sesame seeds is influenced by genotype, environment, and their interactions, resulting in significant variations (Pathak and Dixit 1992; Yol, 2011; Cui et al. 2021). The color of the seed coat is strongly associated with its biochemical composition, influencing both quality and nutritional value. Sesame seeds exhibit a wide range of colors, from white to black (Weiss, 2000), with color intensity affecting fatty acid profiles. As seed color transitions from dark to light, the proportions of palmitic and linoleic acids tend to increase, whereas stearic and oleic acid levels decrease (Beatrice et al. 2006). Additionally, darker-colored seeds generally contain higher protein content and lower oil content compared to lighter-colored seeds (Baydar et al. 1999). Drought is one of the most important abiotic environmental stresses affecting plant growth and reduces a significant portion of agricultural production, especially in arid and semiarid regions (Rahimi-Moghaddam et al., 2021). Despite the optimum drought tolerance of sesame, continuous and severe water deficit during the growing season can negatively affect plant growth and development and reduce qualitative and quantitative yield (Pandey et al., 2021). When plants are exposed to drought stress, they adopt different mechanisms to overcome the harmful effects of stress conditions (Abid et al., 2018; Deihimfard et al., 2023). Stressed plants cope with stress by assisting various defense mechanisms such as biochemical, physiological, and morphological changes (Oguz et al., 2022). In particular, plant defense mechanisms are largely controlled by genetic and environmental factors (Zou et al., 2021). Abid et al. (2018) investigated the physiological and biochemical response of wheat seedlings to water-limited conditions and found that drought stress reduced leaf water content, membrane stability, and photosynthetic activity. Eyni-Nargeseh et al. (2019) evaluated the effects of cessation of irrigation regime on rapeseed genotypes and concluded that rapeseed genotypes grown under drought stress conditions had lower RWC and higher proline content than those fully irrigated. Pourghasemian et al. (2020) investigated the effects of drought stress regimes on sesame and reported that CAT activity was significantly induced in plants exposed to drought stress conditions.

Water scarcity and irregular rainfall patterns pose significant challenges to global agricultural productivity, necessitating the adoption of efficient irrigation strategies. Subsurface drip irrigation (SDI) is an advanced method designed to optimize water use efficiency while minimizing evaporation and runoff. While sesame seed composition and color have been widely studied, the specific effects of irrigation practices on these traits remain unclear.

This study aims to fill this research gap by evaluating the impact of varying irrigation water levels and lateral depths on sesame seed color parameters (L*, a*, b*). We hypothesize that different irrigation levels will result in distinct color changes, affecting consumer preferences and marketability. By identifying optimal irrigation parameters that produce desirable seed colors, this study aims to guide breeding strategies that enhance both seed quality and market value, supporting growers in meeting market demands and improving profitability in international trade. In addition, the level of improvement in seed size and color, which are the most important marketing criteria, was determined by the amount of irrigation. While doing this, the inadequacy of our water resources, the physiology of the plant, different irrigation amounts and different lateral depths, and soil structure were taken into consideration.

Material and Methods

Experimental area and climatic conditions

In 2020, the experiment was conducted in Aksu district, Antalya province, Türkiye. Table 1 shows the meteorological data, including temperature, precipitation, and relative humidity, where collected from the experimental site, along with the long-term averages from 2009 to 2018. Meteorological data were taken at the meteorological station in the experimental area. The experimental field did not receive sufficient seasonal precipitation following planting. The experimental site in 2020 experienced a drier climate compared to the long-term average. While the temperatures remained relatively consistent, with average monthly temperatures ranging from 20.9°C to 28.9°C, the precipitation levels were significantly lower. During the crucial summer months of June, July, and August, no rainfall was recorded, deviating sharply from the historical average of 13.0 mm, 3.0 mm, and 2.0 mm, respectively. This prolonged dry spell, coupled with the high temperatures, likely created stressful conditions for sesame growth and development.

Table 1. Comparison of 2020 Temperature and Precipitation Data with Long-Term Averages (2009–2018).

Months	Temperature (ºC)		Precipitation (mm)		Relative humidity (%)	
	2009-2018	2020	2009-2018	2020	2009-2018	2020
May	20.9	28.9	53.0	1.7	69.9	68.6
June	25.5	23.7	13.0	-	64.8	70.7
July	28.5	28.6	3.0	-	63.5	70.4
August	28.3	28.3	2.0	-	66.0	66.2
September	24.9	25.8	22.0	12.0	67.0	69.0

Experimental soil properties

The soils of the experimental area have a clayey loam texture between 0-60 cm and a loam texture between 60-120 cm. The lime content varies between 23.7-25.6% and it was determined that they are in the very calcareous soil class where the lime content decreases relatively towards the lower layers. The electrical conductivity of the experimental area soils varies between 0.10-0.15 dS m^{-1} (salt-free) and the pH content varies between 8.3-8.4 (moderately alkaline). Field capacity values were calculated as 23.5, 23.4, 23.1 and 23.2 g g-1 for 0-30, 30-60, 60-90 and 90-120 cm, respectively, while the wilting point values were calculated as 10.8, 11.1, 11.7 and 10.8 g g^{-1}. The bulk density values ranged between 1.31-1.43 g cm^{-3}, and it was determined that the bulk density values increased towards the lower layers.

Treatments and experimental design

The research was carried out in the application area of the Western Mediterranean Agricultural Research Institute Aksu Campus in a field trial with 3 replicates in a total of 36 plots in a 2-year period as a gravel trial in a split plot design in randomized blocks. In the study, different lateral depths were sub-factor subjects (20, 30 and 40 cm) and different water levels (100%, 70%, 40% and rain-based production) were the main factor subjects. In the experiment, the plot sizes were selected as 6.8 x 7.7 m (52 m²) in planting and 3.5 x 4.7 m (16.45 m²) in harvesting.

Planting and cultural operations

In the spring, the soil was tilled with a plow, and the experimental area was cleaned of existing weeds. Before planting, the seedbed was prepared by disc harrows and coulters. The installation of the YAD irrigation system was completed before planting. According to the results of the fertility analysis of the experimental area soils in the laboratory, a 10 kg da^{-1} N 109 and 6 kg da^{-1} P_2O_5 fertilization program was applied to the experimental area. The seeds were planted in rows with a 70 cm row spacing and 10 cm row spacing with a seeder on May 19, 2020. Harvesting was done on different dates. The thirsty subjects were harvested first. As the amount of water application increased, the vegetation and harvesting time of the plant increased. The harvest dates of the I1, I2, I3 and I4 subjects are September 28, September 23, September 16 and September 13, respectively.

Irrigation systems

In the subsurface drip irrigation system, fixed flow in-line Φ16 PE dripper pipes were used. Separate ball valves and water meters were placed in each plot to control irrigation water amounts. As a result of the evaluation of the infiltration test and dripper tests conducted in the trial area, a lateral pipeline was placed in each plant row. In addition, the dripper spacing in the system was determined as 30 cm and the dripper flow rate as 2.1 L h^{-1}. Laterals were placed in arcs formed by cleaning the traces opened with a chisel, 20, 30 and 40 cm below the soil surface. The main line and manifold pipes in the system were also placed in arcs opened in the trial area. Air discharge valves were mounted on the manifold outlets.

Soil water content measurement and irrigation

The volumetric water content in the soil profile was monitored with a neutron meter device. Neutronmeter measuring tubes were placed in the soil every 30 cm to a depth of 120 cm to measure the soil water content. The soil moisture below the root depth of 90 cm (90-120 cm) was monitored to determine whether there was deep infiltration. All plots were given outlet water with surface drip irrigation immediately after planting. The deficient moisture in all plots was equalized by bringing it to field capacity after emergence. When 40% of the suitable moisture was consumed, the subject irrigation applications were started. Before irrigation, soil samples were taken from 3 repeated points from all experimental plots and the deficient moisture values were calculated with the gravimetric method. When the deficient moisture reached 40% of the suitable moisture in all plots, the control plots were irrigated to field capacity with D1I1 = 100%, D2I1 = 100% and D3I1 = 100%, and the other plots were irrigated with the determined rates (70% and 40%). In calculating irrigation water, since the percentage of cover was below 35% when the first irrigation was made, the percentage of cover was accepted as 35%. When the percentage of cover (Pc) values exceeded 35%, the actual measured values were used in the calculation (Keller and Bliesner, 1990). The percentage of cover values was calculated as a result of measurements on the same 3 plants selected before each irrigation. This value was calculated by dividing the plant crown development by the planting distance (plant row spacing, 70 cm).

Color Measurements

Samples from the harvested plots were taken for color analysis. In determining the color class, the sesame seed coat color scale from the Sesame Collaboration Panel was used as a reference (Cui et al. 2021). Measurement parameters; illuminator setting is D65, observer angle is 2°C, and measurement aperture is 10 mm. Calibration is done on a white plate (Figure 1). Color measurements were conducted using a Minolta Spectrophotometer CM-5 (Figure 1). The seed color readings were recorded in the CIE L*a*b* color space (Rahimi et al. 2011; Özpolat 2021). This system allows for precise and quantitative assessment of seed color,

Figure 1. Color measurements using the Minolta Spectrophotometer CM-5 device.

providing valuable data for both quality control and breeding purposes. The CIE L*a*b* parameters, commonly employed in color measurement, represent three-dimensional color coordinates. The CIELAB color space, often referred to as Lab*, is a color model that defines color based on three color components: L*, a*, and b*. L* denotes lightness, ranging from 0 (black) to 100 (white). The a* axis represents the red-green color space, with positive values indicating red and negative values indicating green. The b* axis represents the yellow-blue color space, with positive values indicating yellow and negative values indicating blue.

Statistical Analysis

Analysis of variance (ANOVA) was performed to determine the effects of irrigation level and lateral depth on sesame seed color parameters (L, a and b*)**. When significant differences were observed, an LSD test was employed to identify homogeneous groups of means. Additionally, a correlation analysis was carried out to examine the nature and strength of relationships of relationships between treatments and color scale values. For significant correlations, linear and polynomial regression analyses were performed to quantify these relationships, resulting in the derivation of regression equations for color values exhibiting significant associations.

Results and Discussion

Applications started on June 4, 2020. 321, 229, 137 and 15 mm irrigation water was applied to the 20 cm lateral depth I1, I2, I3 and I4 trial subjects, respectively; 256, 184, 111 and 15 mm irrigation water was applied to the 30 cm lateral depth I1, I2, I3 and I4 trial subjects, respectively; 248, 178, 108 and 15 mm irrigation water was applied to the 40 cm lateral depth 173 I1, I2, I3 and I4 trial subjects, respectively. According to soil water budget calculations, ETc values of sesame plants varied between 141-390 mm.

Lightness (L) Variations

The L values, representing seed brightness, ranged from 61.80 to 64.51*. The highest L value (64.51)* was observed at the 30 cm lateral depth with the 100% irrigation level (I1), suggesting that higher water availability at an intermediate lateral depth enhances seed brightness. In contrast, the lowest L value (61.80)* was recorded at the 20 cm depth with the 40% irrigation level (I3), indicating that water stress combined with a shallow drip line may contribute to darker seed coloration.

Red-Green Axis (a) Trends

The a values, which represent the red-green color balance, exhibited minimal variation across treatments (8.51 to 9.06)**. The lowest a value (8.51) was recorded at the 30 cm lateral depth with the rainfed treatment (I4), indicating a slightly greener hue under water-limited conditions. Conversely, the highest a value (9.06)* was observed at the 40 cm depth with the rainfed treatment (I4), suggesting a tendency toward a redder hue when irrigation was withheld at deeper lateral depths.

Table 2. Sesame seed color values at the plot level

Irrigation levels (%)	Lateral depth (cm)	L*	a*	b*
I_1	20	62.07	8.59	22.25
I_2		62.69	8.73	22.49
I_3		61.80	8.99	22.37
I_4		63.38	8.94	24.57
I_1	30	64.51	8.67	25.18
I_2		63.18	8.93	23.67
I_3		62.93	8.97	24.09
I_4		63.03	8.51	25.33
I_1	40	63.66	8.61	23.54
I_2		63.05	8.87	22.96
I_3		63.39	8.90	23.67
I_4		62.53	9.06	24.26

Yellow-Blue Axis (b) Response

The b values, which reflect the yellow-blue spectrum, ranged from 22.25 to 25.33*. The highest b value (25.33)* was observed at the 30 cm lateral depth with rainfed conditions (I4), indicating greater yellow intensity under lower water availability. This suggests that water stress may enhance yellow pigmentation in sesame seeds. Conversely, the lowest b value (22.25)* was recorded at the 20 cm lateral depth with 100% irrigation (I1), signifying a less yellow and slightly cooler color under fully irrigated conditions.

No previous studies have been investigated the impact of varying irrigation water levels and lateral depths in drip irrigation systems on sesame seed color. Gölükcü, (2000) reported L, a*, and b* values of 58.88, 3.93, and 23.13, respectively, for sesame tahini color using a similar color measurement method. In sesame procurement for industrial use, Carbonell-Barrachina, (2009) recommended high L* values along with high seed coat separability percentages and suggested that a* and b* values should be low for the seed coat. Our study recommends irrigation treatments involving different water levels and lateral depths that lead to high L* values and low a* and b* values.

The results of the analysis of variance (ANOVA) evaluating the effects of irrigation level and lateral depth on sesame seed color parameters (L, a, and b*)** are presented in Table 3. The F-values and associated probability levels (p-values) indicate the statistical significance of these factors. . The F-values and associated probabilities indicate the significance of these factors. For lightness (L*), a significant difference was observed only between lateral depths ($p<0.05$). This suggests that changing the lateral depth had a noticeable impact on the lightness of the sesame seeds. However, neither the irrigation level nor the interaction between irrigation level and lateral depth had a significant effect on L*. Regarding the red-green axis (a),* only the irrigation level was found to have a highly significant effect ($p<0.01$). Neither lateral depth nor the interaction term was significant for the a* parameter. For the yellow-blue axis (b*), both irrigation level and lateral depth had highly significant effects ($p<0.01$). The interaction term, however, was not significant (Table 3).

Table 3. The F values and significance levels for the effects of irrigation levels and lateral depth on sesame seed color

	DF	L*	a*	b*
Replication	2	1.24	0.25	2.30
Irrigation level	3	0.95	6.07*	15.23**
Replication x Irrigation	6	0.53	0.49	0.79
Irrigation depth	2	4.06*	0.41	29.33**
Irrigation level x Irrigation depth	6	1.39	2.43	2.69

*: Difference at the significance level of $p<0.05$, **: Difference at the significance level of $p<0.01$.

The sesame seed color values for different irrigation levels and lateral depths are given in Table 4. In general, irrigation levels had a significant impact on the yellowness (b*) of the sesame seeds, while lateral depth influenced both the lightness (L*) and b*. These findings suggested that both irrigation management and the placement of the drip irrigation system can affect the overall color quality of sesame seeds.

No significant differences were observed in L* values among the various irrigation levels, indicating that the lightness of the seeds remained relatively consistent. Significant differences were detected in a* values ($p<0.05$). The 100% irrigation level resulted in a significantly lower a* value compared to the other treatments, suggesting a slightly greener hue. Rainfed level had a significantly higher b* value, indicating a more yellowish hue. The 70% and 40% irrigation levels had significantly lower b* values, suggesting a less yellow hue compared to the rainfed level (Table 4).

Table 4. The sesame seed color variation values and groupings under different irrigation depths and water levels

Treatments	Seed color classification ***		
Irrigation levels	L*	a*	b*
rainfed	63.19	8.89a	24.74a
40%	62.75	8.95a	23.35bc
70%	62.98	8.83a	23.127c
100%	63.45	8.69b	23.73b
LSD	ns	*	**
Lateral depth			
20 cm	63.42b	8.87	22.92c
30 cm	63.37a	8.82	24.63a
40 cm	62.48a	8.84	23.66b
LSD	*	ns	**

*: Difference at the significance level of p<0.05, **: Difference at the significance level of p<0.01, ns: not significant, ***: Values marked with the same letter in the same column are not significantly different.

Considering lateral depth, significant differences were observed in L* values (p<0.05). The 20 cm lateral depth resulted in significantly higher L* values, indicating a lighter seed color compared to the other depths. No significant differences were observed in a* values among the lateral depths, suggesting that the red-green hue remained relatively consistent. Significant differences were observed in b* values (p<0.01). The 30 cm lateral depth resulted in a significantly higher b* value, indicating a more yellowish hue. The 20 cm and 40 cm depths had significantly lower b* values, suggesting a less yellow hue compared to the 30 cm depth (Table 4).

The results of correlation analysis, which reveal the significance, direction, and strength of the relationships between irrigation water levels, lateral depth applications, and sesame seed color characteristics are given in Table 5. A high-probability relationship (95-99%) indicates a meaningful correlation, enabling the development of predictive models using regression analysis to predict future trends (Sayılğan, 2020). Overall, the correlation analysis suggests that lateral depth had a significant impact on the lightness of the sesame seeds, while irrigation water level had a minimal effect on color parameters. A significant negative correlation (-0.46) was found between the irrigation water level and the a* parameter. This indicates that as the irrigation water level increased (e.g., from 40% to 100%), the redness of the sesame seeds decreased, shifting the color towards a greener hue. A significant negative correlation (-0.36) was found between irrigation water level and the b* parameter. This indicates that as the irrigation water level increased, the yellowness of the sesame seeds decreased, resulting in a less vibrant yellow color.

The correlation analysis revealed a significant positive correlation between lateral depth and the L* parameter (r=0.37, p<0.05), suggesting that increased lateral depth (e.g., from 20 cm to 40 cm) led to higher lightness values in sesame seeds, resulting in a brighter seed color. In contrast, no significant correlation was observed between lateral depth and the b* and a* parameters, indicating that lateral depth had little to no impact on these particular color characteristics.

Table 5. The relationship between subsurface drip irrigation applications and changes in sesame seed color

	Replication	Irrigation Water Level	Lateral Depth (cm)	L*	a*	b*
Replication	1.00					
Water Level	0.00 ns	1.00				
Depth (cm)	-0.00 ns	0.00 ns	1.00			
L*	0.19 ns	0.10	0.37*	1.00		
a*	0.06 ns	-0.46*	-0.08 ns	-0.43*	1.00	
b*	0.02 ns	-0.36*	0.27 ns	0.59*	-0.12 ns	1.00

*: Difference at the significance level of p<0.05, **: Difference at the significance level of p<0.01. ns: not significant

The results implied that irrigation water levels can be a valuable tool to influence the color characteristics of sesame seeds. Lower water levels may lead to a more reddish and yellowish seed color, while higher water levels may result in a greener and less yellow seed color. While lateral depth can impact the lightness of the seeds, it does not appear to significantly affect the yellowness. Therefore, the focus should be on optimizing irrigation water levels to achieve desired seed color qualities.

Table 6. The regression analysis for the characteristics with identified correlations

Variable 1	Variable 2	Linear Regression					Polynomial regression				
		R^2	R^2	Mean Square Error	F	p	R^2	R^2	Mean Square Error	F	p
a*	Water Level	0.208	0.185	0.152	8.977	*	0.334	0.293	0.141	8.276	*
b*	Water Level	0.129	0.103	1.062	5.056	*	0.313	0.271	0.957	7.519	*
L*	Lateral Depth	0.139	0.113	0.927	5.496	*	0.197	0.149	0.908	4.072	*
a*	L*	0.183	0.159	0.154	7.657	*	0.183	0.134	0.157	3.716	*
b*	L*	0.353	0.334	0.915	18.576	**	0.364	0.326	0.921	9.467	*

Linear and quadratic polynomial regression analyses were employed to establish a robust model for predicting the relationship between the highly correlated variables of irrigation level and lateral depth and the L*, a*, and b* color values of sesame seeds (Table 6). Both linear and polynomial regression models for a* and b* values were significant ($p < 0.05$), indicating a strong relationship between irrigation water level and redness and yellowness. Higher irrigation water levels were associated with lower a* and b* values, suggesting a decrease in redness and yellowness.

The analysis reveals a significant negative correlation between irrigation water level and the a* parameter of sesame seeds. This implies that as the irrigation water level increases, the redness of the seeds decreases, shifting the color towards a greener hue. The data indicates a clustering of a* values within specific water level ranges. The 0% and 40% water levels exhibited higher a* values, suggesting a more consistent color profile within these groups. In contrast, the 70% and 100% water levels showed a narrower range of a* values, indicating a more uniform color distribution. The highest a* value was observed at the 40% water level,

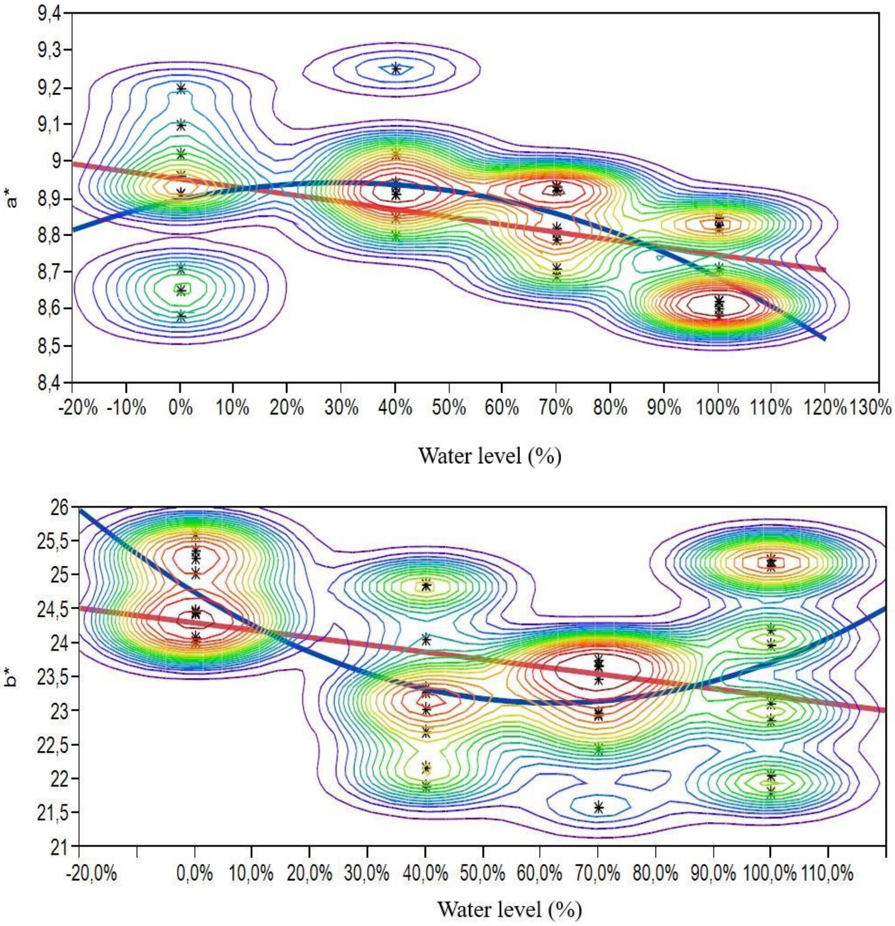
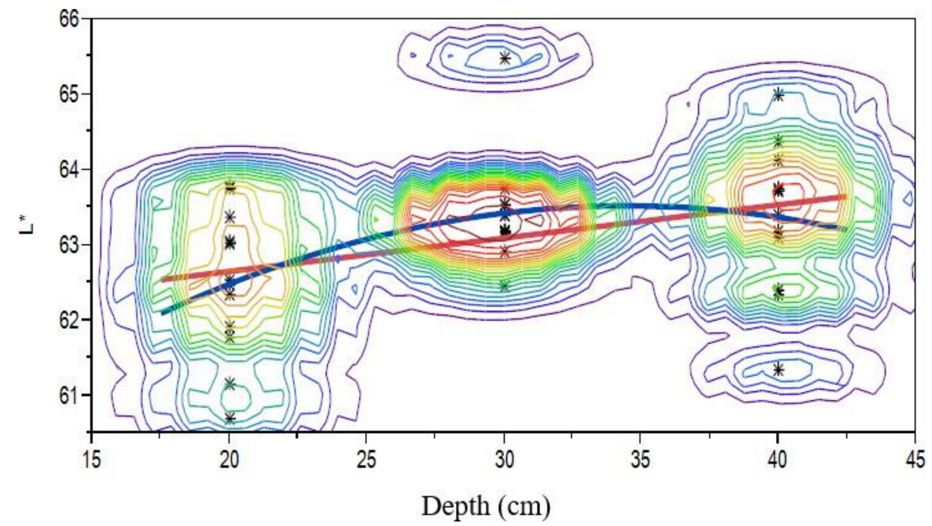


Figure 2. Change and density of a: a* and b: b* color scale values depending on irrigation level

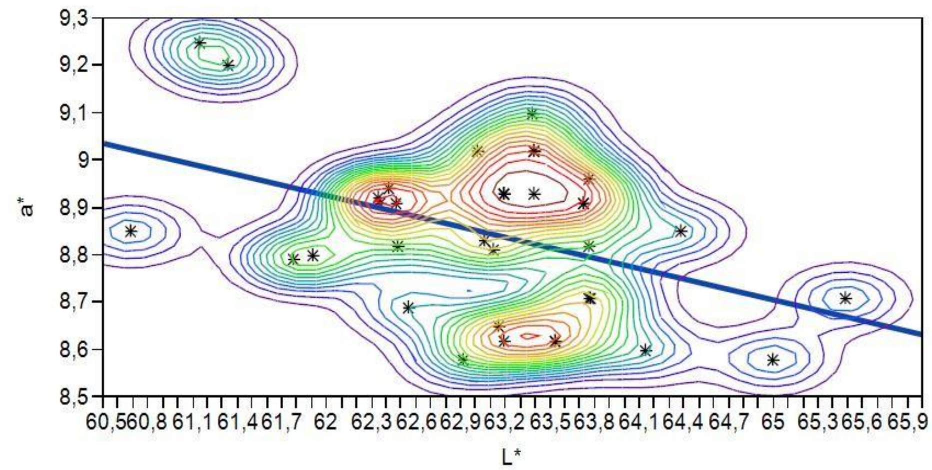
suggesting a relatively redder hue. As the water level increased beyond 40%, the a* values decreased, leading to a gradual shift towards a greener color. Both linear and polynomial regression models effectively captured the relationship between irrigation water level and the a* parameter. The linear regression equation "a* = 8.95 - 0.20 x Water Level" provides a simple approximation of the trend, while the quadratic regression equation "a* = 9.04 - 0.23 x Water Level - 0.52 x (Water Level - 0.52)²" offers a more precise fit by accounting for the curvature in the relationship (Figure 2).

The analysis revealed a significant positive correlation between lateral depth and the L* parameter of sesame seeds. The positive correlation implies that as the lateral depth increases, the lightness of the seeds increases, resulting in a brighter seed color. The data indicates a more concentrated distribution of L* values at the 30 cm lateral depth, suggesting a more uniform color profile within this group. At the 20 cm and 40 cm depths, the L* values were more dispersed, indicating greater variability in seed color. However, the 40 cm depth exhibited a trend towards higher L* values, suggesting a potential increase in lightness. Both linear and quadratic regression models effectively captured the relationship between lateral depth and the L* parameter. The linear regression equation "L* = 61.76 + 0.04 x Depth" provides a simple approximation of the trend, while the quadratic regression equation "L* = 62.09 + 0.04 x Depth - 0.0049 x (Depth - 30)²" offers a more precise fit by accounting for the curvature in the relationship (Figure 3).

The analysis highlighted a significant negative correlation between the a* and L* color parameters of sesame seeds. The negative correlation indicates that as



a



b

Figure 3. In the study; a: L* color scale value change and density depending on irrigation depth, b: a* color scale value change and density depending on grain color L* scale value

the lightness of the seeds increases, the redness decreases. The linear regression equation "a* = 13.48 - 0.07 x L*" effectively captures this negative linear relationship. The quadratic regression equation "a* = 13.48 - 0.07 x L* - 1.644 x 10^{-6} x (L* - 63.09)²" provides a more precise fit, although the linear model appears to be sufficient in this case (Figure 3). This finding suggests that there is a trade-off between lightness and redness in sesame seed color. As the seeds become lighter, the seeds tend to become less red and more towards a greenish hue.

The analysis revealed a highly significant positive correlation between the b* and L* color parameters of sesame seeds. This implies that as the lightness of the seeds increases, the yellowness also increases, resulting in a shift towards a whiter and more yellowish color. The linear regression equation "b* = -18.98 + 0.67 x L*" effectively captures this positive linear relationship. The quadratic regression model "b* = -17.83 + 0.66 x L* - 0.07 x (L* - 63.09)² " provides a more precise fit, although the linear model appears to be sufficient in this case. This finding suggests a strong association between lightness and yellowness in sesame seed color. As the seeds become lighter, they also tend to become more yellow.

Conclusion

The color of sesame seeds, a crucial quality criterion in breeding studies, was significantly influenced by variations in drip irrigation lateral depth and applied irrigation water levels. This study presents novel insights into these effects, demonstrating that both the irrigation water levels and lateral depth of the irrigation system significantly affect the color of sesame seeds, potentially influencing their market appeal and quality.

The findings indicated that seed color changes are directly linked to irrigation water amounts, suggesting that modifications in irrigation practices can affect seed quality. However, these changes generally occur in an undesirable direction concerning seed coloration. As the irrigation level increased, a shift in seed color was observed, transitioning from yellow to blue and from red to green. Similarly, an increase in lateral depth resulted in a change in seed color from dark to white, which was also considered undesirable for maintaining seed quality. Consequently, the results suggest that higher irrigation levels contribute to a decline in seed quality.

To optimize seed quality and color for both market acceptability and breeding purposes, a 70% irrigation water level combined with a 40 cm lateral depth in subsurface drip irrigation is recommended. This specific combination has been found to yield the most desirable seed color and overall quality.

Ethical Approval

We declare that the article is among the studies that do not require ethical approval.

Consent to Participate

Authors of the article declare their approval of participation.

Consent to Publish

The authors declare that the article will be published.

Authors Contributions

F.A.: Conducting fieldwork, collecting data, analyzing data and writing articles; **Ç.S.:** performing and evaluating statistical analyses; **F.A.V.:** Conducting and evaluating laboratory analyses; **Ö.Ö.:** Carrying out field work; **B.C.:** Analysis and evaluation of data.

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Conflicts of Interest

The authors of the article declared that there is no personal or financial conflict of interest within the scope of the study.

Availability of data and materials

For questions regarding the datasets, the corresponding author should be contacted.

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