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The impact of modern irrigation systems on water use efficiency and grape *Vitis vinifera* L growth

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A B S T R A C T

The study was conducted at the Interactive Agricultural Technical College in Mosul, in cooperation with the Water Resources Department, in 2024. Seedlings were planted as desired. The field was divided into four units according to different variation methods: Based on soil moisture using irrometer sensors, Using climate equations (Penman-Monteith),Using Internet of Things (IoT) technology, Using moisture distribution simulation using Hydrus 1D software. The experiment was carried out using a completely randomized block design with four treatments and three replicates. The effect of different irrigation methods on water use efficiency and plant growth was compared and the averages were tested under a 5% probability level. The results showed that IoT technology was the most efficient in saving water and managing irrigation remotely, while the soil moisture measurement method maintained stable moisture content across all depths, ranging between 18.9% - 26%, which is the ideal range for grape growth. The Penman-Monteith equation was effective but showed moisture fluctuations at depths of 15 and 30 cm, while the Hydrus 1D program provided accurate moisture distribution data but needed more precise time tuning. The vegetative characteristics of grapes showed significant superiority of the soil moisture measurement treatment in the main stem diameter of the grape tree and the leaf area of the trees, which reached 15.53 mm and 9623 cm², respectively.

Introduction

Water resources play a vital role in human life and the environment, and the problem of irrigation water scarcity and insufficiency is one of the most significant challenges facing the world today.[1]. Drip irrigation is considered one of the most water-efficient irrigation methods compared to other traditional methods. [2] This system relies on a closed network operating under low pressure, ensuring that water is distributed through pipes and reaches the soil through drippers slowly and repeatedly. Well-designed drip irrigation saves up to 50% of water compared to surface irrigation and 30% compared to sprinkler irrigation by reducing water losses that may be lost through deep infiltration, surface runoff, or evaporation in other irrigation systems. [3], [4], Studies indicate that the agricultural sector consumes about (70-75%) of the total fresh water available annually to irrigate only about 25% of the arable land, which makes efficient water management in this sector essential [5], [6],[7]. The savings don't stop at water alone, but there is also energy savings because the system operates at lower operating pressures compared to sprinkler irrigation systems. This method aims to maintain the root zone moisture level close to field capacity on a continuous basis. [8]. Drip irrigation contributes to maintaining a high level of moisture in the soil, which reduces the capillary tension forces between water and soil particles. This makes it easier for plants to absorb their water needs, even with high osmotic tension resulting from increased salt concentrations in irrigation water. Microirrigation systems, also known as "smart irrigation" or "digital irrigation," rely on a set of sensors and actuators (such as valves and pumps) connected to central control units based on climate and soil parameters. These systems monitor and record real-time data. The field is dependent on climate and soil factors, so the controllers analyze them and automatically trigger the actuators when needed. This technology delivers precisely calculated amounts of water, at the right time and place Asadzadeh, Based on actual plant needs, recent studies have shown that precision irrigation represents a promising solution in the face of the increasing challenges associated with water scarcity and climate change, as it contributes to improving water use efficiency, increasing crop productivity, and reducing the environmental impact by reducing water loss resulting from evaporation, leakage, or unnecessary use [9],[10]. There are several well-established methods for monitoring soil moisture, including traditional soil sampling and drying using a soil auger, TDR moisture sensors, and large-scale monitoring through remote sensing technologies. [11],[12]. While the traditional method of estimating moisture by drying soil samples provides accurate measurements of soil moisture content, it is time-consuming, labor-intensive, and causes significant disturbance to the soil structure [13],[14]. Numerous studies have demonstrated the feasibility of using saline water for irrigation, provided effective water management is followed. [15],Soil is a vital environment for plant growth, and its physical and chemical properties, such as texture, permeability, and moisture retention, affect the efficiency of irrigation systems. Internet of Things (IoT) technologies are used to monitor soil and plants in real time, and automatically analyze data to make accurate irrigation decisions [16] The HYDRUS model is also an important tool for simulating subsurface water movement, while the Penman-Monteith equation provides accurate estimates of evapotranspiration [17]. Grapes Vitis vinifera L are characterized by high nutritional value, as there are more than 700 species and 10,000 varieties of grapes in the world [18] , while some researchers estimate the number at 14,000 varieties [19]. Grapes contain easily absorbed sugars such as glucose and fructose, in addition to vitamins A, B2, B6 and minerals such as potassium, calcium, phosphorus, iron, and manganese. The global cultivated area is 7.38 million hectares. With an annual production of 61.89 million tons, Italy, France, the United States, Spain, China, and Turkey top the list of producing countries. As for Iraq, the cultivated area reached 48,000 hectares with a production of 265,000 tons, and more than 70 varieties are grown, most of them in the north of the country [20] ,[21] Objective of the study This method aims to maintain the root zone moisture level close to field capacity on a continuous basis and improve the efficiency of using drip irrigation to maintain a high level of moisture in the soil, and reduce the capillary tension forces between water and soil particles, which makes it easier for the plant to absorb its water needs..

MATERIALS AND METHODS

The study was conducted in 2024 at the Technical Agricultural College in Mosul / in the Rashidiya , funded from the Ministry of Water Resources, Iraq where 1000 m² of agricultural land was allocated for conducting experiments. The land was plowed using a triple disc plow with two plows perpendicular to each other, then it was leveled and grape trees were planted according to the plan on February 2024. The field soil was **clay loam**, as shown in Table No.(1) showing some physical properties of the study soil

Property	Value	Unit
Clay	340.5	g kg^{-1}

Silt	297	g kg^{-1}
Sand	362.5	g kg^{-1}
Soil texture	Clay loam	
Bulk density	1.43	g cm^{-3}
Field capacity	39	%

1-The Rash Mio variety

is a widely cultivated grape variety, particularly in Dohuk Governorate. It is also widely cultivated in various regions of central and northern Iraq. The cluster is conical with shoulders, and the berries are oval when fully ripe. A drip irrigation system is used to deliver small, regular amounts of water directly to the grape roots.

2- Irrigation Systems and Equipment

The surface drip irrigation network included:

Main and sub-pipes of various diameters.

Manual and electronic valves to control water flow.

Soil moisture sensors (irrometers) buried at various depths (15, 30, 45, 60 cm).

Data loggers connected to sensors to receive and analyze data.

Internet-connected Hunter control system for remote irrigation management.

Electronic weather station.

Experiment design

The study used a randomized complete block design (RCBD) with four main treatments, each with three replicates. Differences between treatments were tested at the 5% probability level. The treatments included four irrigation scheduling systems:

Irrigation Scheduling Using soil moisture

Sensor readings were used to determine the irrigation time when 75% of the available water was depleted. The weight moisture content at field capacity was 26%, and at the wilting point it was 16.5%, meaning the available water content was equivalent to 9.5%. Therefore, irrigation was initiated when the moisture content dropped to approximately 18.9%.

A calibration equation was used to convert sensor readings into weight moisture percentages, and the values were electronically monitored to accurately determine irrigation timing. Irrigation was conducted for 200 minutes per irrigation cycle, using drippers with a discharge of 4.9 liters/hour and electronically controlled by Hunter valves.

Irrigation scheduling using the Penman-Monteith equation.

This system is based on calculating the actual water requirements of the plant based on evapotranspiration data calculated from the Penman-Monteith equation. Climatic data were obtained from a specialized website, and evaporation values were collected daily until an irrigation depth of 3.04 cm was reached, which covers the root zone (60 cm) without wasting water to ineffective depths

Irrigation scheduling using Internet of Things (IoT) technology.

In this system, (WATERMARK MONITOR — 900M) were used to measure humidity around the clock. Data is automatically collected online using a dedicated portal (https://portal.irrometer.com) and analyzed using Excel spreadsheets to determine the appropriate irrigation timing (at 18.9% humidity). Irrigation is fully controlled remotely using the Hydrawise app linked to Hunter systems, enabling irrigation at night or from anywhere outside the field, effectively implementing the Internet of Things (IoT) principle.

. Irrigation scheduling using Hydrus 1D software.

This system was based on simulating soil moisture distribution using Hydrus 1D, a software that handles volumetric moisture. In the clayey loam soil, the volumetric moisture at field capacity was 35.1%, the wilting point was 22.5%, and the available water was 12.6%. Irrigation was scheduled when 60% of the available water had been consumed, i.e., when the moisture content reached 27.54%. [22]

Vegetative growth measurements:

All vegetative growth characteristics of the seedlings were measured in the first week of July and were taken again in October 2024 for all seedlings used in the study (4 seedlings for each experimental unit). The studied vegetative growth characteristics included the following:

Paper area (cm)

The area of a single leaf was estimated according to the method mentioned by [23].

3. Increase in main stem diameter of trees (mm).

Tree diameters were measured for all seedlings at the beginning of July and again in October using a Vernier caliper at a height of 5 cm from the area, and the difference between them was calculated according to the following equation:

Increase in diameter (mm) = Stem diameter (mm) at the end of the tenth month - Stem diameter (mm) at the beginning of the seventh month. Number of branches formed on seedlings (branch.seedling-1).

The number of total lateral branches on the main stem of each seedling was counted at the beginning of July for the main branches only.

3.3 Moisture Measurements:

o Record sensor readings daily.

o Convert data into electronic spreadsheets to determine irrigation intervals.

Results and discussion

Discussion of results based on the moisture content for a full season for each irrigation method.

Soil moisture content analysis is one of the most important indicators in assessing the efficiency of different irrigation systems, as it directly affects plant growth, water consumption, and water resource utilization efficiency. Based on the data extracted from the experiment, the effect of each irrigation method on soil moisture content at dif First: Irrigation method based on field measurements of soil moisture and its effect on moisture content. four depths (15, 30, 45, 60 cm) can be discussed.

Figure (1) represents the moisture distribution of moisture depths using the soil moisture measurement method in the irrigation schedule for grape plants.
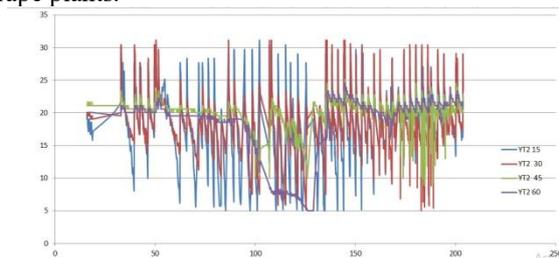
Moisture content analysis:

• Moisture content was maintained stable across all depths, ranging from 18.9% to 26%, the ideal range for grape growth.

• Irrigation was carried out when the soil reached 75% of the available water, preventing sudden drying out or overwatering.

• At a depth of 15-30 cm, moisture fluctuations were minimal, providing an ideal environment for water and nutrient uptake by the roots This is consistent with [23],[24].

• At a depth of 45 cm, a slight degree of fluctuation was observed during the initial growth period (100 days), then began to fluctuate after this time, tending to decrease at the end of each irrigation. This is due to the increased water consumption during this time.

• A depth of 60 cm is observed to be more stable, and this stability means ensuring soil moisture at the field capacity at this depth. This supports irrigation efficiency for the plant, while ensuring that there is no loss of irrigation water added beyond the root zone, as grape roots reach a depth of more than 1 m.

Second: The Internet of Things (IoT) method and its impact on moisture content

Figure (2) represents the moisture distribution of moisture depths using the IoT method in the irrigation schedule for grape plants.
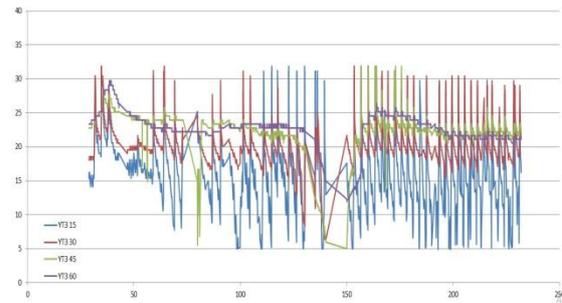
Moisture content analysis:

This method is a response to the lack of soil moisture that is known through devices connected to the Internet, whether it is a mobile phone or a personal computer, and this deficiency is also compensated for through commands to the control devices via the Internet to irrigate the areas that suffer from a lack of moisture, and irrigation is carried out at the optimal level of soil moisture, i.e. by ensuring that no excess water moves outside the root zone, in addition to providing the optimal need for water for the plant. This is consistent with [25].

• It is noted that it is completely consistent with the moisture distribution of the moisture depths using the soil moisture measurement method in the irrigation schedule and applies to all.

• Moisture was maintained stable at all depths, ranging between 18.9% and 25%, making it very close to the soil moisture measurement method.

• At a depth of 15-30 cm, moisture fluctuations were very limited, helping to reduce surface evaporation loss.

• At a depth of 45-60 cm, moisture was stable, indicating no water loss beyond the root zone.

• Irrigation was automatically implemented when needed based on sensor data, preventing overwatering or temporary drought.

The results of this study confirm the effectiveness of smart irrigation systems based on the Internet of Things (IoT) and soil moisture sensors in improving water use efficiency and maintaining stable moisture levels within the grapevine root zone, compared to traditional methods or those based solely on climatic equations. **This is consistent with the findings of both[26],[27],[28].**

Third: The Penman-Monteith equation method and its effect on moisture content

Moisture content analysis:

Figure (3) represents the moisture distribution of moisture depths using the climate information method in the Penman equation.
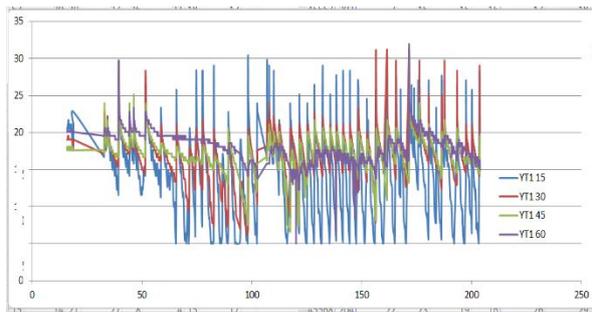
• This method relies on climate data to calculate evapotranspiration rates and determine the required irrigation quantities.

• High fluctuations in surface humidity levels are observed at depths of 15 and 30 cm. This is due to the fact that this method accumulates water consumption over time until it reaches a value that, when added, ensures no movement of irrigation water outside the root zone. • A higher stability in moisture content was also observed at a depth of 45 cm, and this stability decreased with growth and rising temperatures "The results of this study are consistent with the findings of [29] and [25] regarding the effectiveness of the Penman-Monteith equation in estimating irrigation requirements, with some fluctuations observed in the absence of field measurements to support the climatic data.".

• At a depth of 60 cm, this stability was maintained throughout the measurement period, meaning that water did not exceed the root zone.

Fourth: The method of simulating the moisture distribution (Hydrus 1D) and its effect on the moisture content

Figure (4) represents the moisture distribution of moisture depths using the Hydrus method in simulating water movement for the irrigation schedule for grape plants.
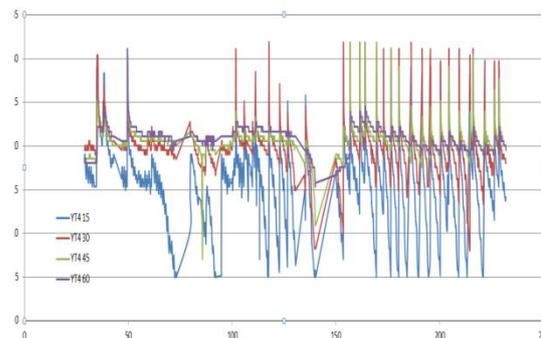

Figure (5) represents the outputs of the Hydrus program for humidity ratios at different depths throughout the grape plant growth period.

Moisture content analysis

• The numerical simulation showed an accurate distribution of moisture within the soil, but it suffered from a delay in the response of irrigation data.

• It is noticeable from this figure that there is a fluctuation in moisture content values at depths of
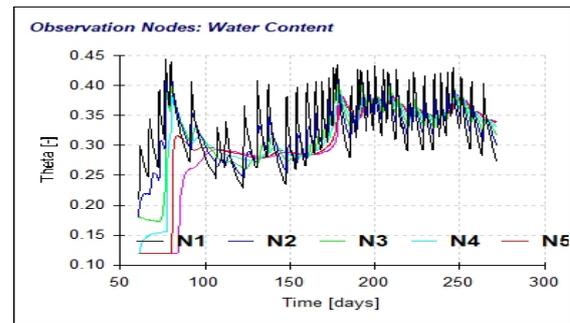
15 and 30 cm. However, the fluctuation at the 15 cm depth is from field capacity to a decrease, while at the 30 cm depth, the fluctuation is from near saturation to close to field capacity. This is due to the fact that the calculations for the added water are to bring the depths 0-45 cm to field capacity.

• As for the depth of 45 cm, it was characterized by stability at the beginning of the season, and its degree of fluctuation increased with the increase in water consumption values. This is normal because the speed of moisture homogenization is less than the speed of supplying the plant with water. This reflects the difference between this technique and previous techniques in the occurrence of fluctuation at the depth of 45 cm. This is due to the delayed response of the simulation process to the lack of moisture. The lack of moisture that occurs, especially when temperatures rise, and this is what can be observed in the last two-thirds of the growth period. This is to achieve a moisture deficiency at this depth until the next irrigation. This point can be overcome, as we mentioned previously, by irrigating at a depth of 50% or less than 35% of the available water.

• The depth is 60 cm and is characterized by high stability. When comparing the values of the actually measured moisture content, which are represented in Figure (4), with the values of the moisture content obtained from the Hydrus program for the same different soil depths and throughout the growth period, which are represented in Figure (5), in which a great consistency is observed in the irrigation dates, but the values that the program gives are high values, considering that the program is based on the volumetric moisture. It is not the weight moisture that is measured by sensors, as it is also noted that the initial values of moisture content are higher in the initial periods of irrigation. This is consistent with [23]. This study demonstrated clear accuracy in representing water movement within the soil profile, which contributed to improving water use efficiency in grape cultivation, especially when compared to traditional irrigation methods. The findings of this study are supported by recent research, including the studies of [2] [30], and [22].

3 characteristics of vegetative growth of grape trees in subsurface irrigation treatments

Table No. (2) shows the effect of irrigation treatments on the vegetative growth characteristics of grape trees in surface irrigation treatments.

Characteristic Treatment	Area (sq cm)	Stem diameter (mm)	Increase in stem diameter (mm)	Branch length (cm)	Number of branches
Penman equation	4494b	13.15b	0.48a	22.19c	4.58a
Soil moisture	a9623	15.53a	1.61a	51.18a	3.60a
IoT	9511a	14.48ab	0.84a	40.39ab	4.28a
HYDRUS		13.12b	0.55a	31.85bc	3.75a

Number of branches:

Table (2) shows that there are no significant differences between the treatments, and the largest number of branches was recorded in the Penman equation treatment, which had the highest number of branches, reaching 4.58 branches per plant.

The results of Table (2) indicate that the irrigation treatment, based on measuring soil moisture, significantly increased the length of the branches, reaching 51.18 cm.

Increase in leg diameter:

From the table results, we note that the largest insignificant increase in stem diameter was recorded in the treatment based on soil moisture estimation, which amounted to 1.61 mm for the main stem of the tree.

Leg diameter:

Table (2) indicates the significant superiority of the soil moisture measurement treatment in the main stem diameter characteristic of the grape tree, which reached 15.53 mm.

Paper space:

It is clear from the results shown in Table (2) that the irrigation method based on measuring soil moisture had a significant impact on the leaf area of the trees, which amounted to 9623 cm².

The superiority of the soil moisture measurement treatment may be attributed to the fact that it is the best irrigation method in terms of controlling the moisture content, as it provides an ideal environment for the roots, which leads to strong growth and high water efficiency, which in turn works to provide the elements ready for absorption by the plant. The results are consistent with what was reached by [31],[32]

Conclusions and recommendations:

We conclude from this study of irrigation scheduling techniques for Grape plants the following:

IoT technology in irrigation scheduling has proven highly successful. The techniques for its implementation and categorization of results have been mastered, making it possible to easily control irrigation water scheduling using this technology. The team has gained experience in managing this type of technology for a period of up to eight months, which is sufficient time for testing within the context of annual climate changes.

The technique of scheduling irrigation using climate information using the Penman equation to calculate water consumption has proven its feasibility and effectiveness in scheduling irrigation water, with no significant difference from the standard method of scheduling irrigation by measuring soil moisture. Since this method is simple and does not require complicated implementation or the provision of special equipment to determine water consumption, we only need to take climate data from a local weather station or use climate data from many websites that download climate information from the Internet. Thus, the slight differences between production using this method and production using this method and the standard method are covered.

It has become possible to schedule irrigation by simulating the water distribution of soil moisture using the Hydrus program, but with the emphasis that the irrigation process is carried out when 50% of the available water is depleted during cold and moderately cold days. This depletion rate must also reach 35% on hot days due to the sensitivity of the program to high soil tensions, and since this method only requires climatic information in addition to Soil information and does not require any other devices or equipment. When we are able to run this program, we can obtain results close to the results given to us by soil moisture sensors in the field.

All methods used in scheduling drip irrigation have proven effective.

References

[1] Abdelmoneim, A. A., Al Kalaany, C. M., Dragonetti, G., Derardja, B., & Khadra, R. (2025). Comparative analysis of soil moisture- and weather-based irrigation scheduling for drip-irrigated lettuce using low-cost IoT capacitive sensors. Sensors, 25(5), 1568. https://doi.org/10.3390/s25051568

[2] Li, W., Zhang, Y., Wang, X., & Zhao, J. (2024). Partitioning and controlling factors of evapotranspiration: hydrological modeling constrained with isotope-based water balance decoupling. Journal of Hydrology, 629, 130109. https://doi.org/10.1016/j.jhydrol.2024.130109

[3] García, L.; Parra, L.; Jimenez, J.M.; Lloret, J.; Lorenz, P. IoT-based smart irrigation systems: An overview on the recent trends on sensors and iot systems for irrigation in precision agriculture. Sensors 2020, 20, 1042. https://doi.org/10.3390/s20041042

[4] Baruah, V.J.; Begum, M.; Sarmah, B.; Deka, B.; Bhagawati, R.; Paul, S.; Dutta, M. Precision

irrigation management: A step toward sustainable agriculture. In Remote Sensing in Precision Agriculture; Academic Press: New York, NY, USA, 2024; pp. 189–215 https://doi.org/10.1016/B978-0-323-91068-2.00021-7

[5]FAO (2020). The State of Food and Agriculture 2020: Overcoming water challenges in agriculture. Rome, Italy: FAO. https://doi.org/10.4060/cb1447en

[6]Kompas, T.; Che, T.N.; Grafton, R.Q. Global impacts of heat and water stress on food production and severe food insecurity. Sci. Rep. 2024, 14, 14398. https://doi:10.1038/s41598-024-65274-z

[7]Ahmed, Mohammed, Al-Hadidi, Abdul-Qader, & Al-Badrani, Wahida. (2025). Evaluation of the quality of wastewater effluents in Mosul city for irrigation purposes. Mesopotamian Journal of Agriculture, 53(1), 29-45. doi: https://10.33899/mja.2025.150808.1470

[8]Dong, Y., Werling, B., Cao, Z., & Li, G. (2024). Implementation of an infield IoT system for precision irrigation management. Frontiers in Water, 6, 1353597. https://doi.org/10.3389/frwa.2024.1353597

[9]Catak,M.IoTBasedSmartIrrigation System with LoRa. In Progress in Intelligent Decision Science; IDS 2020. Advances in Intelligent Systems and, Computing; Allahviranloo, T., Salahshour, S., Arica, N., Eds.; Springer: Cham, Switzerland, 2021; Volume 1301. Springer, Cham. https://doi.org/10.1007/978-3-030-59003-1_5

[10]Raouchi, E.L.; Zouizza, M.; Lachgar, M.; Zouani, Y.; Hrimech, H.; Kartit, A. AIDSII: An AI-based digital system for intelligent irrigation. Softw. Impacts 2023, 17, 100574. [https://doi.org/10.1016/j.simpa.2023.100574

[11]de Jong, S.M.; Heijenk, R.A.; Nijland, W.; van Der Meijde, M. Monitoring soil moisture dynamics using electrical resistivity tomography under homogeneous field conditions. Sensors 2020, 20, 5313. https://doi.org/10.3390/s20185313

[12]Asadzadeh, S.; de Oliveira, W.J.; de Souza Filho, C.R. UAV-based remote sensing for the petroleum industry and environmental monitoring: State-of-the-art and perspectives. J. Pet. Sci. Eng. 2022, 208, 109633. https://doi.org/10.1016/j.petrol.2021.109633

[13]Mukhlisin, M.; Astuti, H.W.; Wardihani, E.D.; Matlan, S.J. Techniques for ground-based soil moisture measurement: A detailed overview. Arab. J. Geosci. 2021, 14, 1–34. https://doi.org/10.1051/bioconf/20201700249

[14]Li, Z.L.; Leng, P.; Zhou, C.; Chen, K.S.; Zhou, F.C.; Shang, G.F. Soil moisture retrieval from remote sensing measurements: Current knowledge and directions for the future. Earth-Sci. Rev. 2021, 218, 103673. DOI: 10.1016/j.earscirev.2021.103673

[15]Guo, Z., Zhao, Y., Liu, H., Wang, X., & Li, J. (2024). Research on the application of IoT for water and fertilizer integration and smart irrigation in cotton production. Applied Mathematics and Nonlinear Sciences, 9(1). https://doi.org/10.2478/amns-2024-2414

[16]Morchid, M., El Hachimi, M. L., & Hachimi, H. E. (2024).High-technology agriculture system to enhance food security: A concept of smart irrigation system using Internet of Things and cloud computing. Journal of the Saudi Society of Agricultural Sciences, 23(2), 191–200.

[17]Irmak, S., et al. (2021). Advances in evapotranspiration estimation and crop water requirement models: A review. *Agricultural Water Management, 243*, 106452. https://doi.org/10.1016/j.agwat.2020.106452

[18]Maul, E., & Töpfer, R. (2015). Vitis International Variety Catalogue (VIVC): A cultivar database referenced by genetic profiles and morphology. BIO Web of Conferences, 5, 01009. https://doi.org/10.1051/bioconf/20150501009

[19]Nicolescu, C. M., Bumbac, M., Radulescu, C., Buruleanu, C. L., Olteanu, R. L., Stanescu, S. G., Gorghiu, L. M., Serban, B. C., & Buiu, O. (2024). Phytochemical Statistical Mapping of Red Grape Varieties Cultivated in Romanian Organic and Conventional Vineyards. Plants, 12(24), 4179. https://doi.org/10.3390/plants12244179

[20]OIV. (2023). *State of the World Vitivinicultural Sector in 2022*. International Organisation of Vine and Wine. Retrieved from https://www.oiv.int/public/medias/9455/en-oiv-state-of-the-world-vitiviniculture-sector-in-2022.pdf

[21]de Almeida Sousa Cruz, M. A., de Barros Elias, M., Calina, D., Sharifi-Rad, J., & Teodoro, A. J. (2024). Insights into grape-derived health benefits: a comprehensive overview. Food Production, Processing and Nutrition, 6, Article 91. https://doi.org/10.1186/s43014-024-00267-z

[22]Chen, J., Smith, D., & Brown, P. (2023). Optimization of irrigation in vineyards using HYDRUS-2D modeling and field measurements. Land, 12(10), 1947. https://doi.org/10.3390/land12101947

[23]You, Y., Song, P., Yang, X., Zheng, Y., Dong, L., & Chen, J. (2022). Optimizing irrigation for winter wheat to maximize yield and maintain high-efficient water use in a semi-arid environment. Agricultural Water Management, 273, 107901. https://doi.org/10.1016/j.agwat.2022.107901

[24]Maan, C., ten Veldhuis, M.-C., & van de Wiel, B. J. H. (2023). Dynamic root growth in response to depth-varying soil moisture availability: a rhizobox study. Hydrology and Earth System Sciences, 27(7), 2341–2355. https://doi.org/10.5194/hess-27-2341-2023

[25]Abdullah, S. S., & Malek, M. A. (2016). Empirical Penman-Monteith equation and artificial intelligence techniques in predicting reference evapotranspiration: a review. International Journal of Water, 10(1), 55–66. DOI: 10.1504/IJW.2016.073741

[26]Pagay, V., et al. (2023). Data-driven irrigation scheduling increases the crop water use efficiency of Cabernet Sauvignon grapevines. Irrigation Science. https://doi.org/10.1007/s00271-023-00866-7 link.springer.com

[27]University of Adelaide & Wine Australia. (2022). Plant sensor-based precision irrigation for improved vineyard water use efficiency, grape and wine composition and quality, and vineyard profitability. Wine Australia.Wine Australia dl.acm.org+14wineaustralia.com+14link.springer.com+14

[28]Author(s) Unknown. (2023). Decision-support system for precision regulated deficit irrigation management for wine grapes. Computers and Electronics in Agriculture. https://doi.org/10.1016/j.compag.2023.107777

[29]García-Gutiérrez, V., Stöckle, C., Gil, P. M., & Meza, F. J. (2021). Evaluation of Penman-Monteith model based on Sentinel-2 data for the estimation of actual evapotranspiration in vineyards. Remote Sensing, 13(3), 478. https://doi.org/10.3390/rs13030478

[30]Wang, L., Qu, J. J., & Zhao, Y. (2023). Estimating soil and grapevine water status using ground-based hyperspectral imaging under diffused lighting conditions. Precision Agriculture, 24(3), 567–584. https://doi.org/10.1007/s11119-023-09981-w

[31]Datta, S., Taghvaeian, S., Ochsner, T. E., Moriasi, D., Gowda, P., & Steiner, J. L. (2018). Performance assessment of five different soil moisture sensors under irrigated field conditions in Oklahoma. Sensors, 18(11), Article 3786. https://doi.org/10.3390/s18113786

[32]Lakhiar, I. A., Yan, H., Zhang, C., Wang, G., He, B., Hao, B., Han, Y., Wang, B., Bao, R., Syed, T. N., Chauhdary, J. N., & Rakibuzzaman, M. (2024). A review of precision irrigation water-saving technology under changing climate for enhancing water use efficiency, crop yield, and environmental footprints. Agriculture, 14(7), 1141. https://doi.org/10.3390/agriculture14071141