

TOWARDS IMPROVED IRRIGATION STRATEGIES: CROP WATER STATUS PROXIES IN CITRUS GROVES

VERS DE MEILLEURES STRATÉGIES D'IRRIGATION: INDICATEURS INDIRECTS DE L'ÉTAT HYDRIQUE DES CULTURES DANS LES VERGERS D'AGRUMES

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ABSTRACT

Improving water use efficiency in irrigated agriculture requires not only technological innovation but also practical frameworks for supporting irrigation management at the farm level. Despite the rapid development of precision irrigation technologies and digital tools, their effective adoption remains constrained by farmers' decision-making processes and their perceptions of risks and costs. In this context, a two-year experimental study was conducted by the researchers of University of Catania (Italy) in collaboration with the "Olive, Fruit and Citrus Research Centre" of the "Italian Council for Agricultural Research and Economics" (CREA-OFA), aiming at evaluating the feasibility of adopting innovative approaches for more efficient and adaptive irrigation management.

The study was carried out in a young citrus orchard characterized by multiple rootstock–scion combinations subjected to contrasting irrigation regimes and located at the CREA-OFA experimental farm in Sicily (Syracuse province, Italy). Specifically, full irrigation (FI) and severe deficit irrigation (DI), with water reductions of 64% compared to FI conditions, were applied using a surface ultra-low drip irrigation system. During the 2024–2025 irrigation seasons (May–September), an innovative monitoring protocol integrating low-cost thermal infrared (TIR) and visible near-infrared (VNIR) proximal sensors was implemented to derive the normalized difference vegetation index (NDVI) and thermal-based crop indicators (i.e., canopy temperature, T_c and crop water stress index, CWSI). The objective was to assess whether affordable proximal sensing technologies could provide reliable and scalable indicators for irrigation management, thereby facilitating the transition from experimental research to on-farm applications.

Results demonstrated that low-cost TIR and VNIR sensors effectively captured both spatial and temporal variability in citrus water status under Mediterranean conditions. In particular, the interaction between irrigation regime and day of the year emerged as the main driver of T_c and NDVI variability across the two irrigation seasons, highlighting the temporal dynamics of crop responses to drought stress. The CWSI clearly discriminated between irrigation levels and revealed significant genotype $\times$ irrigation regime interactions, highlighting contrasting adaptive responses among rootstock–scion combinations. These findings suggest that proximal sensing technologies have reached a sufficient level of maturity to support irrigation management services. However, further research is still needed to develop a structured evaluation framework linking VNIR and TIR data with plant physiological responses and irrigation performance in order to derive user-friendly water status indicators and operational thresholds.

Keywords: Irrigation strategies; Water use efficiency; Adaptive irrigation management; Deficit irrigation; Water stress.

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RÉSUMÉ

L'amélioration de l'efficacité d'utilisation de l'eau en agriculture irriguée nécessite non seulement des innovations technologiques, mais aussi des cadres pratiques d'appui à la gestion de l'irrigation à l'échelle de l'exploitation. Malgré le développement rapide des technologies d'irrigation de précision et des outils numériques, leur adoption effective demeure limitée par les processus décisionnels des agriculteurs et leur perception des risques et des coûts. Dans ce contexte, une étude expérimentale de deux ans a été menée par les chercheurs de l'Université de Catane (Italie), en collaboration avec l'« Olive, Fruit and Citrus Research Centre » du « Italian Council for Agricultural Research and Economics » (CREA-OFA), afin d'évaluer la faisabilité de l'adoption d'approches innovantes pour une gestion de l'irrigation plus efficace et adaptative.

L'étude a été menée dans un jeune verger d'agrumes comportant plusieurs combinaisons porte-greffe-greffon soumises à des régimes d'irrigation contrastés, situé dans la ferme expérimentale du CREA-OFA en Sicile (province de Syracuse, Italie). Plus précisément, une irrigation complète (FI) et une irrigation déficitaire sévère (DI), avec une réduction de l'eau de 64 % par rapport aux conditions FI, ont été appliquées au moyen d'un système d'irrigation goutte à goutte de surface à ultra-faible débit. Au cours des saisons d'irrigation 2024–2025 (mai–septembre), un protocole de suivi innovant intégrant des capteurs proximaux TIR et VNIR à faible coût a été mis en œuvre afin de calculer l'indice de végétation par différence normalisée (NDVI) et des indicateurs thermiques des cultures (c.-à-d. la température du couvert, Tc, et l'indice de stress hydrique des cultures, CWSI). L'objectif était d'évaluer si des technologies abordables de télédétection proximale pouvaient fournir des indicateurs fiables et évolutifs pour la gestion de l'irrigation, facilitant ainsi le passage de la recherche expérimentale aux applications à l'échelle de l'exploitation.

Les résultats montrent que les capteurs TIR et VNIR à faible coût ont efficacement saisi la variabilité spatiale et temporelle de l'état hydrique des agrumes dans des conditions méditerranéennes. En particulier, l'interaction entre le régime d'irrigation et le jour de l'année s'est révélée le principal facteur de variabilité de Tc et du NDVI au cours des deux saisons d'irrigation, mettant en évidence la dynamique temporelle des réponses des cultures au stress dû à la sécheresse. Le CWSI a clairement distingué les niveaux d'irrigation et mis en évidence des interactions significatives entre le génotype et le régime d'irrigation, ce qui révèle des réponses adaptatives contrastées selon les combinaisons porte-greffe-greffon. Ces résultats suggèrent que les technologies de détection proximale ont atteint un degré de maturité suffisant pour soutenir les services de gestion de l'irrigation. Des recherches supplémentaires restent toutefois nécessaires pour élaborer un cadre d'évaluation structuré reliant les données VNIR et TIR aux réponses physiologiques des plantes et aux performances de l'irrigation, afin de définir des indicateurs de l'état hydrique et des seuils opérationnels faciles à utiliser.

Mots clés : Stratégies d'irrigation; Efficacité d'utilisation de l'eau; Gestion de l'irrigation adaptative; Irrigation déficitaire; Stress hydrique.

INTRODUCTION

Climate change and growing competition for water resources are increasingly threatening the sustainability of Mediterranean irrigated agriculture (Fader et al. 2016). Within this context, citrus production, a cornerstone of the Mediterranean economy, is particularly vulnerable to drought conditions and high irrigation demand (Ziogas et al. 2021). Although precision irrigation technologies offer promising solutions, their widespread adoption is often constrained by the high implementation costs faced by small- and medium-scale farmers (Kasereka et al. 2025, Neophytides et al. 2025). In this context, improving water use efficiency in irrigated agriculture therefore requires not only technological innovation, but also practical frameworks capable of supporting irrigation management at the farm level (Evans & Sadler 2008).

Despite the rapid expansion of precision irrigation and digital tools, translating these technologies into measurable improvements in irrigation practices remains challenging, as irrigation decisions are strongly influenced by farmers' experience, skills, and their perceptions of risks and costs (Saitta et al.

2021). Consequently, innovative practices must be systematically evaluated to facilitate their effective adoption and transfer. Within this framework, a two-year collaborative study was conducted by researchers from the University of Catania (Italy) and the “Olive, Fruit and Citrus Research Centre” of the “Italian Council for Agricultural Research and Economics” (CREA-OFA).

The research focuses on the use of low-cost proximal sensing technologies as a bridge between the adoption of innovative irrigation practices and advanced monitoring systems for precision irrigation purposes. Unlike previous studies mainly focused on high-cost instrumentation or single-genotype orchards (Consoli et al. 2017), this study evaluates the operational feasibility of low-cost sensing tools under heterogeneous citrus genetic backgrounds and severe water restrictions. Specifically, the study aims to facilitate the adoption of low-cost thermal and multispectral portable sensors for deficit irrigation (DI) management under different citrus rootstock–scion combinations (Caruso et al. 2024, 2025).

MATERIAL AND METHODS

The experimental site was located at the CREA-OFA farm in the Lentini territory (Syracuse, Sicily, Italy) under semi-arid climate conditions. The study involved young orange trees characterized by multiple rootstock–scion combinations (Caruso et al. 2024, 2025), including ‘Tarocco Meli’ and ‘Tarocco TDV-VCR’ grafted onto different rootstocks as given in **Table 1**.

Table 1. Selection of the citrus rootstock–scion combinations used in this study

Combination	Rootstock	Grafting
2	M5723	MELI
3	M4277A	MELI
7	M5761	MELI
10	62-109-40	MELI
11	US812	MELI
14	FAO30584	TDV
15	FAO30591	TDV
18	MORTON	TDV
20	CARRIZO	TDV
21	CARRIZO	MELI

Two irrigation regimes were established: (i) a full irrigation (FI) treatment, supplying 100% of the estimated crop water requirement (ET_c) on the irrigation sectors named BL1-1, BL2-3, BL3-5 in **Figure 1**, and (ii) a DI treatment, supplying approximately 37% of ET_c on the sectors named BL1-2, BL2-4, BL3-6 in **Figure 1**.

Note that ET_c rates were estimated using the single crop coefficient method based on the FAO-56 Penman–Monteith approach on the basis of local agrometeorological observations (Allen et al. 1998). Note that DI was applied using the partial root-zone drying strategy, with irrigation application on one side of the root-zone while the other side was kept dry, alternating the sides every two weeks (Consoli et al. 2017, Saitta et al. 2021).

An innovative ultra-low drip irrigation (ULDI) system, manufactured by Irritec® company, was adopted to improve water distribution uniformity both at FI and DI conditions. The ULDI system was made of six independent irrigation sectors with three surface irrigation lines per tree row (two and one with drippers at flow rate of 0.8 L h^{-1} and 0.6 L h^{-1} , respectively), and emitters spaced 0.6 m along the surface drip-lines (**Figure 1**).

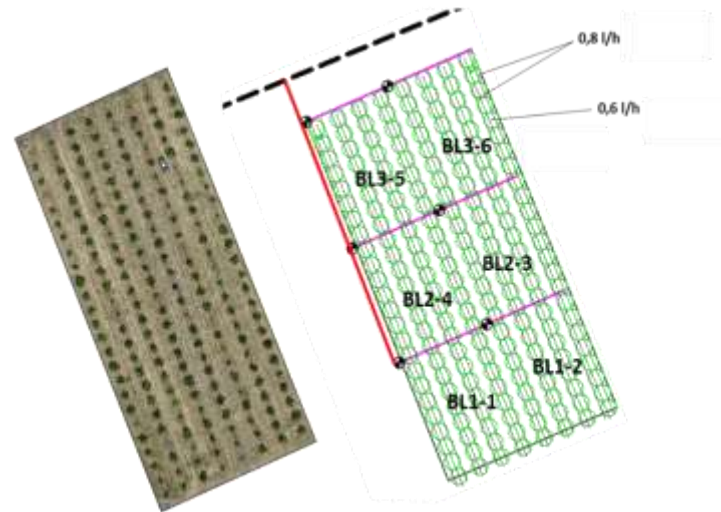


Figure 1. Overview of the experimental citrus orchard and irrigation sectors manufactured by Irritec®. The sectors BL1-1, BL2-3, BL3-5 and BL1-2, BL2-4, BL3-6 refer to full irrigation (FI) and deficit irrigation (DI) conditions, respectively.

Field data acquisition

A smart methodological protocol integrating low-cost thermal infrared (TIR) and visible near-infrared (VNIR) portable sensors was implemented at the study site (Pappalardo et al. 2023, Toscano et al. 2025). Specifically, TIR and VNIR images were acquired from 52 sample trees representing 10 different rootstock–scion combinations (**Table 1**) under both FI and DI regimes.

For this purpose, a low-cost thermal camera (FLIR One Pro, Teledyne FLIR LLC, Arlington, VA, USA) and a multispectral sensor (MAPIR Survey3 RGN, San Diego, CA, USA) were used. The thermal and VNIR sensors featured optical resolutions of 640×480 and 4000×3000 pixels, respectively. The thermal sensor operated within the $8\text{--}14\ \mu\text{m}$ spectral range, whereas the multispectral sensor acquired imagery in the green (550 nm), red (660 nm), and near-infrared (850 nm) bands.

Field VNIR–TIR data acquisition was performed on 14 dates throughout the 2024–2025 irrigation seasons (May–September). On each acquisition date, VNIR and TIR images were collected from all 52 sample citrus trees. Additionally, two leaves per tree were selected to identify cold and hot thermal reference surfaces (T_{hot} and T_{cold} respectively) for the computation of the crop water stress index (CWSI) (Idso et al. 1981).

$$\text{CWSI} = \frac{T_c - T_{\text{cold}}}{T_{\text{hot}} - T_{\text{cold}}}$$

where, T_c is the canopy temperature ($^{\circ}\text{C}$), while T_{cold} and T_{hot} represent the non-stressed and fully stressed thermal reference temperatures, respectively.

Further details on VNIR and TIR data acquisition and processing, including the identification of thermal reference surfaces (T_{hot} and T_{cold}), are provided in Pappalardo et al. (2023) and Toscano et al. (2025).

To ensure robustness and strengthen the interpretation of sensor-derived indicators, independent plant-based measurements were also collected, including stem water potential, while analyses of key biochemical stress markers are currently ongoing, such as hydrogen peroxide, abscisic acid, malondialdehyde, and proline. In addition, UAV-based VNIR and TIR imagery was acquired to characterize within-orchard spatial variability and evaluate the consistency between proximal and UAV-based sensing approaches, although these results are beyond the scope of the present study.

Data pre- and post-processing phases

VNIR image post-processing initially involved reflectance calibration of the acquired multispectral imagery. Subsequently, the normalized difference vegetation index (NDVI) was computed according to Rouse et al. (1974) for each image. A total of 20 NDVI sample points were extracted from each raster using QGIS software (v. 3.16) to support subsequent statistical analyses.

TIR images were analysed to extract canopy temperature (T_c) and compute the CWSI following the standard procedure proposed by Idso et al. (1981), based on thermal reference surfaces (T_{hot} and T_{cold}). The post-processing workflow for thermal features extraction and CWSI computation is given in **Figure 2**.

The protocol in **Figure 2** includes following steps (i): (i) manual digitalization and extraction of 20 sample points for T_c determination for each sample tree; (ii) identification and extraction of cold (T_{cold}) and hot (T_{hot}) thermal references at the tree level, using 10 sample points from two reference leaves per tree and acquisition date under each irrigation treatment; and (iii) implementation of the CWSI formulation using the median T_c value together with the minimum and maximum threshold values corresponding to the 10th and 90th percentiles of the cold and hot reference leaves, respectively, for each acquisition date and tree.

Three-way analyses of variance (ANOVA) were performed on NDVI, T_c and CWSI, to evaluate the effect of water regime, day-of-the-year (DOY) and rootstock–scion combinations over the irrigation seasons of interest using Statistix (Version 9.0). Tukey's honestly significant difference (HSD) test was applied to identify the observed differences, with the significance level set to p-value < 0.05.

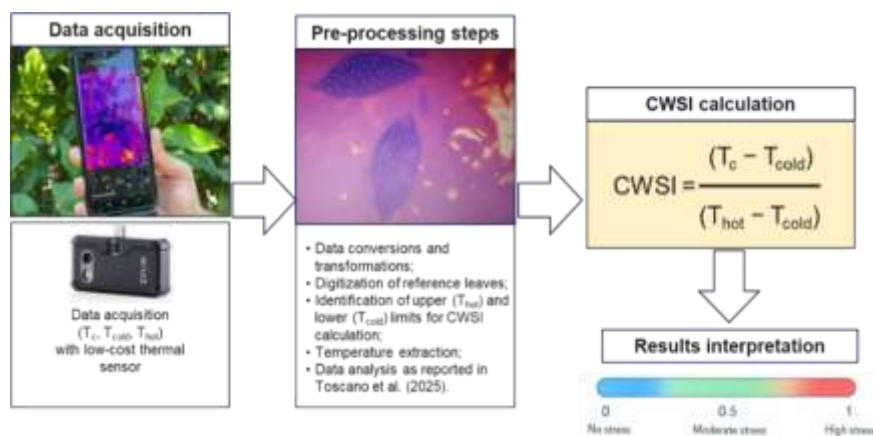


Figure 2. Work flow for crop water status determination

RESULTS AND DISCUSSION

The 2024–2025 irrigation seasons were characterized by typical Mediterranean summer conditions, with cumulative reference evapotranspiration (ET_0) reaching 859 mm. DI strategies implemented through ultra-low drip irrigation systems maintained satisfactory performance, while substantially reducing water inputs and enhancing plot-scale water use efficiency, achieving water savings of up to 64% compared to FI.

The proximal sensing monitoring results demonstrated that low-cost TIR and VNIR sensors effectively captured both spatial and temporal variability in citrus water status under Mediterranean conditions (Pappalardo et al. 2023, Toscano et al. 2025). In particular, ANOVA results indicated that the interaction between irrigation regime and DOY was the main driver of T_c and NDVI variability over the two irrigation seasons, highlighting the temporal dynamics of crop responses to drought conditions

(Berríos et al. 2024). Note that in 2024, the average T_c values were 34.68 ± 3.81 °C and 35.24 ± 3.72 °C under FI and DI conditions, respectively. Similar T_c patterns were observed in 2025, with mean values of 32.24 ± 2.65 °C for FI and 32.99 ± 2.79 °C for DI.

In the same way, NDVI captured seasonal vegetation dynamics but showed lower sensitivity to irrigation treatments compared with thermal indicators, with slightly higher values under FI (0.75 ± 0.01 and 0.67 ± 0.01 in 2024 and 2025, respectively), than under DI (0.74 ± 0.05 and 0.65 ± 0.01 in 2024 and 2025, respectively) (**Figure 3**). This suggests that, although DI trees exhibited slightly reduced vegetation indices, they maintained sufficient photosynthetic capacity throughout the stress period (Toscano et al. 2025). The CWSI confirmed significant differences between irrigation strategies and revealed significant rootstock–scion combination $\times$ irrigation regime interactions, highlighting contrasting adaptive responses among genotypes. Further analyses are ongoing to relate these responses to ancillary physiological and biochemical indicators, as well as fruit quality and yield traits.

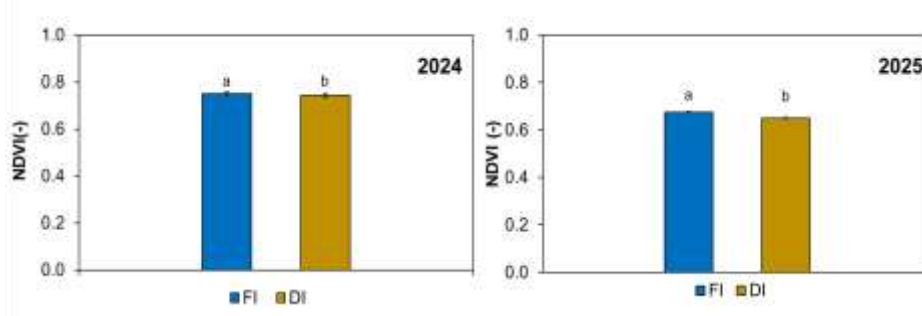


Figure 3. Temporal dynamic of the normalized vegetation index over the 2024-25 irrigation seasons.

CONCLUSION

From a broader perspective, this study indicates that innovative sensing technologies have reached sufficient technical maturity to support irrigation management services. However, their practical impact depends on standardized protocols, validation against physiological benchmarks, and translation into clear decision-support indicators. Converting VNIR and TIR signals into user-friendly water status metrics and operational thresholds would enable farmers to evaluate irrigation strategies, compare alternatives, and progressively refine management decisions according to their objectives. Overall, low-cost sensors represent a viable alternative to expensive scientific instrumentation for routine irrigation monitoring. The integration of CWSI and NDVI into farm protocols enables dynamic DI management, supporting climate resilience in Mediterranean citrus orchards. Future research will focus on refining CWSI thresholds for selected rootstock–scion combinations, quantifying long-term improvements in water use efficiency, and evaluating the scalability of the proposed approach across diverse citrus genotypes and Mediterranean agro-climatic and pedological conditions.

ACKNOWLEDGMENTS

This study was carried out within the framework of the projects PRIMA DIONYSUS "Operational adaptation Nexus based systems solutions in Mediterranean Region" (Grant Agreement No 2341), "Approcci Metodologici innovativi a supporto dell'Irrigazione di Precisione – AMIP" (PIANO di inCentivi per la Ricerca di Ateneo 2020/2022. Linea di Intervento 3 Starting Grant), and "Innovazioni nelle tecniche di osservazione basate su sensori di PROssimità a supporto dell'Agricoltura di Precisione ed applicazioni ambientali – PRO-AP" (PIANO di inCentivi per la Ricerca di Ateneo 2024/2026". Linea di Intervento 1- Progetti di Ricerca Collaborativa). Authors wish to thank the researchers and the personnel of Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria, Centro di Ricerca Olivicoltura, Frutticoltura e Agrumicoltura (CREA-OFA) of Acireale (CT) for their hospitality at the field site and, specifically, Dr. Marco Caruso for selecting the rootstock–scion combinations used in this study. Authors acknowledge Nicolò Uccellatore and other Di3A collaborators for helping during the proximal sensing dataset collection.

REFERENCES

- Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. Crop Evapotranspiration—Guidelines for Computing CropWater Requirements. *FAO Irrig. Drain. Pap.* 1998, 56, 147–151.
- Berríos, P., Temnani, A., Zapata-García, S., Sánchez-Navarro, V., Zornoza, R., & Pérez-Pastor, A. (2024). Effect of deficit irrigation and mulching on the agronomic and physiological response of mandarin trees as strategies to cope with water scarcity in a semi-arid climate. *Scientia Horticulturae*, 324, 112572.
- Caruso, M., Giuffrida, A., La Malfa, S. (2024). 'Rootstocks for the Mediterranean citrus industry: current choices and new releases', *Italus Hortus*, 31(1), pp. 01-17.
- Caruso, M., Giuffrida, A., La Malfa S., Ferlito, F., Russo, G., Las Casas, G., Torrisi, B., Scire, M., Nicolosi, E., Porrello, D., Russo, R., Cortese, M., Pietropaolo, D. (2025). 'The rootstock breeding and evaluation program at CREA, Italy', *Acta Horticulturae*, accepted for publication.
- Consoli, S., Stagno, F., Vanella, D., Boaga, J., Cassiani, G., & Roccuzzo, G. (2017). Partial root-zone drying irrigation in orange orchards: Effects on water use and crop production characteristics. *European Journal of Agronomy*, 82, 190-202.
- Evans, R. G., & Sadler, E. J. (2008). Methods and technologies to improve efficiency of water use. *Water resources research*, 44(7).
- Fader, M., Shi, S., von Bloh, W., Bondeau, A., & Cramer, W. (2016). Mediterranean irrigation under climate change: more efficient irrigation needed to compensate for increases in irrigation water requirements. *Hydrology and Earth System Sciences*, 20(2), 953-973.
- Idso, S.B.; Jackson, R.D.; Reginato, R.J. Normalizing the Stress-Degree-Day Parameter for Environmental Variability. *Agric. Meteorol.* 1981, 24, 45–55.
- Kasereka, S. K., Tashev, T., Medagbe, Y. C. N., Ocama, O. V., Ilunga, G. W., Kyungu, E., & Kyamakya, K. (2025). Smart Irrigation for Precision Agriculture: A Pathway to Sustainable Farming in Low-Income Regions. In *2025 International Conference on Big Data, Knowledge and Control Systems Engineering (BdKCSE)* (pp. 1-9). IEEE.
- Neophytides, S. P., Neofytou, E., Eliades, M., Hadjimitsis, D. G., & Mavrovouniotis, M. (2025). Water Stress Assessment in Mediterranean Citrus Orchards Using Machine Learning and Remote Sensing. In *2025 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)* (pp. 57-62). IEEE.
- Pappalardo, S., Consoli, S., Longo-Minnolo, G., Vanella, D., Longo, D., Guarrera, S., ... & Ramírez-Cuesta, J. M. (2023). Performance evaluation of a low-cost thermal camera for citrus water status estimation. *Agricultural Water Management*, 288, 108489.
- Rouse, J.W.; Haas, R.H.; Schell, J.A.; Deering, D.W. Monitoring Vegetation Systems in the Great Plains with ERTS. *NASA Spec. Publ.* 1974, 351, 309.
- Saitta, D., Consoli, S., Ferlito, F., Torrisi, B., Allegra, M., Longo-Minnolo, G., ... & Vanella, D. (2021). Adaptation of citrus orchards to deficit irrigation strategies. *Agricultural Water Management*, 247, 106734.
- Toscano, S., Consoli, S., Longo-Minnolo, G., Guarrera, S., Continella, A., Modica, G., ... & Vanella, D. (2025). Using Low-Cost Proximal Sensing Sensors for Detecting the Water Status of Deficit-Irrigated Orange Orchards in Mediterranean Climatic Conditions. *Agronomy*, 15(3), 550.
- Ziogas, V., Tanou, G., Morianou, G., & Kourgialas, N. (2021). Drought and salinity in citriculture: Optimal practices to alleviate salinity and water stress. *Agronomy*, 11(7), 1283.