TARMAKDER
TARIM MAKİNALARI DERNEĞİ

Tarım Makinaları Bilimi Dergisi
Journal of Agricultural Machinery Science
http://dergipark.org.tr/tr/pub/tarmak

e-ISSN: 2651-4230

Research Article / Araştırma Makalesi

21(2), 2025: 139-161

Satellite-Based Monitoring of Vegetation and Soil Moisture Indices for Stress Detection and Irrigation Planning in a Semi-Arid Apple Orchard

Yarı Kurak İklim Koşullarında Bir Elma Bahçesinde Stres Tespiti ve Sulama Planlaması için Uydu Tabanlı Bitki Örtüsü ve Toprak Nemi Endekslerinin İzlenmesi

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Article Info

Received date : 20.05.2025
Revised date : 26.08.2025
Accepted date : 19.08.2025

Keywords:

Remote sensing indices
Soil moisture interaction
Phenological stress detection

How to Cite:

Altikat, A., (2025). "Satellite-Based Monitoring of Vegetation and Soil Moisture Indices for Stress Detection and Irrigation Planning in a Semi-Arid Apple Orchard", Journal of Agricultural Machinery Science, 21(2): 139-161.

ABSTRACT

Sustainable irrigation management is crucial for fruit production in semi-arid regions. This study utilized satellite data collected between 2020 and 2025 to evaluate plant growth and changes in soil moisture in a 15.59-acre, drip-irrigated apple orchard located in eastern Türkiye. Spectral indices, such as NDVI, SAVI, and NDRE, along with radar-based indices like RVI and RSM, were combined to analyze the temporal and spatial patterns of plant stress. The results revealed significant stress conditions in 2020, 2021, and 2023. In contrast, 2024 saw 44% of the orchard reach the medium-high vegetation cover class. High correlations (r ≈ 0.99) were found between RSM, NDVI, and RVI indices, indicating that plant health is directly related to soil moisture. The SAVI and NDRE indices, on the other hand, enabled the sensitive monitoring of both early- and late-stage stress. These data defined area-based productivity maps and stress zones, and a field-level decision support framework was established to support irrigation decisions. The study proposes a repeatable method for precision agriculture applications, contributing to the mitigation of the effects of climate variability on yield.

Makale Bilgisi

Alınış tarihi : 20.05.2025
Düzeltilme tarihi : 26.08.2025
Kabul tarihi : 19.08.2025

Anahtar Kelimeler:

Uzaktan algılama indeksleri
Toprak nemi etkileşimi
Fenolojik stres tespiti

Atıf için:

Altıkat, A., (2025). "Yarı kurak iklim koşullarında bir elma bahçesinde stres tespiti ve sulama planlaması için uydu tabanlı bitki örtüsü ve toprak nemi endekslerinin izlenmesi", Tarım Makinaları Bilimi Dergisi, 21(2): 139-161.

ÖZET

Sürdürülebilir sulama yönetimi, yarı kurak bölgelerde meyve üretimi için kritik öneme sahiptir. Bu çalışmada, 2020 ile 2025 yılları arasında toplanan uydu verileri, Türkiye'nin doğusunda bulunan 63 dekar büyüklüğünde, damla sulama sistemine sahip bir elma bahçesindeki bitki büyümesi ve toprak nemi değişikliklerini değerlendirmek için kullanılmıştır. NDVI, SAVI ve NDRE gibi spektral indeksler ile RVI ve RSM gibi radar tabanlı indeksler birleştirilerek bitki stresinin zamansal ve mekansal örüntüleri analiz edilmiştir. Sonuçlar, 2020, 2021 ve 2023 yıllarında önemli stres koşulları ortaya çıkarken, 2024 yılında bahçenin %44'ünün orta-yüksek bitki örtüsü sınıfına ulaştığını ortaya koymuştur. RSM, NDVI ve RVI indeksleri arasında yüksek korelasyonlar (r ≈ 0,99) bulunmuş olup, bu da bitki sağlığının toprak nemi ile doğrudan ilişkili olduğunu göstermektedir. SAVI ve NDRE indeksleri ise erken ve geç aşama stresin hassas bir şekilde izlenmesini sağlamıştır. Bu veriler, alan bazlı verimlilik haritaları ve stres bölgeleri tanımlamış ve sulama kararlarını desteklemek için tarla düzeyinde bir karar destek çerçevesi oluşturulmuştur. Çalışma, iklim değişkenliğinin verim üzerindeki etkilerini azaltmaya katkıda bulunan, hassas tarım uygulamaları için tekrarlanabilir bir yöntem önermektedir.

1. INTRODUCTION

Apple (*Malus domestica*) cultivation in semi-arid and Mediterranean regions such as eastern Türkiye, southern Spain, and central Italy is increasingly threatened by climate-driven variability in precipitation and soil moisture. These vulnerabilities make it imperative to deploy scalable, real-time tools for crop monitoring that support precision irrigation and adaptive water management (Ippolito, 2023).

Spectral vegetation indices derived from remote sensing platforms have become essential instruments for monitoring plant health and stress. NDVI, while widely used to quantify vegetative vigor and biomass, often saturates in dense canopies and misrepresents sparsely vegetated systems. For younger or open-canopy orchards, the Soil Adjusted Vegetation Index (SAVI) corrects soil background reflectance. At the same time, the Normalized Difference Red Edge Index (NDRE) captures variations in chlorophyll concentration, enabling detection of late-season stress (Huete, 1988). In a multi-year study across Mediterranean mango orchards, NDRE consistently outperformed NDVI in early detection of water stress under deficit irrigation regimes (Sillero-Medina & González-Pérez, 2025).

Complementary to these optical indices, radar-based metrics—namely the Radar Vegetation Index (RVI) and Radar Soil Moisture Index (RSM)—offer cloud-independent assessments of canopy structure and surface water content. Kaya & Öztürk (2023) demonstrated strong positive correlations ($r > 0.70$) between NDVI and RSM-derived volumetric water content (VWC) in wheat systems under semi-arid conditions in Türkiye, validating the relevance of combined radar-optical frameworks.

Importantly, many remote sensing-based studies are limited by a single-season scope or the absence of meteorological variables, which constrains temporal generalizability. Nalçaoğlu et al. (2025), in their study on olive yield prediction in Muğla, Türkiye, demonstrated that integrating NDVI with precipitation, temperature, and vapor pressure deficit (VPD) in a neural network model improved yield prediction accuracy by over 20%. This suggests that vegetation index data alone may be insufficient to fully characterize the interactions between plants, soil, and climate.

Building on these findings, the current study employs a multi-temporal, multi-index remote sensing strategy to monitor crop stress and guide irrigation decisions in a drip-irrigated apple orchard located in the Iğdır Plain, eastern Türkiye. Sentinel-1 SAR and Sentinel-2 MSI data are used to extract NDVI, SAVI, NDRE, RVI, and RSM over six consecutive growing seasons (2020–2025). The study aims to (1) characterize temporal patterns of vegetative stress, (2) map spatial productivity zones, and (3) construct a satellite-supported decision framework for efficient irrigation scheduling in perennial horticultural systems.

2. MATERIALS AND METHODS

2.1. Study Area

This study was conducted in a commercial apple orchard located in the semi-arid region of eastern Türkiye, within the Iğdır Plain (39.937° N, 44.011° E) (Figure 1). The orchard spans 15.59 acres (63,107 m^2), characterized by sandy-loam Cambisol soils, low annual precipitation (270–320 mm), and high reference evapotranspiration rates ($ET_0 \approx$ 1,100–1,300 mm/year). Summers are hot and dry, and winters are cold, necessitating precise irrigation management. The field has a drip irrigation system, yet irrigation decisions have traditionally relied on empirical observations rather than objective, data-driven assessments.

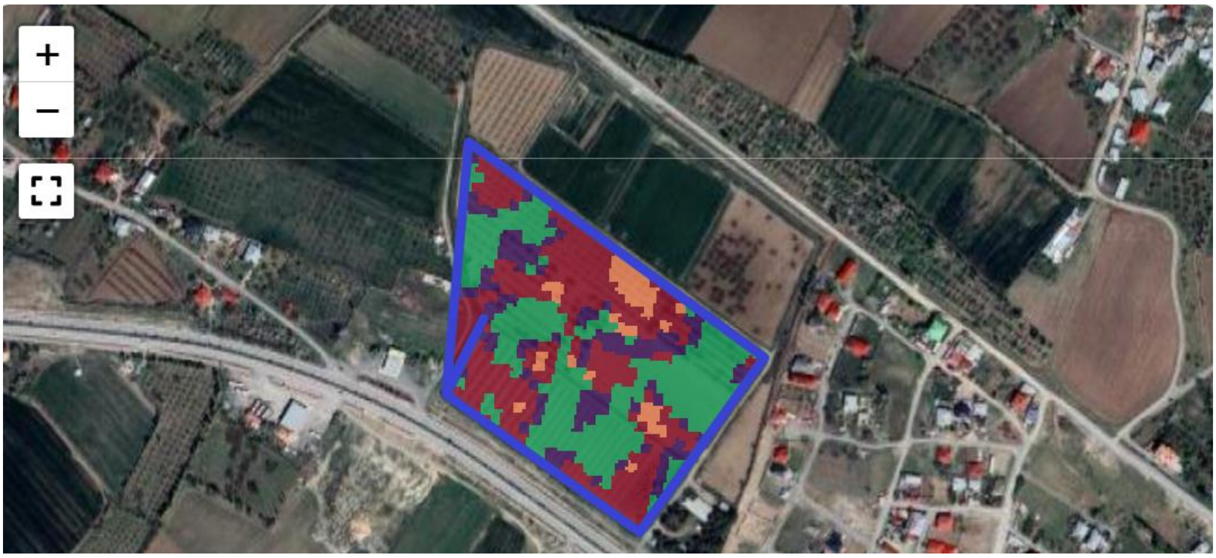


Figure 1. Zonal classification of field conditions based on remote sensing data in the delineated apple orchard area

2.2. Remote Sensing Data Acquisition and Platform

Satellite-based data were obtained via the Farmonaut® platform (https://www.farmonaut.com/), which integrates optical data from Sentinel-2 and radar data from Sentinel-1 (Copernicus Programme). Sentinel-2 imagery offers 10–20 m spatial resolution across visible, red-edge, and near-infrared bands, while Sentinel-1 provides all-weather C-band radar data with ~10 m resolution.

Although Farmonaut is a commercial service provider, its satellite-based outputs are directly derived from validated European Space Agency (ESA) products. The platform's internal processing uses standard vegetation index algorithms published in peer-reviewed literature. However, no independent ground-truth validation was conducted in this study, and results should be interpreted in that context. The outputs were visually and statistically checked for internal consistency and temporal coherence.

2.3. Vegetation and Soil Moisture Indices

To assess vegetation dynamics and surface soil moisture over the study area between 2020 and 2025, five vegetation and soil indices were derived from Sentinel-1 and Sentinel-2 imagery. Satellite images for all years were acquired on April 11.These indices—Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI), Normalized Difference Red Edge (NDRE), Radar Vegetation Index (RVI), and Radar Soil Moisture (RSM)—enable robust monitoring under various environmental and phenological conditions. Table 1 outlines each index, its spectral band formula, purpose, and reference.

Table 1. Vegetation and soil moisture indices used in the study

Index	*Equation*	*Reference*
NDVI	(B8 – B4) / (B8 + B4)	Xu et al., (2022)
SAVI	((B8 – B4) / (B8 + B4 + L)) × (1 + L), L = 0.5	Vidican et al., (2023)
NDRE	(B8a – B5) / (B8a + B5)	Xu et al., (2022)
RVI	VH / VV	Ma et al., (2020)
RSM	Derived via the backscatter model	Ma et al., (2020)

The bands used in these equations, along with their functions, are listed below.

B4 (Red, ~665 nm): Absorbed by chlorophyll pigments, essential for identifying vegetation stress in NDVI/SAVI calculations (Xu et al., 2022; Vidican et al., 2023).

B5 (Red Edge 1, ~705 nm): Sensitive to changes in chlorophyll content; used in NDRE to monitor plant nitrogen status (Xu et al., 2022).

B8 (NIR, ~842 nm): High reflectance in healthy vegetation due to leaf cell structure; fundamental for NDVI/SAVI (Vidican et al., 2023; Ma et al., 2020).

B8a (Red Edge 3, ~865 nm): Enhances detection of canopy structure in NDRE, especially during reproductive growth stages (Xu et al., 2022).

VH / VV (Radar Polarizations): Sentinel-1's dual-polarized radar bands used in RVI; robust under cloud and light limitations (Ma et al., 2020).

Radar Soil Moisture (RSM): Surface soil moisture estimated by combining radar polarizations using empirical inversion models (Ma et al., 2020).

All indices were exported as classified raster layers and manually digitized in ArcGIS Pro to compute total area per vegetation class. Surface areas were converted from m^2 to hectares for comparative analysis.

The thresholds used in the classification were as follows:

NDVI ≥ 0.2

NDRE ≥ 0.2

SAVI ≥ 0.2

RVI ≥ 0.3

These threshold values were determined based on prior literature (e.g., Guimarães et al., 2024; Crespo et al., 2024) and partially adjusted through empirical calibration by observing visual transitions in the classified outputs. The rationale behind selecting these thresholds is explicitly noted when discussing the classification results for each index.

All satellite images used to compute NDVI, SAVI, NDRE, RVI, and RSM values for each year were acquired on approximately April 11, representing the early vegetative phase of apple trees, prior to full canopy closure. This consistent acquisition date enables inter-annual comparison of early growth conditions and facilitates consistent phenological interpretation across years.

2.4. Data Processing and Spatial Analysis

Satellite images for all years were acquired on April 11. Data were organized chronologically, processed through QGIS/ArcGIS software, and reclassified into three vegetative categories:

Low (−1 to 0.2)

Medium (0.2–0.4)

High (0.4–0.6 for NDVI, 0.5–0.7 for RVI, etc.)

Spatial patterning was analyzed to determine inter-annual variability and detect stress-prone subzones. Geospatial zonal summaries were created annually and cross-referenced with decision thresholds to identify areas that are both productive and vulnerable to environmental stress.

2.5. Decision Support Framework

A field-level decision support strategy was developed based on the processed index data. The framework involved:

Zonal mapping based on index thresholds (e.g., NDVI ≥ 0.2 for active growth).

Temporal anomaly detection for years with unusually low RSM or NDRE values.

Inter-index correlation analyses to validate the relationship between canopy vigor and soil moisture.

Spatial segmentation to identify sub-field management zones for targeted irrigation interventions.

Field-scale productivity zones were delineated using yearly classified NDVI, RVI, NDRE, and SAVI indices. Zones exceeding index thresholds (e.g., NDVI ≥ 0.2, RVI ≥ 0.3) were identified as productive zones. These maps were compiled into a zonal decision-support model to guide irrigation frequency and intensity planning by identifying persistently low-performing subzones.

2.6. Spatial Resolution Limitations and Soil Background Correction Strategies

In young orchard systems with sparse canopy cover, the spatial resolution of satellite imagery poses significant challenges for accurate vegetation monitoring. In the study area, the average row and plant spacing was approximately 10 meters, resulting in canopy coverage of only 5–10% per pixel during the early years (2020–2022). Given that Sentinel-2 imagery has a spatial resolution of 10–20 meters (100–400 m^2 per pixel), the dominant reflectance signal captured was from bare soil rather than vegetation canopy.

To address this issue, the following correction strategies were employed:

Use of Soil-Adjusted Vegetation Index (SAVI): The SAVI index, incorporating a correction factor (L = 0.5), was included to minimize soil background noise under low canopy conditions (Huete, 1988; Peres & Cancelliere, 2021).

Inclusion of Radar-Based Indices (RVI and RSM): Unlike optical indices, radar data from Sentinel-1 is less sensitive to surface reflectance variability and provides structural and moisture-related signals independent of sunlight and cloud conditions (Hu et al., 2024).

Empirical Threshold Calibration: Index classification thresholds were partially adjusted by visual validation to align with real canopy distribution patterns, thereby reducing classification noise due to soil dominance in early years (Guimarães et al., 2024).

Temporal Integration: A six-year temporal series (2020–2025) was employed to observe trends, rather than relying on single-year snapshots, which can be skewed by sparse vegetation.

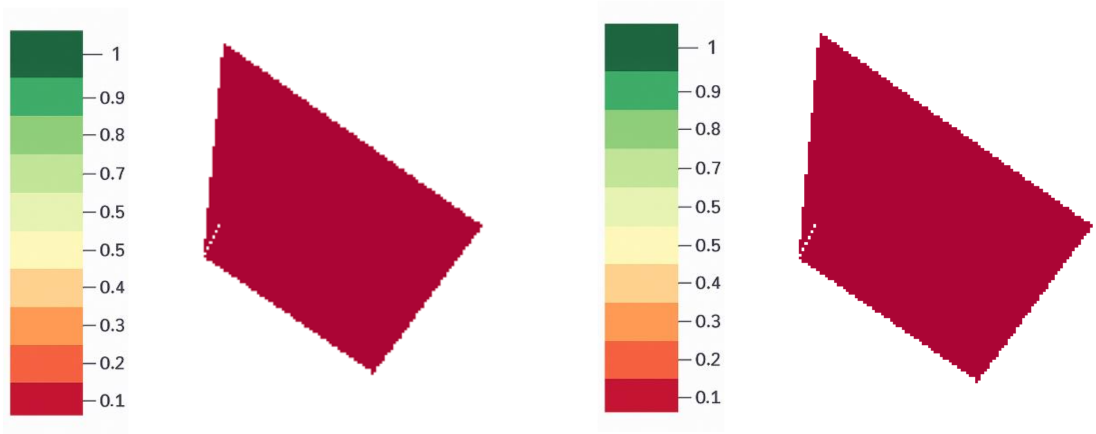
These strategies collectively improved index reliability in a low-density canopy system, providing a more accurate reflection of plant health over time.

3. RESULTS AND DISCUSSION

3.1. General NDVI Change Trends (2020-2025)

The temporal evaluation of NDVI values across the apple orchard from 2020 to 2025 revealed significant interannual variability in vegetative development. Figure 2 presents annual NDVI maps and displays a summary of vegetation class distributions categorized into low (–1 to 0.2), medium (0.2–0.4), and high (0.4–0.6) NDVI zones.

In 2020 and 2021, NDVI values across the entire orchard fell within the low classification range, indicating minimal vegetation cover and low photosynthetic activity. During these years, 100% of the 63,107 m^2 field was classified as unproductive, suggesting a combination of environmental stressors and insufficient plant establishment.

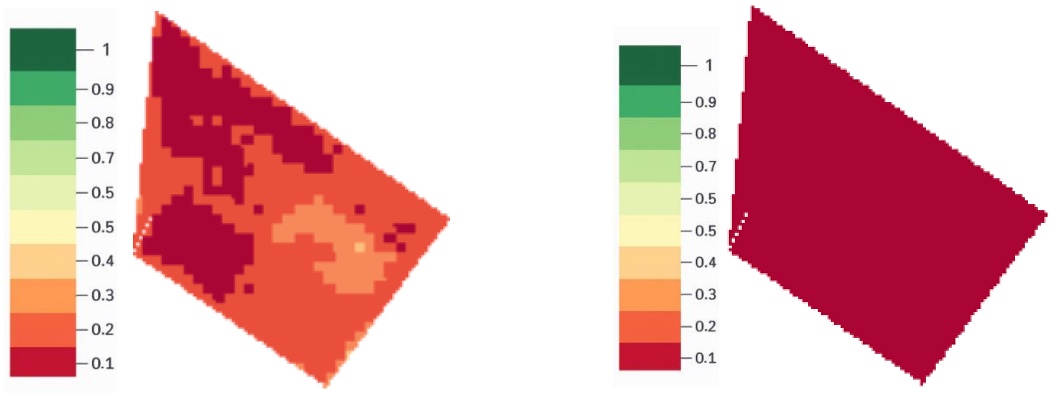


2020 **2021**

Figure 2. NDVI map for 2020 – 2021

In 2022, early signs of vegetative recovery were observed, particularly in the northeastern portion of the field. Approximately 6,546 m^2 (10.4%) of the orchard transitioned into the medium NDVI class, while the remaining 56,561 m^2 remained within the low classification (Figure 3). This shift suggests improved environmental conditions or partial regeneration of plant biomass.

However, the upward trend was not sustained in 2023. NDVI maps once again showed uniform reversion to low values, with 100% of the area classified as vegetatively inactive. This decline implies that adverse climatic conditions, such as drought, pest pressure, or ineffective field management, may have affected the orchard (Figure 3).



2022 2023

Figure 3. NDVI map for 2022 – 2023

In contrast, 2024 marked the most productive year in terms of vegetation development. A total of 25,821 m^2 (40.9%) of the orchard exhibited medium NDVI values, and 1,849 m^2 (2.9%) reached the high NDVI class (Figure 4). These values reflect optimal canopy growth and photosynthetic performance, likely from favorable environmental conditions or agronomic improvements.

By 2025, NDVI values declined sharply, with the entire orchard reverting to the low classification range (Figure 4). This regression underscores the production system's vulnerability to environmental and operational inconsistencies, highlighting the need for more sustainable and adaptive field management practices.

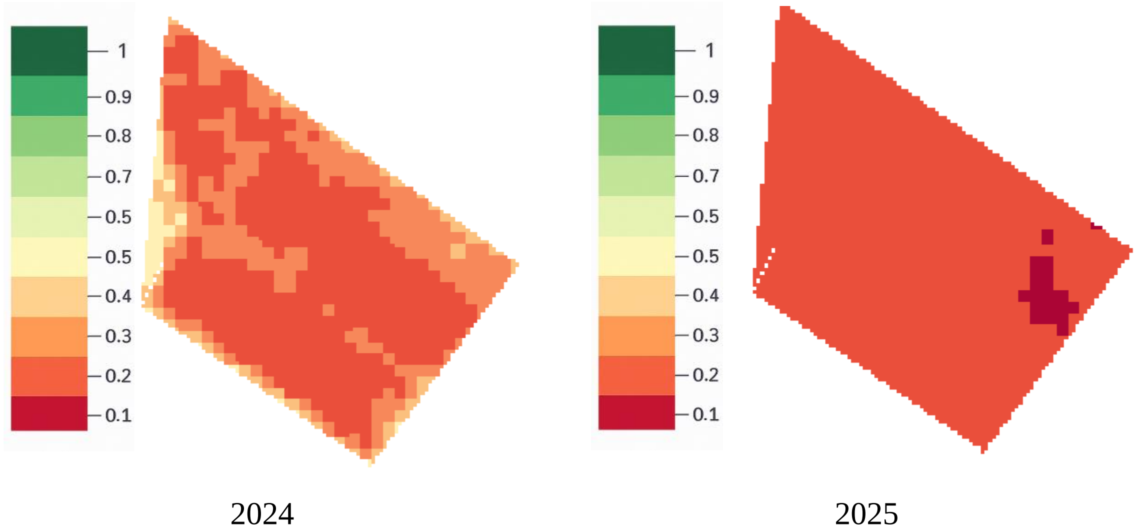


Figure 4. NDVI map for 2024 – 2025

Figure 5 illustrates the spatial distribution of NDVI values within the apple orchard from 2020 to 2025, categorized into three classes: low, medium, and high. The data reveals significant fluctuations in plant growth across these years.

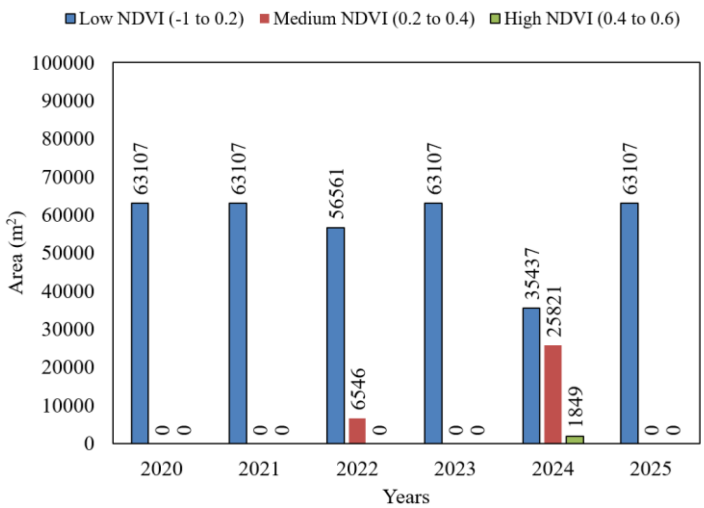


Figure 5. Annual NDVI-Based Vegetation Class Distribution in Apple Orchard

In 2020 and 2021, the orchard consistently exhibited low NDVI values, ranging from -1 to 0.2. This trend indicates a complete lack of plant production or insufficient photosynthetic activity among the existing flora. Notably, the entire area of 63,107 m^2 was classified as being in the low NDVI category for both years.

A marked improvement in plant growth was observed in 2022, with approximately 6,546 m^2 of the orchard achieving medium NDVI values (0.2-0.4). However, most of the area, encompassing 56,561 m^2, remained within the low NDVI classification. This shift indicates a resumption of plant growth, the emergence of new plants, and an increase in chlorophyll content.

Unfortunately, this positive trend could not be maintained in 2023, as the entire orchard reverted to the low NDVI classification. The whole area of 63,107 m^2 was categorized as unproductive, indicating an interruption in agricultural yield likely attributable to adverse environmental factors such as drought, disease, or soil degradation.

2024 marked a notable turning point, characterized by the most favorable NDVI developments. The orchard witnessed 25,821 m^2 classified as medium NDVI and an additional 1,849 m^2 achieving high NDVI values (0.4-0.6). This year can be considered a peak in plant health and agricultural productivity, with approximately 44% of the area reaching medium and high NDVI levels, which suggests that agronomic interventions were effective.

Conversely, projections for 2025 indicate a significant decline in NDVI values, with the entire orchard reverting to the low NDVI classification. This decline underscores the challenges in achieving sustainable production and reveals the system's heightened sensitivity to external perturbations.

In summary, the analysis highlights 2024 as the most productive year for the apple orchard, while the years 2020, 2021, 2023, and 2025 are identified as periods of minimal productivity. Despite the signs of recovery in 2022, the subsequent decline in 2025 emphasizes the unsustainable nature of the current agricultural practices under varying environmental conditions.

The temporal NDVI assessment conducted over the six years revealed pronounced fluctuations in vegetation vigor, strongly influenced by environmental conditions and management practices. The complete dominance of low NDVI values during 2020, 2021, 2023, and 2025 reflects recurring periods of vegetative stress, potentially associated with water scarcity, insufficient agronomic inputs, or extreme temperature events. In contrast, 2024 stood out with a significant portion of the orchard—over 44%—classified under medium to high NDVI zones, indicating optimal canopy development and robust photosynthetic performance. These patterns are consistent with prior findings in semi-arid agroecosystems, where NDVI has been used as a reliable proxy for crop biomass, chlorophyll concentration, and yield potential (Stagakis et al., 2012; Gaznayee et al., 2023).

Moreover, the observed rise and fall in NDVI values across the years highlight the limitations of conventional, experience-based irrigation management. Without data-driven and adaptive interventions, the orchard appears highly vulnerable to environmental stressors. Previous research supports the idea that integrating NDVI into real-time irrigation strategies improves water-use efficiency and stabilizes production under climate variability (Hasan et al., 2024). The drastic regression in 2025, following the peak in 2024, reinforces that one-time agronomic improvements are insufficient unless embedded within a sustained precision agriculture framework (Lakhiar et al., 2024). Additionally, NDVI-based zonal mapping has been shown to support spatially targeted inputs, improving resource allocation and crop resilience (Guimarães et al., 2024).

These results suggest that NDVI, when monitored consistently across time and space, effectively quantifies current vegetative status and forecasts agronomic risk. Thus, integrating NDVI monitoring into orchard decision-support systems is advantageous and essential for ensuring long-term sustainability and resilience in semi-arid fruit production systems.

3.2. Evaluation of Soil-Plant Relationship with RVI and RSM Data

Radar-based remote sensing technologies offer significant advantages for effectively monitoring agricultural areas, particularly in semi-arid climates with high cloud cover. In this study, RVI and RSM data were analyzed and interpreted in conjunction with NDVI values to assess plant growth and soil moisture dynamics in an apple orchard. In this way, plant-soil relationships were revealed both spatially and temporally, and the evolution of stress-induced variability over the years was evaluated.

Figure 6 compares the average RVI, RSM, and NDVI values over the years. The RSM values were relatively low in 2020, 2021, and 2023, resulting in both RVI and NDVI values remaining at their minimum levels. This situation reveals that plant growth is severely disrupted, especially during periods when drought effects are evident. In 2022, the partial increase in soil moisture led to a limited but significant rise in RVI and NDVI values, marking an essential indicator of the resumption of plant production. The year 2024 stood out as an exceptional period, during which optimum soil moisture and strong, balanced plant growth were achieved simultaneously, reaching the highest values of the study, with averages of both RSM (0.45), RVI (0.35), and NDVI (0.42). However, this positive momentum could not be sustained in 2025; parallel to the decline in RSM level, NDVI and RVI values also decreased significantly, thus clearly demonstrating the instability in productivity and the lack of sustainability in the production process.

2020 was the year when the lowest values were observed in terms of plant growth and soil moisture. The RVI map (Figure 7) indicates that most of the area has values ranging from 0.2 to 0.3, with only limited areas exceeding 0.4. This implies low leaf density and poor vegetative reflectance. The RSM map (Figure 7) also supports these observations, showing significant water stress in the eastern and southeastern regions, with values ranging from 0.1 to 0.2. Insufficient soil moisture coincides with low RVI values, indicating almost no plant growth throughout the year. In 2021, a similarly low growth profile continued. RVI data (Figure 5) remained at low levels, especially in the eastern regions, and only in the western parts was a partial increase observed, ranging from 0.4 to 0.5. However, these increases are not significant on an area basis. The RSM map (Figure 8) reveals a more fragmented structure than the previous year. Moisture uniformity could not be achieved in the area, and water deficiency reached severe levels, especially in the central and eastern regions.

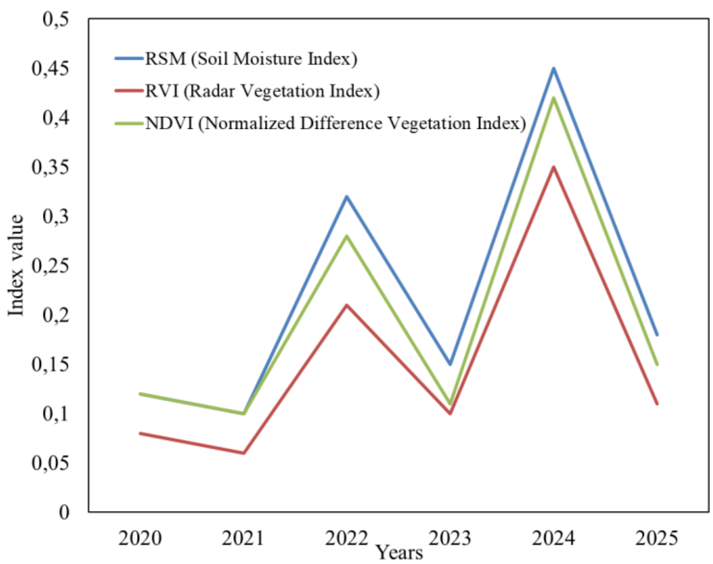
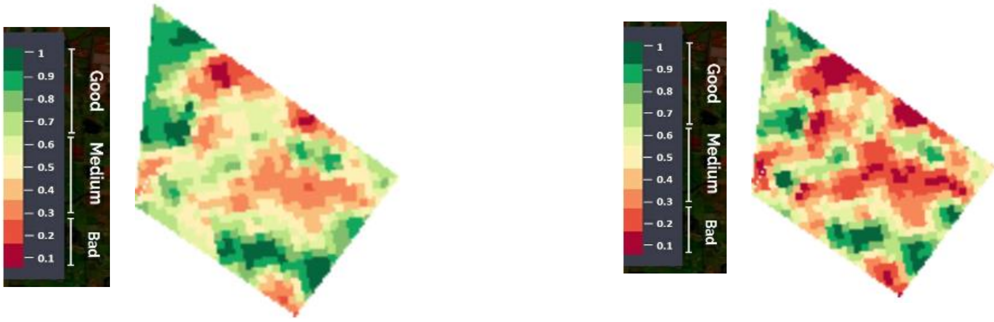


Figure 6. Temporal Variation of RSM, RVI, and NDVI in Apple Orchard

RVI (Radar Vegetation Index) RSM (Radar Soil Moisture)

Figure 7. RVI-RSM changes in 2020



RVI (Radar Vegetation Index) RSM (Radar Soil Moisture)

Figure 8. RVI-RSM changes in 2021

The year 2022 started to show positive development signals compared to the previous two years. The RVI map (Figure 9) shows values reaching 0.5 in the northwest and southeast regions, indicating an increase in the leaf area index. RSM data (Figure 9) reveals that regions with soil moisture in the 0.3-0.5 band are expanding in area. This increase in soil moisture supported vegetative growth, and partial production potential was realized in the garden. This year can be considered a transition year in which the return to production begins. 2023 was when the recovery of 2022 could not be sustained, and the soil-plant system weakened again. The RVI map (Figure 10) shows low vegetation density with a predominance of red and orange tones. RVI values dropped below 0.2, especially in the central and western regions. RSM data (Figure 10) reveals a similar decline, with low moisture levels in most areas with values in the 0.1-0.3 band. The decrease in soil moisture is directly reflected in the NDVI; the area has fallen back to the "Low NDVI" class.

RVI (Radar Vegetation Index) RSM (Radar Soil Moisture)

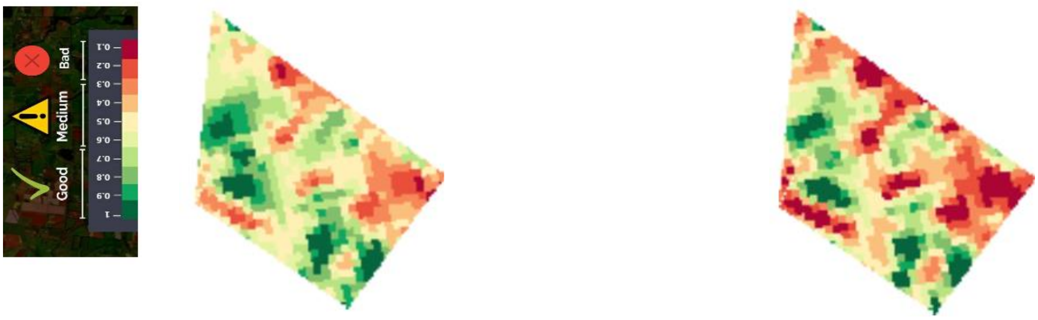
Figure 9. RVI-RSM changes for 2022

RVI (Radar Vegetation Index) RSM (Radar Soil Moisture)

Figure 10. RVI-RSM changes for 2023

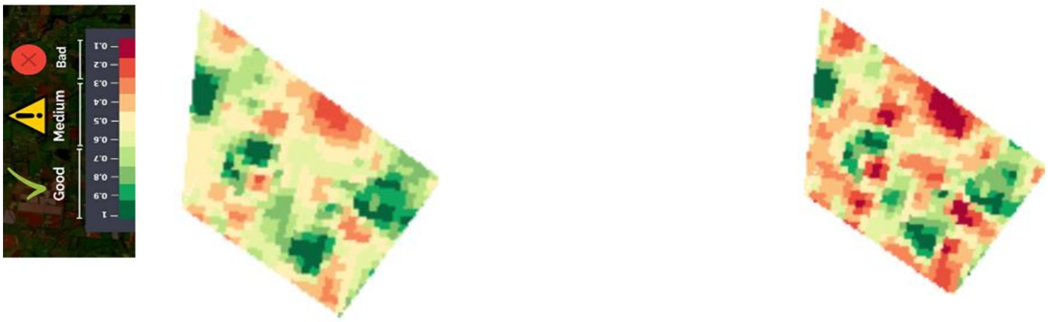
2024 stands out as the most productive year for the apple orchard according to all radar data and NDVI measurements. The RVI map (Figure 11) shows strong vegetative development, reaching 0.5-0.7 levels in most orchards. Vegetative reflections are intense in these areas, and the leaf area is at its maximum. The RSM map (Figure 11) also supports this development, with values in the range of 0.4-0.6 throughout the garden, indicating sufficient water in the soil. The moisture profile is more balanced and homogeneous. In line with the NDVI data, 2024 is the period with the healthiest plant growth. In 2025, the high growth in 2024 could not be sustained. The RVI map (Figure 12) again shows radar reflections predominantly in the 0.3-0.4 band despite the green areas opening up. This indicates a decrease in leaf growth. The RSM data (Figure 12), on the other hand, shows that vegetative growth is limited due to a renewed drop in soil moisture. Moisture levels have fallen below 0.2 in many garden parts, indicating unsustainable production. NDVI data confirms these developments, placing the area in the “Low NDVI” band.

The findings of this manuscript indicate that integrating radar-based data with optical-based NDVI offers a high degree of accuracy and timeliness in agricultural monitoring processes. Specifically, the year-by-year examination of the relationships between soil moisture (RSM) and plant growth (NDVI and RVI) is reinforced by empirical evidence showing that productivity is closely linked to plant health and soil conditions. Notably, 2024 represents the peak of productivity; however, the decline observed in 2025 suggests that this level of productivity may not have been maintained, potentially due to climatic stresses or deficiencies in management practices.



RVI (Radar Vegetation Index) RSM (Radar Soil Moisture)

Figure 11. RVI-RSM changes for the year 2024



RVI (Radar Vegetation Index) RSM (Radar Soil Moisture)

Figure 12. RVI-RSM changes for the year 2025

The integration of radar-based vegetation (RVI) and soil moisture (RSM) indices with optical NDVI data in this study provided a nuanced understanding of plant–soil interactions over time, particularly under semi-arid conditions. The results demonstrated a precise temporal alignment between RSM and vegetative indices, reinforcing that radar-derived metrics effectively detect water stress and its influence on plant health (Pradipta et al., 2022). During years such as 2020, 2021, and 2023, when RSM values were notably low, corresponding declines in RVI and NDVI confirmed that limited soil moisture availability directly constrained canopy development and photosynthetic activity. These findings align with previous studies emphasizing the importance of integrating soil moisture variability into crop health diagnostics to enhance yield forecasting and management responsiveness (Duarte & Hernandez, 2024; Sishodia et al., 2020).

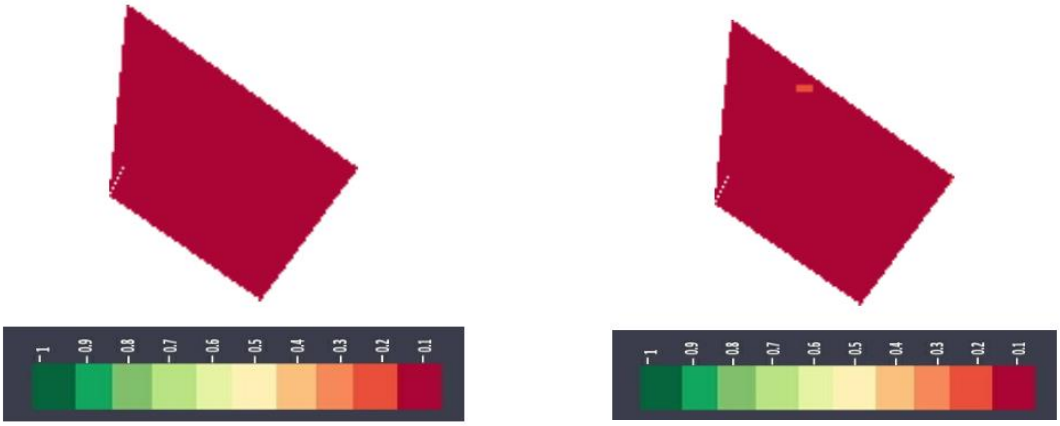
The sharp contrast observed in 2024, where high RSM levels corresponded with peak NDVI and RVI values, further illustrates the synergy between water availability and vegetative performance. Such insights echo recent literature that has underscored the benefits of radar-based monitoring in overcoming the limitations of optical indices during cloudy or drought-prone seasons (Hu et al., 2024). The ability of RVI to capture real-time biomass changes even under suboptimal optical conditions makes it particularly valuable for operational irrigation planning (Yang et al., 2024). However, despite the prior year's gains, the rapid regression in 2025 highlights the fragility of systems that lack continuous, adaptive soil-plant monitoring. This aligns with recent findings that stress the need for combining high-frequency remote sensing with precision irrigation frameworks to achieve sustainable production in climate-sensitive horticultural zones (Dong et al., 2024).

In conclusion, this study's temporal co-variation of RSM, RVI, and NDVI validates their combined use in stress detection. It also provides a replicable model for soil-plant interaction monitoring in other semi-arid orchard systems. Future agricultural monitoring platforms should prioritize multisensor fusion approaches to ensure resilience in the face of increasing climatic variability.

3.3 NDRE and SAVI Data on Plant Stress

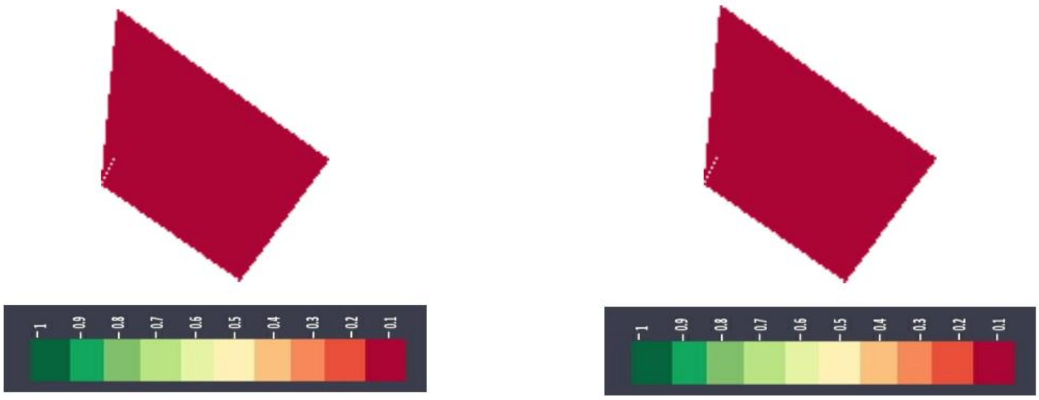
NDRE (Normalized Difference Red Edge) and SAVI (Soil Adjusted Vegetation Index) are effective remote sensing indices used for stress detection at different stages of plant development. In this study, SAVI was used to assess plant performance during the early developmental stage, while NDRE was used to determine plant vigor during the maturation stage. The data from 2020 and 2025 show that both indices complement agricultural stress monitoring.

NDRE and SAVI maps for 2020, presented in Figure 13, show extremely low index values across the field. Dark red and burgundy tones in both years characterize the maps. A similar pattern is observed in the 2021 maps (Figure 14). According to the area distributions, the area falls between -1 and 0.1 in the SAVI classification, while for NDRE, almost the whole area falls between -1 and 0.1. This indicates that vegetation was absent at the beginning of development (SAVI) and later in the season (NDRE) and that severe water and nutrient stress was experienced.



2020 NDRE 2020 SAVI

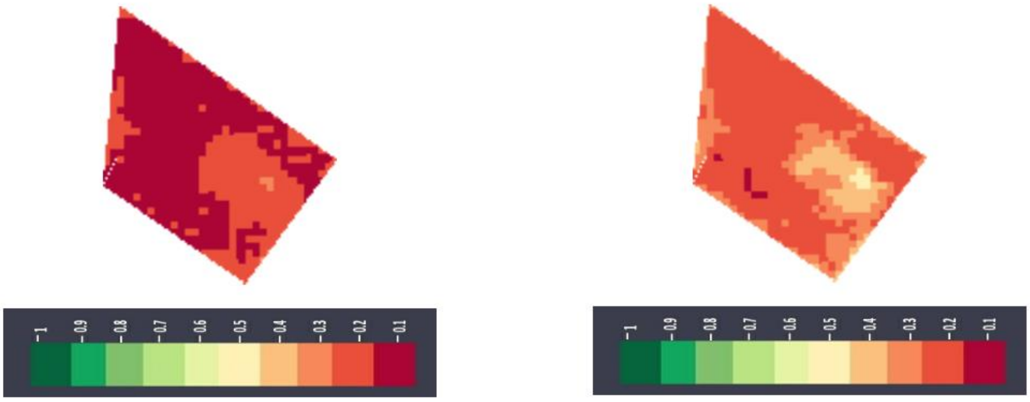
Figure 13. NDRE and SAVI change for 2020



2021 NDRE 2021 SAVI

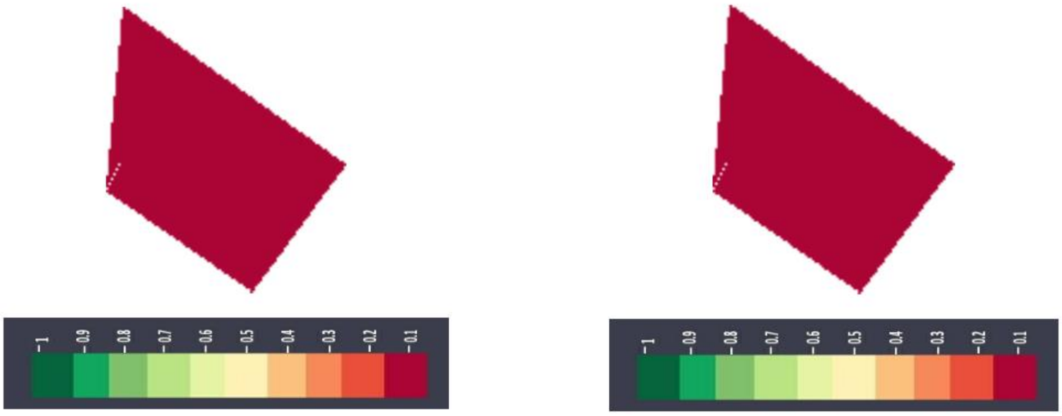
Figure 14. NDRE and SAVI changes for 2021

In 2022, both indices showed the first signs of partial improvement. As depicted in Figure 15, the areas highlighted in orange and yellow on the SAVI map indicate a positive change. In contrast, the NDRE map reveals light green tones emerging in the eastern and western regions. Area data demonstrates the emergence of a 9264 m^2 zone within the NDRE range of 0.2-0.3, suggesting limited plant vitality late in the season. However, the data for 2023 indicates a decline in both SAVI and NDRE values (Figure 16). Notably, the SAVI values reverted to red, signaling that stress was prevalent during early development. In the NDRE map, areas remain marginally between 0.2 and 0.3, particularly in the southwest, indicating some recovery towards the end of the season. Overall, the area primarily exhibited poor development.



2022 NDRE 2022 SAVI

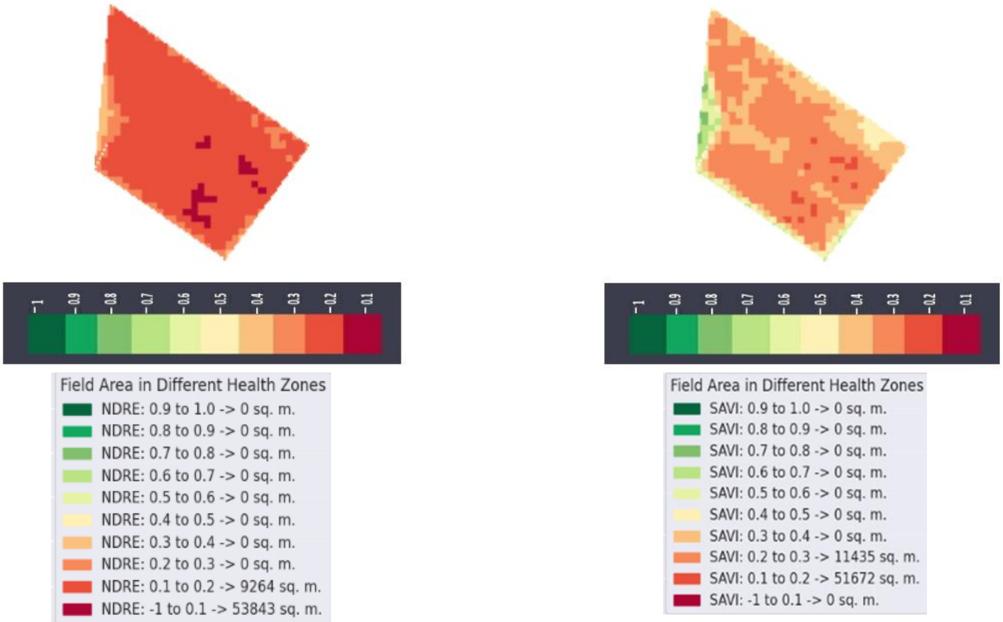
Figure 15. NDRE and SAVI changes for 2022



2023 NDRE 2023 SAVI

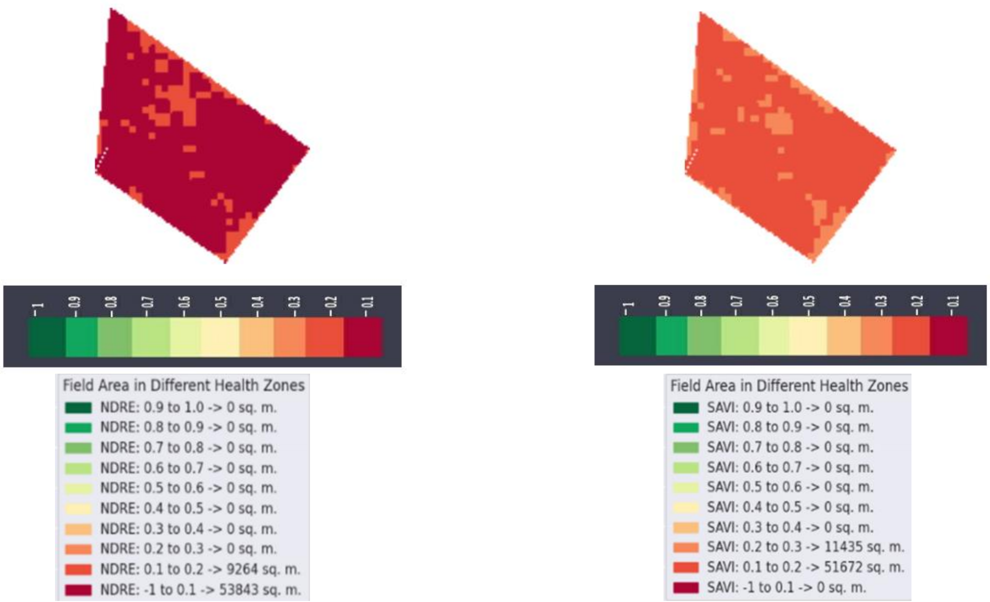
Figure 16. NDRE and SAVI changes for 2023

The highest values for NDRE and SAVI are recorded in 2024. The prevalence of green and yellow tones is depicted in Figure 17, and the k-l maps are noteworthy. In the SAVI metric, a development area of 11,453 m^2 was identified within the range of 0.2-0.3, while 51,627 m^2 fell within the range of 0.1-0.2. For the NDRE data, a significant area of 9,264 m^2 was found in the 0.2-0.3 range, and 53843 m^2 was identified in the 0.1-0.2 range (Figure 17). These findings suggest that plant growth is sustainable, with stress minimized during the initial stages and subsequent periods. However, the data for 2025 suggests that this development could not be maintained, leading to a return to stress conditions. In the maps presented in Figure 18, although scattered areas within the 0.1-0.2 range in SAVI, NDRE has reverted to the -1 to 0.1 range, with most of the area returning to a red color. This reflects how environmental factors, such as moisture or nutrient deficiencies towards the end of the season, adversely impact the production process.



2024 NDRE **2024 SAVI**

Figure 17. NDRE and SAVI changes for 2024



2025 NDRE **2025 SAVI**

Figure 18. NDRE and SAVI changes for 2025

Integrating NDRE and SAVI indices in this study has proven valuable for evaluating plant stress responses at distinct phenological stages in a semi-arid apple orchard. NDRE effectively captured variations in chlorophyll content and physiological activity during the late season. SAVI offered improved insights into early-stage growth under sparse canopy conditions by minimizing soil background effects (Peres & Cancelliere, 2021). The consistently low index values observed in 2020 and 2021 across both metrics reflected a complete absence of vegetative development, confirming severe stress likely caused by combined water and nutrient limitations. This finding aligns with earlier research that highlights the vulnerability of perennial fruit crops in water-limited systems, particularly during the establishment phase when root development is incomplete (Sellami et al., 2022).

Although limited, the improvement observed in 2022 indicates the early signs of physiological recovery, particularly in the eastern and western zones. This trend was especially evident in NDRE, which showed spatial clusters of medium stress levels (0.2–0.3), corroborating the use of red-edge indices as sensitive indicators of plant vitality under moderate stress conditions (Crespo et al., 2024; Anderson, 2024). However, the decline seen again in 2023 emphasizes the transitory nature of this recovery and the lack of consistency in soil-plant interaction management. These findings reflect broader trends reported in recent precision agriculture literature, suggesting that intermittent improvements in remote sensing indices may not lead to long-term productivity gains unless supported by stable irrigation and nutrient management regimes (Guimarães et al., 2024).

In contrast, 2024 marks the only year NDRE and SAVI values reached optimal levels across a substantial portion of the orchard, indicating synchronization between early vegetative growth and sustained physiological performance. The spatial expansion of medium-index zones in both maps demonstrates that multispectral monitoring of plant stress dynamics offers reliable spatiotemporal resolution for guiding agronomic decision-making (Carella et al., 2024). Nevertheless, the dramatic regression in 2025, particularly in NDRE, reinforces the need for continuous, multi-index-based stress monitoring. The findings emphasize that while NDRE and SAVI independently provide valuable insights, their combined use enhances the reliability of stress detection frameworks and supports more informed adaptive management in semi-arid orchard systems (Sharma et al., 2025).

3.4. Detection of Anomaly and Stress Periods

The interaction of various factors, including climatic variables, soil characteristics, and management practices, influences plant development in agricultural production systems. Some years may exhibit significant deviations (anomalies) or stress conditions regarding production potential within this complex structure. Remote sensing-based crop indices (NDVI, RVI, SAVI, NDRE, etc.) are highly sensitive to detect such periods. In this study, the periods of 2020 and 2023 are characterized by anomalies and stress conditions. Remote sensing data obtained in these years clearly show that environmental conditions significantly affect crop production during these periods.

2020 stands out as a period when low values were recorded in all NDVI, RVI, and SAVI data, and agricultural stress continued in the early development phase until the end of the season. RSM values below 0.1 indicate almost no moisture in the soil, while NDRE maps show that most of the area is between -1 and 0.1, indicating that plant growth does not occur during the season. The area classifications indicate that NDVI corresponds to the “Low” class (63107 m^2). RVI values are concentrated by a homogeneous distribution of red color tones in SAVI and NDRE, indicating widespread stress in both early and late plant performance. These findings, in agreement with the meteorological data, suggest that 2020 was a season of drought, and as a result, seed emergence and vegetative development were not adequately realized. Therefore, 2020 is considered a critical year with a high level of agro-stress anomaly in this study. Following a partial recovery in 2022, 2023 is notable for a decline in agricultural performance. Visual and quantitative data show decreased soil moisture and sparse vegetation cover. The NDVI value has returned to the “Low” class, and the entire area falls within this group. According to RSM data, the humidity level is below the critical threshold of 0.2.

Notably, this year's SAVI maps show almost no growth, while NDRE maps indicate limited areas (in the 0.2-0.3 band) with weak vegetation presence towards the end of the season. Radar reflections (RVI) are also weak, indicating a low leaf surface area. In this context, 2023 was below expectations, constituted a breaking point in sustainable production, and was recorded as an "anomaly" in this respect. This year's decline interrupted the recovery trend in 2022, creating instability in productivity.

2020 and 2023 are the years when stress levels are the highest and development is the weakest in terms of both plant health and soil conditions. These years stand out when minimum values are observed in all remote sensing-based indices, and production processes are interrupted by various environmental pressures. The combined evaluation of NDVI, RVI, SAVI, and NDRE proves to be an effective tool in the early detection of these anomaly periods and in determining the management measures to be taken in the following years.

Identifying 2020 and 2023 as anomaly and high-stress years underscores the importance of multi-index remote sensing in capturing both the timing and severity of agroecological disturbances. Over these years, the decline in NDVI, RVI, SAVI, and NDRE values indicates widespread physiological stress affecting early and late phenological stages. Notably, the RSM data falling below 0.1 in 2020 and under 0.2 in 2023 highlights critical soil moisture deficiencies that likely compromised seed emergence, vegetative development, and reproductive success (Sishodia et al., 2020). Such multi-dimensional remote sensing diagnostics enable early warning detection that surpasses the limitations of single-variable monitoring systems (Anderson, 2024). Similar applications have demonstrated that the simultaneous use of vegetation and moisture indices enhances spatial precision and enables rapid detection of stress zones in orchards and specialty crops under irregular climatic conditions (Peres & Cancelliere, 2021; Crespo et al., 2024).

The widespread low SAVI and NDRE values in both years, particularly the absence of medium or high zones, confirm that both early canopy development and end-of-season physiological vigor were suppressed, consistent with observations in drought-prone citrus and olive orchards (Sellami et al., 2022). The complete dominance of low NDVI in 2020 (100% of 63,107 m^2) and its reappearance in 2023 suggest an unsustainable production environment vulnerable to climatic shocks and agronomic mismanagement (Guimarães et al., 2024). These findings support broader conclusions regarding the importance of year-on-year anomaly tracking in preventing yield collapse and guiding adaptive strategies in perennial fruit systems (Sharma et al., 2025).

Thus, the combined use of spectral and radar indices offers a retrospective diagnosis of stress periods and a forward-looking decision-making tool. Integrating such a multi-index framework into orchard management systems could dramatically improve the resilience of tree-based agriculture against agroclimatic extremes.

3.5. Field-based Productive Development Trends

Plant indices such as NDVI, RVI, NDRE, and SAVI, derived from remote sensing technologies, are crucial in revealing spectral reflections and annual development levels per unit area. Analyses conducted between 2020 and 2025 indicated that trends in the productive development of apple orchards varied annually. Notably, areas classified within the "Medium" (0.2-0.4) and "High" (0.4-0.6) ranges of the NDVI classification serve as direct indicators of plant health and development intensity. Likewise, thresholds of RVI ≥ 0.3, NDRE ≥ 0.2, and SAVI ≥ 0.2 were established as criteria for assessing productive development. Annual comparisons of all these indices were converted into hectares and organized into tabulated forms (Table 2).

Table 2. Productive development areas (ha)

Year	*NDVI (≥0.2) [ha]*	*RVI (≥0.3) [ha]*	*SAVI (≥0.2) [ha]*	*NDRE (≥0.2) [ha]*
2020	0	0	0	0
2021	0	0	0	0
2022	0,65	0,21	1,15	0,93
2023	0	0	0	0,09
2024	6,2	2,58	6,26	2,93
2025	0	0	1,84	0

In 2020 and 2021, no areas exhibited productive development across all plant indices. This period is characterized by significant stress due to inadequate soil moisture and poor vegetative growth. In 2022, a modest yet positive shift was observed in the NDVI and NDRE data, with the SAVI value reaching 1.15 hectares, indicating the onset of partial plant development at the beginning of the season. However, this improvement could not be maintained in 2023, when development began to decline once more, and only 0.09 hectares in the NDRE category could be classified as productive; development nearly ceased across all other indices.

The year 2024 marked the peak of growth across all indices. For NDVI, 6.2 hectares achieved values above 0.2; the highest spectral reflections in RVI and NDRE were recorded this year. The increase in SAVI data to 6.26 hectares signals that optimal development was reached early in the season and at its conclusion. By 2025, the SAVI value decreased to 1.84 hectares, with no areas identified in the productive class for NDVI, RVI, and NDRE. This suggests a decline in plant growth, likely due to moisture deficiencies or management shortcomings by the end of the season.

According to the annual hectare-based analysis, 2024 represented the year with the largest productive areas in the apple orchard during both the early and late development periods. In contrast, 2020, 2021, and 2023 were marked by high stress levels, with virtually no productive development. The combination of SAVI and NDRE data provided a reliable framework for monitoring in-season development, while NDVI and RVI illustrated these dynamics at the field level. In this context, hectare/year analyses based on remote sensing indices lay a robust foundation for assessing past productivity and planning for future production.

The annual hectare-based analysis of NDVI, RVI, SAVI, and NDRE indices from 2020 to 2025 reveals the interannual variability in plant performance and the value of multi-index frameworks in quantifying spatial productivity across phenological stages. The absence of productive areas in 2020, 2021, and 2023 confirms the system's high sensitivity to stress, particularly soil moisture deficiencies, which aligns with earlier studies highlighting that remote sensing indices are reliable indicators of vegetative suppression under drought stress (Sishodia et al., 2020). The modest improvements observed in 2022—especially in SAVI and NDRE—suggest partial canopy development and a return of photosynthetic activity, consistent with previous reports noting that red-edge indices effectively detect early physiological recovery (Sellami et al., 2022).

2024 represents a turning point, with concurrent increases across all indices, reaching 6.2 ha in NDVI, 6.26 ha in SAVI, and 2.93 ha in NDRE, signaling optimum productivity from early growth through maturation. This finding supports the growing consensus that combining structure-sensitive indices, such as RVI, with chlorophyll-related metrics, like NDRE, yields a more comprehensive depiction of plant health and vigor across seasons (Guimarães et al., 2024; Carella et al., 2024). By contrast, the regression observed in 2025, where productive zones nearly vanished except for a residual 1.84 ha in SAVI, illustrates the fragility of gains made without sustained management or favorable climatic conditions.

Moreover, the data reinforce that using hectare-level thresholds in remote sensing strengthens the spatial resolution of productivity assessments and provides an empirical foundation for yield forecasting and adaptive resource allocation (Berry et al., 2024). When integrated into decision-support platforms, such metrics can enable orchard managers to retrospectively analyze growth patterns while proactively tailoring inputs in future seasons (Sharma et al., 2025). In this context, NDRE and SAVI appear especially promising as in-season monitoring tools, while NDVI and RVI offer complementary field-level validation of development dynamics.

Despite the observed fluctuations in NDVI and other vegetation indices over the six years, it is essential to consider the structural characteristics of the orchard that may have influenced spectral responses, particularly during the early seasons. The young apple trees in the study area had minimal canopy cover, and large inter-row spacing (~10 m) led to significant soil exposure, resulting in a dominant soil background reflectance in satellite pixels. This phenomenon has been previously identified as a limitation in remote sensing of perennial crops in their juvenile phase (Crespo et al., 2024; Sharma et al., 2025).

To mitigate these effects, the study incorporated SAVI and radar-based indices (RVI, RSM), which are better suited to sparse vegetation conditions and less sensitive to soil reflectance. The convergence of results across SAVI, NDRE, and radar indices in later years (particularly 2024) supports the validity of the multi-index framework even under initial spectral dilution. These adaptations align with precision agriculture practices recommended for orchard monitoring under sparse canopy conditions (Guimarães et al., 2024). The future use of high-resolution UAV imagery or crown-based object detection is recommended to enhance early-stage vegetation discrimination and improve pixel-level accuracy.

3.6. Future Research

This study demonstrated the effectiveness of integrating spectral and radar-based vegetation and soil moisture indices for monitoring plant development and stress dynamics in a semi-arid apple orchard. While the findings offer significant insights, several key areas remain for future research. First, extending the scope of the analysis to include real-time meteorological data (e.g., precipitation, vapor pressure deficit, and solar radiation) could improve the predictive accuracy of vegetation response models. Integrating multi-source environmental data with remote sensing outputs would enable more robust forecasting of anomaly events and crop yield.

Second, the current study utilized threshold-based classification for index interpretation; however, machine learning or deep learning models (e.g., Random Forest, LSTM, CNN) could be developed to automate the identification of spatial and temporal stress patterns. These approaches may provide higher-resolution decision support and adaptively respond to inter-seasonal variability.

Third, future studies should investigate the scalability and transferability of the proposed index-based monitoring framework across various crop types, soil textures, and agroclimatic zones. The generalizability of NDRE and SAVI as indicators of early- and late-season stress in other perennial systems, such as vineyards, citrus, or olive groves, remains an open research avenue.

Moreover, coupling UAV-based hyperspectral and thermal imagery with satellite data may bridge the spatial resolution gap and enhance field-level precision, particularly in intra-orchard zone classification. Integrating economic and agronomic outcomes, such as cost-benefit analyses of irrigation optimization based on remote sensing, could provide stakeholders with practical implementation pathways. Future studies should consider UAV-based imagery or high-resolution satellites (e.g., PlanetScope) to isolate tree crowns using object-based classification. This would allow precise masking of non-canopy areas, significantly improving index fidelity. Such approaches have also been recommended by Sharma et al. (2025) and Guimarães et al. (2024), particularly for orchard systems with sparse early-stage canopies and heterogeneous stress patterns.

A key limitation of this study is the absence of recorded field-level irrigation volumes and schedules, which would have allowed for a more detailed correlation analysis between RSM values and irrigation events. Future studies are recommended to integrate soil moisture probes and irrigation logs to enhance the interpretation of radar-based indices. This gap is frequently cited in the literature as a significant challenge in remote-sensing-based soil moisture assessment frameworks (Duarte et al., 2025; Sishodia et al., 2020). Integrating meteorological data, such as precipitation, temperature, and vapor pressure deficit (VPD), with RSM and RVI indices would enable a more robust temporal interpretation of soil–plant–climate interactions across phenological stages. Future studies should consider UAV-based imagery or high-resolution satellites (e.g., PlanetScope) to isolate tree crowns using object-based classification. This would allow precise masking of non-canopy areas, significantly improving index fidelity. Integrating meteorological data, such as precipitation, temperature, and vapor pressure deficit (VPD), with RSM and RVI indices would enable a more robust temporal interpretation of soil–plant–climate interactions across phenological stages. Such integration strategies have also been advocated by recent studies, which utilize multispectral and thermal UAV imagery in conjunction with VPD and weather station data to enhance water stress diagnostics (Mali et al., 2025).

Lastly, future work should investigate the development of cloud-based platforms or mobile applications capable of translating multi-index remote sensing data into real-time advisory tools for growers and irrigation managers. Such advancements would reinforce the transition from observational monitoring to actionable, site-specific agricultural intelligence.

4. CONCLUSION

Based on the findings from the six-year (2020–2025) analysis of satellite-derived vegetation and moisture indices in a drip-irrigated apple orchard:

- 2020 and 2023 were identified as high-stress anomaly years, with all indices (NDVI, RVI, SAVI, NDRE, RSM) indicating minimal vegetation cover and severe soil moisture deficits.
- 2024 emerged as the most productive year, with over 44% of the orchard area classified in medium to high NDVI zones, and SAVI and NDRE confirming early and late-season physiological performance.
- SAVI and NDRE proved to be complementary indicators for detecting seasonal stress dynamics, offering more substantial resolution in early (SAVI) and late (NDRE) development stages.
- Radar and spectral index integration revealed strong correlations, particularly between RSM, RVI, and NDVI ($r \approx 0.99$), reinforcing the use of multi-index frameworks in soil-plant diagnostics.
- Productive zone mapping based on hectare thresholds (e.g., NDVI ≥ 0.2, RVI ≥ 0.3) provided field-scale insights valuable for retrospective yield assessment and future irrigation planning.
- The lack of sustainability observed in 2025, following the peak in 2024, highlighted the vulnerability of current practices and the need for continuous, adaptive management strategies.

- Multi-index analysis enabled precise identification of temporal anomalies and spatial variability, offering a replicable methodology for other perennial cropping systems in water-limited environments.

Artificial Intelligence Declaration

The author gratefully acknowledges the use of ChatGPT for grammatical and linguistic enhancement during the preparation of this manuscript. After utilizing these tools, they reviewed and edited the content as needed and accepted full responsibility for the content of the publication.

REFERENCES

Anderson, K. (2024). Detecting environmental stress in agriculture using satellite imagery and spectral indices. (Doctoral dissertation, Obafemi Awolowo University). https://www.researchgate.net/publication/378122204

Berry, A., Vivier, M. A., & Poblete-Echeverría, C. (2024). Evaluation of canopy fraction-based vegetation indices, derived from multispectral UAV imagery, to map sensor status variability in a commercial vineyard. *Irrigation Science, 43, 135-153*. https://doi.org/10.1007/s00271-023-00907-1

Carella, A., Bulacio Fischer, P. T., Massenti, R., & Lo Bianco, R. (2024). Continuous plant-based and remote sensing for the determination of fruit tree water status. *Horticulturae*, 10(5), 516. https://doi.org/10.3390/horticulturae10050516

Crespo, N., Pádua, L., Santos, J. A., & Fraga, H. (2024). Satellite remote sensing tools for drought assessment in vineyards and olive orchards: A systematic review. *Remote Sensing,* 16(11), 2040. https://doi.org/10.3390/rs16112040

Dong, H., Dong, J., Sun, S., Bai, T., Zhao, D., & Yin, Y. (2024). Crop water stress detection based on UAV remote sensing systems. *Agricultural Water Management*, *303*, 109059. https://doi.org/10.1016/j.agwat.2024.108259

Duarte, E., & Hernandez, A. (2024). A review on soil moisture dynamics monitoring in semi-arid ecosystems: Methods, techniques, and tools applied at different scales. *Applied Sciences,* 14(17), 7677. https://doi.org/10.3390/app14177677

Gaznayee, H. A. A., Zaki, S. H., & Al-Quraishi, A. M. F. (2023). Integrating remote sensing techniques and meteorological data to assess the ideal irrigation system performance scenarios for improving crop productivity. *Water,* 15(8), 1605. https://doi.org/10.3390/w15081605

Guimarães, N., Sousa, J. J., Pádua, L., Bento, A., & Couto, P. (2024). Remote sensing applications in almond orchards: A comprehensive systematic review of current insights, research gaps, and prospects. *Applied Sciences,* 14(5), 1749. https://doi.org/10.3390/app14051749

Hasan, S. S., Alharbi, O. A., Alqurashi, A. F., & Fahil, A. S. (2024). Assessment of desertification dynamics in arid coastal areas by integrating remote sensing data and statistical techniques. *Sustainability,* 16(11), 4527. https://www.mdpi.com/2071-1050/16/11/4527

Hu, X., Li, L., Huang, J., Zeng, Y., Zhang, S., & Su, Y. (2024). Radar Vegetation Indices for Monitoring Surface Vegetation: Developments, Challenges, and Trends. *Science of the Total Environment,* 921, 170854. https://doi.org/10.1016/j.scitotenv.2024.170854

Huete, A. R. (1988). A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment, 25*(3), 295–309. https://doi.org/10.1016/0034-4257(88)90106-X

Ippolito, M. (2023). Assessing crop water requirements and irrigation scheduling at different spatial scales in Mediterranean orchards using models, proximal and remotely sensed data (Doctoral dissertation). *Italian National Repository.* https://tesidottorato.depositolegale.it/handle/20.500.14242/172965

Kaya, P. D. S. N., & Öztürk, R. E. (n.d.). Soil quality and vegetation index assessments for rice and wheat cultivations: A review. ResearchGate Preprint. https://www.researchgate.net/publication/376851588

Lakhiar, I. A., Yan, H., Zhang, C., Wang, G., He, B., & Hao, B. (2024). A review of precision irrigation water-saving technology under a changing climate for enhancing water use efficiency, crop yield, and environmental footprints. *Agriculture*, *14*(7), 1141.

Mali, S. S., Scobie, M., Baillie, J., Plant, C., & Shammi, S. (2025). Integrating UAV-based multispectral and thermal infrared imagery with machine learning for predicting water stress in winter wheat. *Precision Agriculture*, 26(3), 44. https://link.springer.com/article/10.1007/s11119-025-10239-z

Nalçaoğlu, Ç., Nalçaoğlu, D. H., Doğru, A. & Yaprak, S. (2025). Predicting olive yield in Mediterranean climate zones of Türkiye using remote sensing and artificial neural networks: A case study of Muğla Province. Preprints. https://www.preprints.org/frontend/manuscript/7b9ac7d093830875cf265d810cec131a/download_pub

Odi-Lara, M., Campos, I., Neale, C. M. U., & Ortega-Farías, S. (2016). Estimating evapotranspiration of an apple orchard using a remote sensing-based soil water balance. *Remote Sensing,* 8(3), 253.

Peres, D. J., & Cancelliere, A. (2021). Analysis of multi-spectral images acquired by UAVs to monitor water stress of citrus orchards in Sicily, Italy. In World Environmental and Water Resources Congress 2021 (pp. 251–260). https://doi.org/10.1061/9780784483466.025

Pradipta, A., Soupios, P., Kourgialas, N., Doula, M., & Dokou, Z. (2022). Remote sensing, geophysics, and modeling to support precision agriculture—Part 2: Irrigation management. *Water,* 14(7), 1157. https://doi.org/10.3390/w14071157

Sellami, M. H., Albrizio, R., Čolović, M., & Hamze, M. (2022). Selection of hyperspectral vegetation indices for monitoring yield and physiological response in sweet maize under different water and nitrogen availability. *Agronomy,* 12(2), 489. https://doi.org/10.3390/agronomy12020489

Sharma, H., Sidhu, H., & Bhowmik, A. (2025). Remote sensing using uncrewed aerial vehicles for water stress detection: A review focusing on specialty crops. *Drones,* 9(4), 241. https://doi.org/10.3390/drones9040241

Sillero-Medina, J. A., & González-Pérez, J. (2025). Deficit irrigation regimens on soil moisture, production parameters of mango (Mangifera indica L.), and spectral vegetation indices in the Mediterranean region. *Heliyon,* 11, e2799. https://www.sciencedirect.com/science/article/pii/S2352938524002799

Sishodia, R. P., Ray, R. L., & Singh, S. K. (2020). Applications of remote sensing in precision agriculture: A review. *Remote Sensing,* 12(19), 3136. https://www.mdpi.com/2072-4292/12/19/3136

Stagakis, S., González-Dugo, V., & Cid, P. (2012). Monitoring water stress and fruit quality in an orange orchard under regulated deficit irrigation using narrow-band structural and physiological remote sensing indices. *ISPRS Journal of Photogrammetry and Remote Sensing,* 71, 47–61. https://doi.org/10.1016/j.isprsjprs.2012.05.002

Yang, X., Gao, F., Yuan, H., & Cao, X. (2024). Integrated UAV and satellite multi-spectral for agricultural drought monitoring of winter wheat in the seedling stage. *Sensors,* 24(17), 5715. https://doi.org/10.3390/s24175715

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Research Assistant Alperay ALTIKAT was born in Erzurum in 1997. He completed his undergraduate studies in 2020 at Atatürk University, Faculty of Agriculture, Department of Field Crops. In 2021, he earned his master's degree at Iğdır University, Institute of Natural Sciences, Department of Biosystems Engineering. He started his doctoral studies the same year and is currently continuing his research at the Department of Biosystems Engineering, Graduate School of Science, Iğdır University. Since 2023, he has worked as a Research Assistant in the Department of Horticulture, Faculty of Agriculture, Iğdır University. His areas of expertise include biochar production and application, artificial intelligence, hyperspectral imaging, renewable energy technologies in agriculture, and closed plant production systems. In this role, he has served as both a project leader and researcher in funded projects at the national and international levels and has published numerous scientific articles, book chapters, and conference papers.

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