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Yield characteristics and environmental effects of plastic covers on table grape with relation to chemical, physical, radiometric and satellite analyses

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Abstract. Climate change poses a significant challenge for global viticulture, with growing evidence of its negative impact on thermal and hydric regimes, both of which are essential for the development of table grapes. The use of plastic covering in vineyards is a widespread technique aimed at protecting both vegetation and grapes from external factors. The covering modifies the microclimate and allows the extension of the harvest period by advancing or delaying grape ripening. This study investigates the effects of six different plastic films on table grapes using a multidisciplinary approach integrating chemical, physical, radiometric and satellite analyses. The study was conducted in 2024 in a commercial vineyard located in the countryside of Noicattaro in the Apulia region (Italy). Each plastic film had a different chemical composition, with specific spectral behaviour in terms of light transmission, reflection and absorption. The minimum and maximum temperatures, together with the relative humidity, were recorded for each plastic film to evaluate the environmental and production effects. Regarding the production results, significant differences were recorded in the case of the production parameter per plant (kg*vine) and, above all, in the case of total solid soluble per plant (TSS*vine). This last parameter, obtained from the product between the total concentration of sugars (°Brix) and the yield (kg*vine), reflects the real physiological conditions experienced by the plants. It varied from a maximum of 5.6 kg to a minimum of 3.3 kg, for the best and worst conditions respectively. These parameters, as well as other properties such as rheological and colorimetric features (CIE-Lab) were evaluated with significant differences. Continuous temperature and relative humidity measurements were recorded under the plastic films, giving the possibility to reconstruct the number of hours during which the temperature exceeded the physiological threshold of 35 °C. The results showed that the temperature increase was significantly greater with the warmest plastic cover, with 162 threshold exceedance events, while with the coolest cover, the threshold was exceeded only 3 times. This highlights the significant influence of the type of plastic on the heating of the underlying environment. The highest TSS value of 17 °Brix was recorded under the coolest condition, where the physiological threshold of 35 °C was exceeded only 3 times. The Sentinel-2 satellite played a crucial role in monitoring NDVI dynamics throughout the entire growth cycle, with specific corrections applied to minimize spectral interference caused by the plastic films.

1. Introduction

At the start of the table grape growth cycle, plastic films are used to protect the vines from rain and moisture. It is crucial that the radiometric properties of these films do not cause environmental stress. This condition is especially critical for the new table grape varieties recently introduced on the market.

Market demand for these novel varieties is high due to their favourable morphological characteristics, like their high firmness. However, this particular aspect makes these grapes susceptible to cracking in the presence of high relative humidity or rainfall. Thus, the importance of moisture and humidity control in the vineyard. Moreover, it is worth noting that, even though some of these varieties are mid-ripen ones, it could be more useful to induce earlier ripening and manage them as if they were early varieties. In fact, the earlier the harvest, the lower the chances of encountering high humidity or rainfall, which are most prevalent in September and October. It is therefore of key importance the choice of an adequate plastic film which determines the levels of sun radiation absorbed, transmitted or reflected, that influences the vineyard environment [1-2].

To allow the berries to ripen as soon as possible, it may be necessary to use commercially available films designed for varieties with a short growing cycle, such as earlier maturing varieties. Several types of plastic films are already on the market. However, these films are not always suitable for this purpose. The most critical issue is that these films are designed to produce the greatest amount of heat for the earliest possible precocity. In these cases, the vines usually experience physiological stress due to high temperatures.

Furthermore, for the earlier varieties, a recovery period generally occurs after the harvest starting from the end of June. In fact, from June onwards, the vines have the opportunity to replenish their energy and reserve compounds because the plastic films have been removed from the vineyard. Until October, the vines are not subject to any kind of stress, especially excessive heat. During this period, they are in the best possible conditions: they are well irrigated, have full access to natural light, do not have to produce fruits and have the right environmental temperature to complete important processes such as shoot lignification.

However, it is worth noting that this kind of compensation is not achievable for a mid-term variety, because, for this, the period from July to October is not a resting phase but a physiological phase coinciding with the ripening of the grapes. Furthermore, the plastic film remains over the vines, continuing to absorb energy from the sun. Under these conditions, films used for early variety management should not be applied, due to radiation loss and, worse, to thermal stress. The aim of this study was to contribute to the search for plastic films with the best radiometric properties to cultivate a mid-term variety. Therefore, data such as yield, color, crunchiness, flesh consistency, and chromatic characteristics were measured and compared for a white mid-ripening grape variety cultivated under six different plastic films.

In this study, remote sensing technology was employed as a non-destructive technique that allows a continuous evaluation of crop health, vigour and water status under the different plastic films.

This technology has become essential for monitoring agricultural systems and vegetation indices, particularly the Normalized Difference Vegetation Index (NDVI) [3–4] which is calculated using satellite data.

Among the available platforms, the Sentinel-2 mission, developed by the European Space Agency (ESA) as part of the Copernicus Program, plays a pivotal role in precision agriculture thanks to its advanced optical capabilities [5].

However, it is known that plastic materials introduce spectral interference due to their wavelength-dependent reflectance and transmittance, as well as potential scattering effects. Consequently, the satellite signal is modified before reaching the sensor, which makes it difficult to retrieve accurate vegetation information. Specific correction methodologies have therefore been tested to correct the satellite information.

2. Materials and methods

2.1. Field conditions

Each plastic film had a different chemical composition, with specific spectral behaviour in terms of light transmission, reflection and absorption. The minimum and maximum temperatures, together with the relative humidity, were recorded for each plastic film to evaluate the environmental and production effects. The study was carried out on the seedless table grape variety Autumn Crisp® in 2024 in a commercial vineyard located in southern Italy, (Puglia region, 223 m a.s.l.). After bud break in the last week of March, the vineyard was covered with six different types of commercial plastic sheets, T1, T2, T3, T4, T5 and T6, with thickness ranging from 135 µm to 195 µm.

To limit as much as possible, the influence on the atmosphere underneath the different films, especially the temperatures and the light interference, four replicates were planned for each film. The plots were composed by 5 adjacent rows, 12.5 m wide and 60 m long, with row and vine spacing of 2.5 m x 2,5 m, for a total area of 750 m^2.

The films covered the experimental plots continuously throughout the flowering, veraison and ripening stages until harvest. The harvest was performed on the 4th of October when approximately 20 kg of grapes were collected from each replicate. From each of these quantities, a sample of 16 bunches (four for each replicate) were randomly selected for yield and technological parameters measurement. Texture analysis and color analysis (CIE Lab coordinates) were performed on 5 and 10 berries per replicate, respectively.

2.2. Spectro radiometric measurements on plastic films

Measurements were taken on several 2 x 2 cm film fragments. Prior to measurement, each fragment underwent a cleaning process consisting of 30 minutes of washing in 100 ml of water and 1 ml of Decon Contrad 70 Liquid Detergent (Thermo Fisher Scientific) in an ultrasonic bath. The film was rinsed for approximately 1 minute in a flow of water and then immersed in 100 ml of water in an ultrasonic bath for 15 minutes. The water used in the cleaning process was deionized-water, obtained from a Millipore Milli-Q system (Aldrich). Then, films were dried in a flow of nitrogen. Each spectrum acquired was the result of 10 successive accumulations, so that the result was not influenced by extemporaneous fluctuations. The transmittance and reflectance spectra at normal incident light was acquired using a double beam UV-VIS-NIR spectrophotometer (Varian Cary 5) in the range of 200 -1500 nm, with a data interval of 1 nm and a scan rate of 600 nm/min. Reflectance measurements were performed by using an integrating sphere. All the analyzed spectra were recorded with the zero line/baseline correction. Two kinds of lamps, a Deuterium for measurement in the ultraviolet range and a tungsten lamp for measurement in the visible and near-infrared ranges, are used as the light sources of a spectrophotometer.

2.3. Yield parameters

At harvesting, the vine yield (kg*vine^{-1}) was determined by averaging the yield of 16 vines (4 per replicate). The average cluster weight was obtained by weighing 40 clusters (10 for replicate picking at the same position along the fruit cane). Berry weight was determined from 160 berries. All picked clusters per replicate were completely destemmed and samples were used to average the berry weight using a technical balance (OHAUS Corporation-USA mod: NVL2101/2)

2.4. Texture measurements

The rheological characteristics of the berries were tested using the Zwick/Roell brand Texture Analyzer mod. BT1-FR0.5TND14 (Zwick GmbH & Co.Gk - August-Nagel-Strasse 11), equipped with a compression load cell with a nominal force of 500 N. The following parameters were determined:

- Berry Hardness (N): maximum force value during the first compression cycle;
- Berry Cohesiveness (-): strength of internal bonds that "reform" the berry structure;
- Berry Springiness (mm): height that the berry recovers during the time between the end of the first cycle and the beginning of the second;
- Berry Gumminess (N): energy required to disintegrate a semisolid food (berry) until it is ready for swallowing;
- Berry Chewiness (mJ): energy required to chew a solid food (berry) until it is ready for swallowing.

2.5. CIEL*a*b color measurements

Color is one of the most important characteristics of skin for table grape cultivars. From the visible spectrum for each berry the CIE Lab color coordinates: L* (lightness, ranging from 0 to 100), a* (values ranging from reddish when positive to greenish when negative), b* (values ranging from yellow when positive to blue when negative), were calculated. Standard illuminant C was utilized as the reference. CM-5 - Konica Minolta Corp. Spectro-photometer was used to collect visible spectra of all the berries between 360 and 740 nm. Color data were provided as CIELab coordinates, which define the color according to a three-dimensional space.

2.6. Thermal measurements

A total of 18 weather stations continuously recorded temperature and relative humidity at hourly intervals. Each plastic cover was investigated using n.3 Watch Dog stations, installed in the following positions, on the same plant, at the center of the row:

- Over the canopy (TOP),
- Near the canopy (CANOPY),
- Near the soil (SOIL).

The thermal data were classified in daytime and nighttime (sunrise and sunset in function of the position of the vineyard and corrected astronomically).

2.7. Satellite Data Acquisition and Processing

In this study, we developed a Python-based tool to automate the retrieval of Sentinel-2 imagery from the Copernicus Data Space Ecosystem, using the OpenEO API. To enhance the reliability of the analysis, a filtering procedure was implemented to retain only high-quality, atmospherically consistent data, thereby improving the robustness and accuracy of vegetation indices such as NDVI. Laboratory measurements of reflectance and transmittance spectra were used to isolate the true vegetative signal by accounting for spectral distortions introduced by plastic covers. Correction factors, specific to each type of plastic film and spectral band, were applied to ensure accurate NDVI computation and to mitigate potential overestimation or underestimation of vegetation signals caused by the plastic films. For each film type, pixel-level reflectance data were extracted and analyzed across selected Sentinel-2 spectral bands: Red (B04, 665 nm) and Near-Infrared (B08, 842 nm).

2.8. Statistical Analysis

The comparison of the means at harvest was performed using a one-way ANOVA, followed by Tukey's post-hoc test ($p < 0.05$) using the Origin Pro Software 2024a. In all the tables the p-level was employed for calculating statistical significance, which was indicated by a star in bold when $p \leq 0.05$.

3. Results and discussion

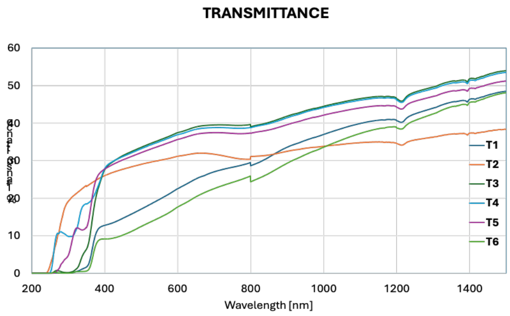
3.1. Spectro radiometric results

The Spectro-radiometric analysis of the plastic films showed distinct film sheet typologies (Figure 1). In the UV bands T6 T3 and T1 were characterized by the lowest transmittance, whilst T4 and T5 demonstrated the highest ones. In the visible spectrum T3 and T4 showed the highest transmittance and T2 the lowest. Intermediate behavior was shown by T1 and T6. About reflectance, it was observed that T6, T5, T3 and T1 exhibited the lowest reflectance and the T4 and T2 the highest. In relation to the visible spectrum T2, T6 and T1 represented the film with the highest reflectance and the T4, T5 and the T3 the film with the lowest.

3.2. Yield

The yield parameters and fruit composition of the mid-term ripening variety, Autumn Crisp®, were subjected to analysis. The variety exhibited varied responses regarding yield parameters as a consequence of the film sheets covering. At harvest (4th October), Autumn Crisp® displayed (Table 1) considerable differences in yield and total soluble solids per vine (TSS*vine). The yield was found to be significantly lower for T1 (22.45 kg*vine) T5 (28.88 kg*vine) and T6 (28.70 kg*vine) compared to the highest yield observed in T4 (33.54 kg*vine) T2 (33.42 kg*vine) and T3 (31.29 kg*vine).

A



B

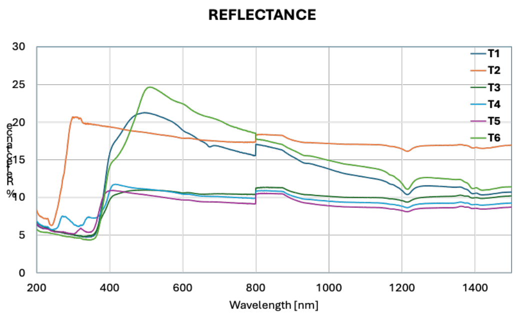


Figure 1. Transmittance (A) and reflectance (B) comparison of the six plastic films.

Table 1. Autumn Crisp® - Yield parameters of grapes.

Plastic cover	Variables		
	Yield * vine (kg)	TSS * vine (kg)	Yield * Ha (t)
T1	22.45 (6.88) b	3.58 (0.94) b	35.92 (11.01) b
T2	33.42 (6.0) a	5.23 (0.94) ab	53.47 (9.61) a
T3	31.29 (8.63) a	5.28 (1.45) ab	50.06 (13.81) a
T4	33.54 (9.48) a	5.66 (1.60) a	53.67 (15.17) a
T5	28.88 (7.74) ab	4.33 (1.16) b	46.21 (12.39) ab
T6	28.70 (6.66) ab	4.47 (1.04) b	45.93 (10.66) ab
p	*	*	n.s.

Different letters among means and SD values (in brackets) in the same column indicate significant differences at $p < 0.05$.

Also, these last films were found to significantly increase the TSS per vine; T2 (5.23 TSS*vine) T3 (5.28 TSS*vine) and T4 (5.66 TSS*vine) (Table 1). Among the films with the best results in TSS per vine, the best bunch weights (Table 2) were observed in T4 (845.07 g) and T2 (930.59 g). The T3 and T4 plastic film was confirmed to perform better also in the case of the TSS level which was 16.9 and 16.87 °Brix respectively (Table 3).

Table 2. Autumn Crisp® - Morphologic parameters of grapes.

Plastic cover	Variables		
	Bunch weight (g)	Berry weight (g)	Rachis weight (g)
T1	732.06 (282.55) b	11.37 (1.28) a	12.80 (6.06) b
T2	930.99 (236.74) a	11.51 (0.87) a	14.68 (4.78) ab
T3	787.68 (201.50) b	11.05 (1.54) a	13.46 (4.14) ab
T4	845.07 (258.11) ab	9.70 (1.77) b	15.81 (5.92) a
T5	870.05 (285.11) ab	10.78 (1.51) a	17.06 (5.63) a
T6	753.48 (287.54) b	11.23 (1.66) a	13.71 (4.67) ab
p	*	*	*

Different letters among means and SD values (in brackets) in the same column indicate significant differences at $p < 0.05$.

Table 3. Autumn Crisp® - Organoleptic parameters of grapes.

Plastic cover	Variables		
	TSS (°Brix)	Titratable acidity (g/L)	pH
T1	15.95 (1.57) ^{ab}	3.88 (0.10) ^{b}	3.91 (0.14)
T2	15.65 (0.17) ^{ab}	4.15 (0.25) ^{b}	3.91 (0.07)
T3	16.9 (0.98) ^{a}	4.75 (0.74) ^{b}	3.87 (0.07)
T4	16.87 (0.45) ^{a}	4.94 (0.74) ^{b}	3.97 (0.10)
T5	15.0 (1.38) ^{b}	5.02 (0.75) ^{a}	3.91 (0.18)
T6	15.6 (0.28) ^{ab}	4.93 (0.92) ^{ab}	3.90 (0.04) ^{ab}
p	*	*	n.s.

Different letters among means and SD values (in brackets) in the same column indicate significant differences at $p < 0.05$.

3.3. Texture analysis

Berry weight plays a more important role for some texture parameters (Table 4) and seems to be positively related to hardness [6].

Table 4. Autumn Crisp® - Texture analysis of grapes.

Texture variables	Plastic cover						
	T1	T2	T3	T4	T5	T6	p
Springiness (mm)	3.08 (0.28) ^{a}	3.05 (0.19) ^{a}	3.01 (0.31) ^{ab}	2.98 (018) ^{ab}	3.08 (0.27) ^{a}	2.91 (0.25) ^{b}	*
Gumminess (N)	14.82 (4.87) ^{a}	12.94 (2.80) ^{b}	12.80 (2.45) ^{b}	14.40 (3.80) ^{ab}	12.91 (4.29) ^{b}	114.92 (3.79) ^{a}	*
Chewiness (mJ)	46.03 (16.09) ^{a}	39.38 (8.34) ^{b}	38.88 (9.72) ^{b}	42.94 (10.90) ^{ab}	39.54 (12.46) ^{b}	43.59 (11.39) ^{ab}	*
Cohesiveness (-)	0.44 (0.08) ^{a}	0.40 (0.05) ^{b}	0.42 (0.07) ^{ab}	0.43 (0.06) ^{a}	0.42 (0.06) ^{ab}	0.42 (0.05) ^{ab}	*
Hardness (N)	34.12 (10.31) ^{ab}	31.05 (9.60) ^{bc}	30.26 (55.60) ^{c}	33.04 (7.26) ^{abc}	29.78 (7.27) ^{c}	35.28 (7.48) ^{a}	*

Different letters among means and SD values (in brackets) in the same rows indicate significant differences at $p < 0.05$.

This was true for T3, T6 and T1, which had some of the highest berry weight values in the presence of some of the highest hardness values. In these cases, only higher hardness was supported by higher berry weight. By contrast, it seems that, for T4, hardness was linked to TSS levels rather than berry weight. These contrasting relationships between berry weight and firmness could be explained by the characteristics of the Autumn Crisp® cultivar, which naturally has a very high firmness value ranging from 29.78 N to 35.28 N.

3.4. Color parameters

The different plastic sheets appeared to exert a valuable and interesting influence on the color parameters of the berries (Table 5). At the harvest it was observed that the T4 had a notable impact on the L* parameter, when compared to all the remaining plastic films that all showed lower values in L* parameter and consequently a lower glimmer effect of the skin.

Table 5. Difference among film plastic on color measurement of grapes at harvest on Autumn Crisp®.

Plastic cover	Cie-Lab Color		
	L *	a *	b *
T1	44.94 (2.61) ^{a}	-3.43 (0.48) ^{ab}	11.20 (11.69) ^{ab}
T2	43.83 (2.35) ^{b}	-3.51 (0.38) ^{a}	10.92 (1.38) ^{ab}
T3	43.38 (2.64) ^{b}	-3.23 (0.44) ^{c}	10.58 (1.78) ^{b}
T4	44.25 (1.90) ^{a}	-3.45 (0.40) ^{ab}	11.00 (1.90) ^{ab}
T5	43.87 (2.12) ^{b}	-3.59 (0.44) ^{a}	11.54 (1.87) ^{a}
T6	43.73 (2.65) ^{b}	-3.32 (0.37) ^{bc}	10.64 (1.37)
p	*	**	*

Different letters among means and SD values (in brackets) in the same column indicate significant differences at $p < 0.05$.

Regarding the a* parameter, all the T1, T2, T4 and T5 were similar, with a more greenish effect, and only the T3 plastic film was different, inducing a more notable reddish effect on the skin. Similarly to the a* parameter, it appears that a consistent group of films was linked to higher b* values (T1, T2, T4 and T5), as there were no differences between them. Only T6 can be considered statistically different, showing the lowest value (10.64) for the b* parameter.

3.5. Thermal results

The number of hours during which the temperature exceeded the 35 °C threshold (T > 35 °C) varied significantly according to the type of plastic cover used (Table 6). The highest number of exceedances was recorded under T5 (162 hours), indicating a pronounced heating effect. In contrast, T2 exhibited the lowest number, with only 3 occurrences, suggesting it offered the best thermal protection. The other covers showed intermediate values: T4 (15), T3 (11), T6 (10), and T1 (8). These findings underscore the strong influence of plastic film type on the vineyard microclimate, particularly regarding thermal stress.

Table 6. Number of hours with temperature above 35 °C under different plastic films.

Plastic cover	[Hours] T > 35 [°C]
T1	8
T2	3
T3	11
T4	15
T5	162
T6	10

3.6. Satellite results

As previously mentioned, the NDVI was investigated as a possible indicator of the physiological state of vines under different conditions induced by plastic films. To successfully eliminate the interference caused by the plastic films, applying film-specific reflectance correction significantly improved the reliability of the vegetation indices retrieved from Sentinel-2 imagery.

This innovative method enabled more accurate discrimination of canopy health, vigour and water content in covered cropping systems, such as vineyards. For each plastic film, the vegetation index NDVI was reconstructed (Figure 2).

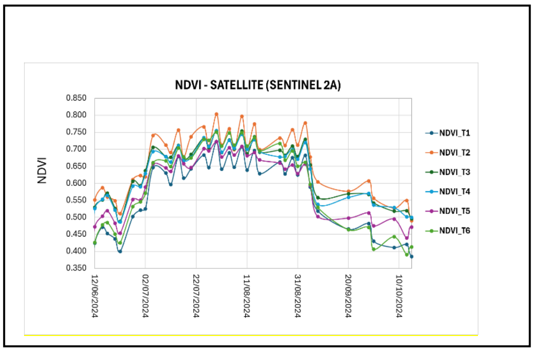


Figure 2. NDVI Index based on satellite data along the growth cycle of the Autumn Crisp®.

This index was plotted over time to observe vegetation dynamics under various plastic film conditions. Analysis of the average vegetation indices across the six plastic films (T1–T6) revealed distinct patterns in canopy behaviour, indicating the measurable impact of film optical properties on grapevine physiology (Table 7).

The NDVI, was highest in T2 (0.62), followed by T3 (0.60) and T4 (0.59). This suggests that the plastic film used in T2, T3, T4 allowed for better preservation or enhancement of canopy development, likely due to favourable light transmission/reflectance characteristics. In contrast, T1 (0.52), T5 (0.55) and T6 (0.55) showed the lowest NDVI values, possibly due to more opaque or reflective film properties reducing the effective radiation signal. Furthermore, the method's sensitivity and the effectiveness of the applied corrections are supported by the clear correlation observed in Figure 2 between peaks in NDVI values and the timing of scheduled irrigation, displaying a sinusoidal trend throughout summer. A decrease in NDVI values was consistently recorded prior to each weekly irrigation event, reflecting transient water stress.

Table 7. Difference among plastic films of NDVI averaged values along the growth cycle

	Plastic cover						
	T1	T2	T3	T4	T5	T6	p
NDVI	0.52 (0.14) b	0.62 (0.12) a	0.60 (0.12) ab	0.59 (0.12) ab	0.55 (0.13) ab	0.55 (0.16) ab	**

Different letters among means and SD values (in brackets) in the same column indicate significant differences at $p \leq 0.05$.

The ANOVA/Tukey results revealed statistically significant differences among plastic films ($p = 0.0037$), suggesting that the NDVI index is affected by type selection of plastic films.

This result supports the hypothesis that the radiometric properties of the plastic covers modulate the spectral response of the underlying vegetation and emphasize the need to account for these effects when interpreting remote sensing data in covered cropping systems.

4. Conclusions

Overall, the Autumn Crisp® behaved very differently in relation to the different plastic films. These plastic films had a strong influence on the productive parameters of the variety and on some morphological parameters such as the weight of the bunch and rachis. The variety showed different responses in the berry reflectance values of the visible spectra, L*, a*, b*, when grown under the six types of plastic film.

A lower influence of the plastic film on the texture parameters was observed. Finally, it should be noted that the plastic films analyzed in the study represent only a small part of the possible film typologies available on the market. Therefore, further studies are recommended for a better understanding of the effects of the Spectro-radiometric characteristics of the possible different polymers, especially to avoid any undesirable consequences on the yield and the market requirements for the table grapes. These results support the hypothesis that plastic film properties modulate the spectral response of the underlying vegetation and emphasize the need to account for these effects when interpreting remote sensing data in covered cropping systems.

NDVI index calculated with corrections in relation to the plastic film radiating characteristics demonstrated that it could be a reliable system for satellite utilization even for analyzing vine physiology under the plastic covering.

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