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Estimation of the CARI Vegetation Index from Spectral Signatures of Stenocereus queretaroesis in Southern Zacatecas

Estimación del índice de vegetación CARI a partir de firmas espectrales del Stenocereus queretaroensis en el sur de Zacatecas

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Abstract

This work addresses the lack of protocols for estimating vegetation indices in Stenocereus queretaroensis, a species of ecological and productive importance in southern Zacatecas. The objective was to analyze its spectral response over several months to identify indices capable of distinguishing physiological states and growth stages. Spectral signatures were collected in the field using a portable spectrophotometer from January to June, evaluating 109 plants. As a result, calculations of the CARI vegetation index are presented, showing differences associated with chlorophyll and carotenoid content, confirming its usefulness as a reliable indicator.

Keywords— Spectrophotometry, Vegetation indices, Stenocereus spp., Spectral signatures

Resumen

En este trabajo se aborda la falta de protocolos para la estimación de índices de vegetación en Stenocereus queretaroensis, especie de importancia ecológica y productiva en el sur de Zacatecas. El objetivo fue analizar su respuesta espectral durante varios meses para identificar índices capaces de diferenciar estados fisiológicos y etapas de crecimiento. Se recolectaron firmas espectrales en campo con un espectrofotómetro portátil, de enero a junio, evaluando 109 plantas. Como resultado se presentan los cálculos del índice de vegetación CARI que presenta las diferencias asociadas al contenido de clorofila y carotenoides, confirmando su utilidad como indicadores fiables.

Palabras clave— Espectrofotometría, Índices de vegetación, Stenocereus spp., Firmas espectrales

I. Introduction

Light is a fundamental factor for vegetation. When solar radiation reaches a plant, a portion is absorbed by pigments and cellular structures, another portion is transmitted through the tissues [1], and a fraction is reflected outward. These optical processes particularly: absorption, transmission, and reflectance, describe the physical interactions between plants and electromagnetic radiation. Plants reflect and absorb radiation differentially according to their physiological and biochemical status. For example, within the visible spectrum, reflectance may vary around 400–450 nm (blue), 500–550 nm (green), or 600–700 nm (red), while in the near-infrared region (NIR; 700–900 nm) reflectance

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typically increases due to leaf internal structure. The relationship between the intensity of radiation reflected at each spectral band constitutes the spectral signature, which enables the characterization of physiological and structural properties of vegetation [2].

The spectral signatures analysis not only allows for understanding the fundamental optical processes in plants but also opens the possibility of applying them to species of ecological and productive interest. The interpretation of reflectance across different wavelengths becomes a key tool for identifying the physiological state of plants and, consequently, for designing non-invasive monitoring strategies [3]. In this context, it is important to focus attention on species such as cacti of the genus *Stenocereus spp.*, whose environmental and economic significance demands more precise and systematized characterization methods.

In Mexico, the genus *Stenocereus spp.* includes cactus species characterized by their resistance to extreme temperature conditions, low water requirements, and fruits with high mineral content and antioxidant properties [4, 5]. However, the phenological monitoring of Stenocereus queretaroensis shows limitations that have hindered its systematic study. Among the main challenges are the absence of standardized protocols for the physiological characterization of this species, the variability in spectral response associated with different developmental stages, and the difficulty of assessing tissue condition without resorting to destructive methods [6]. These limitations restrict the possibility of conducting accurate evaluations under controlled conditions, highlighting the need to develop non-invasive and reproducible methodologies for its analysis.

Altogether, the interaction of light with plant tissues, the potential of spectral signatures, and the relevance of the genus Stenocereus spp. emphasize the need to establish methodological strategies that enables a more precise and non-invasive analysis of its physiology. Establishing standardized protocols will not only contributes to the scientific understanding of these species but will also provides applicable tools for sustainable management, conservation, and productive use of their resources.

This study examines the temporal variation of the spectral response of Stenocereus queretaroensis with the aim of calculating vegetation indices that enables non-invasive assessment of its physiological status. In addition, a phenological classification approach based on spectral signatures is developed to identify changes and growth stages under controlled conditions. The working hypothesis proposes that specific indices derived from spectral signatures can reliably discriminate among the different physiological states of Stenocereus queretaroensis, thereby providing a robust tool for its monitoring.

II. Literature Review

II.1. Spectral Reflectance

Spectral reflectance is a key optical property of plants and refers to the fraction of electromagnetic radiation reflected at different wavelengths of the spectrum (Equation 1). This phenomenon is fundamental for studying vegetation health and physiological condition, as different plant organs—such as leaves, stems, and flowers—reflect varying proportions of light depending on their structural and biochemical characteristics [7]. In reflectance studies, broad-spectrum incident light is typically used, focusing on specific wavelength ranges such as the visible and near-infrared regions [8].

$$R = \frac{I_r}{I_i} \tag{1}$$

where R represents the spectral reflectance (expressed as a percentage or on a scale from 0 to 10), I_r is the intensity of light reflected by the sample, and I_i is the intensity of the incident light on the sample [9].

Reflectance in vegetation is influenced by a wide range of internal and external factors. Internal factors includes leaf structure, maturity, pigmentation, nutritional status, anatomy, and water content; while external factors involves solar exposure, phyllotaxy, and the presence of diseases [8, 10]. In [8] emphasized the importance of pigment composition, leaf anatomy, and environmental conditions such as turgor and evapotranspiration, all of which directly affect the reflectance signal.

The study of spectral reflectance has become essential in precision agriculture, as it enables the evaluation of crop health, species identification, and biodiversity monitoring [11]. Each plant exhibits a unique spectral pattern depending on its physiological condition or growth stage: healthy green plants typically show higher reflectance in the near-infrared region and lower reflectance in the red band, while stressed plants display the opposite pattern [12].

II.2. Spectral Signatures

Spectral signatures represents the characteristic pattern of absorption, reflection, and transmission of electromagnetic radiation by a material, acting as a distinctive "fingerprint" that allows for its identification and characterization. In plants, these signatures are influenced by chemical composition and physiological status, resulting in variations in reflectance related to chlorophyll, water, and other pigments [13]. They are commonly represented graphically, illustrating the relationship between wavelength and reflected intensity (Figure 1).

Spectral signatures are powerful tools in vegetation studies because they make it possible to assess plant

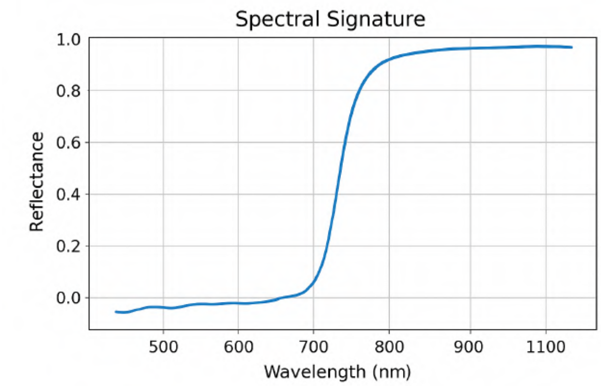

Figure 1: *Graphical representation of a spectral reflectance signature.*

health, detect diseases, estimate water content, identify species, and analyze environmental stress effects. Their acquisition is carried out using instruments such as spectrometers and radiometers [14]. A healthy plant typically presents a pronounced peak in the green band and high reflectance in the near-infrared region, whereas a stressed plant exhibits reduced infrared reflectance and greater red reflectance [15, 12]. These differences provide valuable information about physiological processes without the need for destructive sampling.

II.3. Vegetation Indices

Vegetation indices are mathematical formulations designed to exploit the information derived from the optical properties of plants. By combining reflectance values from specific spectral bands, these indices allow precise and non-invasive estimation of parameters such as chlorophyll content, plant vigor, photosynthetic activity, and water status [16]. Among the most widely used indices are NDVI, EVI, SAVI, GNDVI, and NDRE (Table 1). Their application in agriculture, ecology, and environmental conservation enables non-destructive monitoring of crops, early detection of water or nutrient deficiencies, and timely decision-making for sustainable management [17, 3, 18].

The protection and cultivation of endangered plant species, along with the application of remote sensing in precision agriculture, have become strategic areas aimed at optimizing resources, ensuring food security, and preserving biodiversity [27, 28].

III. Methodology

The studied cultivation site is located along the road to Guadalupe Victoria in the municipality of Jalpa, Zacatecas, Mexico (21.717515° N, 102.976155° W) (Figure 2), at an approximate altitude of 1750 m a.s.l., under semi-arid temperate climate conditions. Although a detailed soil analysis was not performed, the presence of local crops such as maize, maguey, and nopal, along with naturally occurring pitayos, suggests moderate soil fertility typical of a semi-arid area, sufficient to support both cultivated and native species.

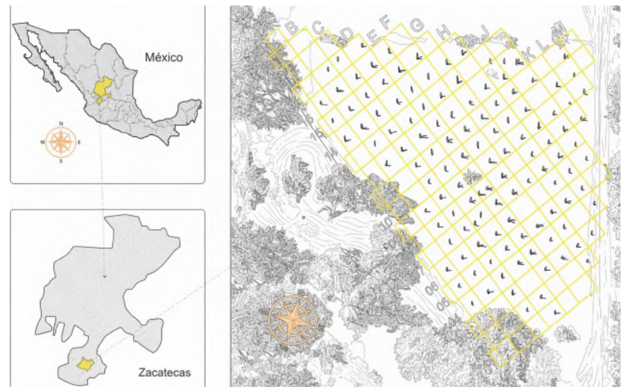

Figure 2: *Representation of the sampling site location.*

The analyzed specimen corresponds to Stenocereus queretaroensis, a columnar cactus that can reach up to 10 m in height and form tree-like structures through branched stems. It produces nocturnal pinkish-white flowers and fruits known as “pitayas de mayo”, which exhibit morphological and chromatic variability in pulp, shape, and weight (100–300 g). Stems feature 6–8 ribs with a specific arrangement of radial and central spines, flowers present reddish buds and a white perianth, and fruits have sweet pulp, deciduous yellow spines, and black seeds. Its geographic distribution is concentrated in southern Zacatecas. Figure 3 shows a Stenocereus (pitayo) specimen that serves as a representative reference of the plants present in the plot.

Figure 3: *Young Stenocereus queretaroensis plant.*

Table 1: *Some Vegetation Indices within the 400–700 nm range*

Index	Equation	Reference
PRI (Photochemical Reflectance Index)	$PRI = \frac{R_{531}-R_{570}}{R_{531}+R_{570}}$	[19]
CARI (Chlorophyll Absorption Ratio Index)	$CARI = (R_{700} - R_{670}) - 0.2 \times (R_{700} - R_{550})$	[20]
MCARI (Modified Chlorophyll Absorption in Reflectance Index)	$MCARI = [(R_{700}-R_{670})-0.2\times(R_{700}-R_{550})\times(R_{700}/R_{670})]$	[21]
TCARI (Transformed Chlorophyll Absorption Ratio Index)	$TCARI = 3 \times [(R_{700} - R_{670}) - 0.2 \times (R_{700} - R_{550}) \times \frac{R_{700}}{R_{670}}]$	[21]
RARSB (Red-Edge Atmospheric Resistant Index)	$RARSB = \frac{R_{675}}{R_{650}\times R_{700}}$	[22]
RGRI (Red Green Ratio Index)	$RGRI = \frac{R_{550}}{R_{670}}$	[23]
PSRI (Plant Senescence Reflectance Index)	$PSRI = \frac{R_{680}-R_{500}}{R_{750}}$	[24]
ARI (Anthocyanin Reflectance Index)	$ARI = \frac{1}{R_{550}} - \frac{1}{R_{700}}$	[25]
CRI (Carotenoid Reflectance Index)	$CRI_{550} = \frac{1}{R_{510}} - \frac{1}{R_{550}}, \quad CRI_{700} = \frac{1}{R_{510}} - \frac{1}{R_{700}}$	[26]

The experimental design involved in situ acquisition of spectral signatures from 109 plants using a portable YS45 spectrophotometer. The plot was organized into a grid of rows and columns, assigning unique alphanumeric labels to each plant. Fixed reference points were established along each pitayo to ensure consistency in sample collection and measurement repeatability. For each plant, three stem segments (basal, middle, and young) were selected. Figure 4 illustrates the methodology through a schematic diagram. Measurements were conducted between 8:00 and 10:00 a.m., positioning the sensor perpendicular to the surface and calibrating with a white reference before each session.

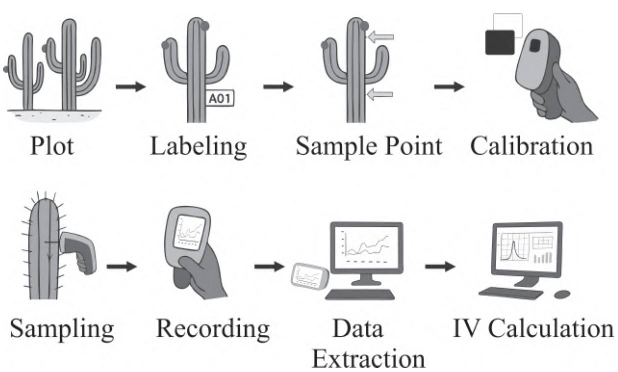

Figure 4: *Methodology for in situ spectral signature acquisition.*

The YS45 spectrophotometer employs a 45/0 optical system, D65 light source, 8 mm aperture ($\Phi 8$), dual-matrix CMOS detector, and concave diffraction grating. Spectra were recorded in the 400–700 nm range at 10 nm intervals with repeatability $\Delta E^* \leq 0.05$, and data were exported to MATLAB to generate spectral reflectance curves and organize monthly datasets in text files. The spectral data were acquired using the SQCT software included with the YS45 and saved as .csv/.txt files for subsequent processing in software such as MATLAB.

IV. Results

Figure 5 shows the set of spectral signatures corresponding to the youngest part of the pitayo plants during January, along with the curve representing the median of all spectral curves for that month.

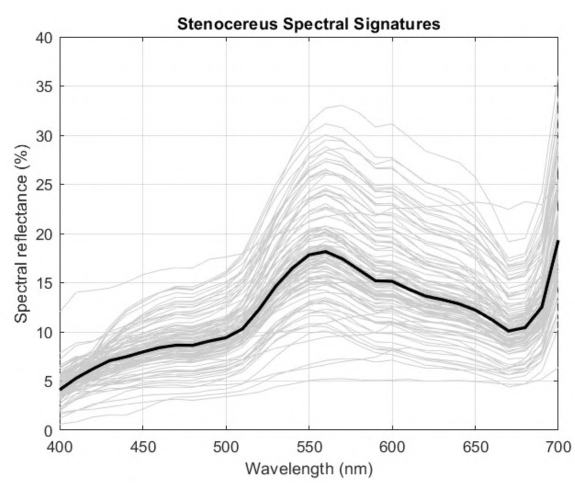

Figure 5: *Spectral signatures of the young part of pitayo plants during January.*

The main feature observed in this graph reflects typical vegetation behavior, with a peak around 540–560 nm, corresponding to higher reflectance in the green region, and lower values in the blue and violet regions (400 nm). Additionally, an increase is observed near 700 nm, marking the beginning of the near-infrared (NIR) region, which is associated with plant vigor and water content.

The CARI vegetation index was calculated using the formulas presented in Table 1. Based on reflectance values at the specified wavelengths, vegetation indices were estimated for the months from January to June for the three stem sections of the pitayo. The results for the mature and young sections are presented in Figure 6. The collected spectral signatures also allow straightforward calculation of other vegetation indices such as SR7, GRVI, PRI, ARI, CRI550, and CRI700.

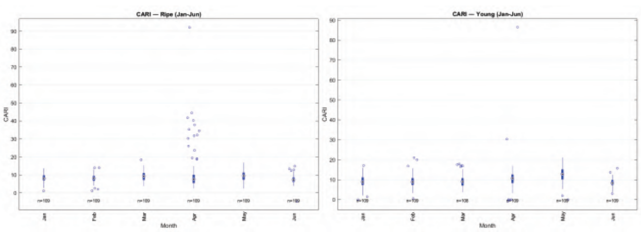

Figure 6: *Box plot of CARI vegetation indices for January–June.*

The data presented are raw and unfiltered; therefore, some apparent outliers may reflect measurement errors. The median CARI values for most months range around 8–12, suggesting relatively stable central values across months for each plant section, without drastic variation.

Figure 7 shows the average CARI values from January to June. From January to March, CARI values were similar across all three pitayo sections (mature, middle, and young), ranging between 8 and 11 with low variability. In April, the middle section showed a marked increase, reaching around 20 and displaying high dispersion, while the other two sections remained nearly unchanged. In May, values in the middle section returned to normal levels (approx. 12), the young section increased slightly (12–14), and the mature section remained stable. By June, all sections showed similar values (7–9). The variation observed in April coincides with the onset of fruit production in the pitayos, as observed in the field.

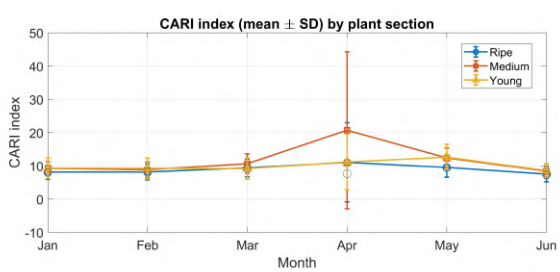

Figure 7: *Average CARI vegetation index of pitayo plants.*

Trends in median CARI values (Figure 8) indicates an increase in the young and middle sections from March to May, followed by a decline in June, while the mature section remained more stable. Since CARI is associated with the spectral signal of foliar pigments (mainly carotenoids and their relationship with chlorophyll), this pattern may reflect carotenoid accumulation, relative chlorophyll reduction, or a specific phenological event. Correlation with chlorophyll-specific indices and/or chemical measurements is recommended to confirm the underlying cause.

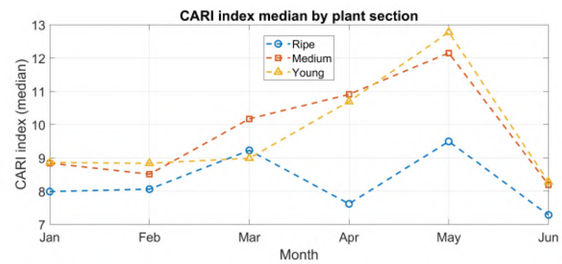

Figure 8: *Median CARI values of pitayo plants.*

V. Conclusion

This study recorded and analyzed spectral signatures of Stenocereus queretaroensis over six months, revealing temporal variation in the CARI vegetation index across different stem sections. Overall, values remained stable between January and March, with minimal variability among the mature, middle, and young sections. However, a notable increase was observed in the middle section in April, accompanied by high data dispersion, coinciding with the onset of the fruiting period. Subsequently, values returned to similar levels in May and June.

These results suggest that variations in the CARI index may be linked to physiological changes associated with fruit development and foliar pigment dynamics. The information provides a useful basis for understanding spectral patterns in pitayo plants and highlights the importance of continued complementary measurements to relate optical indices to biochemical and phenological parameters of the species.

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