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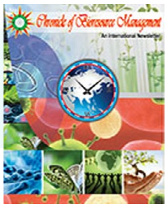

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High-throughput Plant Phenotyping and Vegetation Indices: A Synergy for Future Farming

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Abstract

High-throughput plant phenotyping (HTP) and vegetation indices (VIs) are revolutionizing modern agriculture by enabling rapid, non-destructive, and large-scale assessment of plant traits. HTP platforms, utilizing advanced imaging technologies such as multispectral and hyperspectral sensors, capture detailed data on plant growth, health, and stress responses. Vegetation indices derived from spectral reflectance at specific wavelengths quantitatively assess key parameters like biomass, chlorophyll content, and canopy structure. Indices such as Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI), Enhanced Vegetation Index (EVI), CIgreen etc. offer robust tools for monitoring crop vigor, nutrient status, and environmental adaptation. Integrating HTP with VIs accelerates crop improvement by providing precise, high-resolution phenotypic data, supporting the development of resilient, resource-efficient cultivars. As these technologies evolve, their synergy promises to enhance yield prediction, resource management, and sustainable farming practices, ultimately ensuring food security in the face of climate change and global population growth.

1. Introduction

In the quest to feed a growing global population and combat the challenges posed by climate change, agricultural science is undergoing a significant transformation. High-throughput phenotyping (HTP) stands out as one of the most promising advancements in this field. This cutting-edge technology is revolutionizing the way scientists study plants, offering unprecedented insights into plant growth, development, and responses to environmental stresses. By leveraging HTP, researchers are paving the way for more resilient, productive, and sustainable agricultural practices. Plant phenotyping is the process of measuring and analyzing the observable traits of plants, such as height, biomass, leaf area, flowering time etc. These traits, also known as phenotypes, are influenced by both genetic and environmental factors. Traditionally, phenotyping has been a

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labor-intensive and time-consuming task, often requiring manual measurements and observations. However, with the advent of high-throughput technologies, the landscape of plant phenotyping is changing dramatically. HTP technologies enable the rapid and non-destructive collection of plant biochemical and physiological traits on a large scale. Most common HTP platforms employ unmanned vehicles equipped with a variety of image sensors, such as RGB imaging, thermal imaging, IR imaging, fluorescence imaging, multispectral imaging, hyperspectral imaging, Radar, LiDAR, and satellite imaging. Among these, RGB and hyperspectral imaging tools are commonly employed to evaluate both the quantitative and qualitative characteristics of plants (Figure 1). Typically, the raw image data must be processed into different indices since plants reflect light at specific wavelengths differently, depending on their growth stages and conditions.

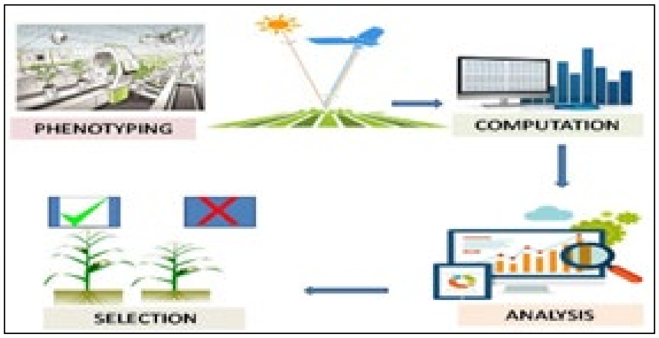

Figure 1: Selection procedure in High-throughput phenotyping (Jangra et al., 2021)

2. Vegetation Indices

Vegetation indices (VIs) are widely used to assess plant health and growth conditions, including soil characteristics, moisture levels, and nutrient content. These indices represent a statistical transformation of initial spectral reflectance derived from two or more wavelength bands, allowing for the measurement and interpretation of various vegetation aspects, such as height, biomass, and canopy characteristics. VIs enables reliable spatial and temporal comparisons of terrestrial photosynthetic activity and variations in canopy structure. Obtained from remotely sensed canopies, vegetation indices utilize straightforward and effective algorithms to quantitatively and qualitatively evaluate vigor, vegetation cover, and growth dynamics. Since they are based on simple transformations of spectral bands, these indices can be calculated directly without bias or assumptions regarding land cover class, soil type, or climatic conditions (Table 1).

Table 1: High-throughput vegetation indices

Index	Formula	Reference
SR	NIR/Red	Anderson et al. (1993)
NDVI	(NIR-Red)/(NIR+Red)	Tucker (1979)
SAVI	(1+L) (NIR-Red/ (NIR+Red+L), L=0.5	Huete (1988)
DVI	NIR - Red	Richardson and Wiegand (1977)
TVI	√(NDVI+0.5)	Deering (1975)
GNDVI	(NIR-Green)/ (NIR+Green)	Huete et al. (2002)
CIgreen	(NIR-Green)-1	Gitelson et al. (2005)
CIred-edge	(NIR/Red edge)-1	Gitelson et al. (2005)

The Simple Ratio (SR) is the most basic ratio-based index, calculated by dividing the reflectance in the near-infrared (NIR) band by the reflectance in the red band. Simple Ratio value <1 indicates non-vegetation, while a value >1 indicates vegetation. Although SR gives a general indication of vegetation, it has a couple of drawbacks. Firstly, if the reflectance in the red band is zero, calculating the SR value is impossible. Additionally, the SR can have a wide range of values due to varying red reflectance, making comparisons challenging. These issues were addressed with the development of the NDVI. The Normalized Difference Vegetation Index (NDVI) is the most widely used index for assessing vegetation greenness, and ranges from -1 to +1. Chlorophyll, which gives plants their green color, absorbs visible light. This means that healthy vegetation absorbs most of this visible light, while unhealthy vegetation reflects more visible light and absorbs less near-infrared (NIR) light. Therefore, NDVI is determined by comparing near-infrared (NIR) with visible red light. However, NDVI has a significant drawback: it is sensitive to factors such as soil brightness and color, atmospheric conditions like cloud cover and shadows, as well as leaf canopy shadows. In regions with sparse vegetation where soil is exposed, NDVI can be influenced by soil reflectance. To address this limitation, Huete (1988) proposed the Soil Adjusted Vegetation Index (SAVI) as a modification of the NDVI that includes a correction factor for soil brightness, denoted as L, which is adjusted based on the amount of vegetation present, typically set to 0.5 for effectiveness in most scenarios. Richardson and Wiegand (1977) introduced the DVI (Difference Vegetation Index) as a simpler algorithm for calculating vegetation indices. DVI can differentiate between soil and vegetation, but it is ineffective in shaded areas. Consequently, DVI fails to provide accurate information when reflected wavelengths are influenced by factors such as topography, atmosphere, or shadows.

The Transformed Vegetation Index (TVI) is a modified form of NDVI designed to avoid negative values of NDVI. It is calculated by adding 0.50 to the NDVI value and then taking the square root of the results. This adjustment aims to transform NDVI values, which approximate a Poisson distribution, into a normal distribution. However, negative values still occur for NDVI values < -0.5. There is no technical difference between NDVI and TVI in terms of image output or detecting active vegetation. TVI values below 0.71 are classified as non-vegetation, whereas values above 0.71 indicate the presence of vegetation. The Green Normalized Difference Vegetation Index (GNDVI) is similar to NDVI; however, it emphasizes the green light spectrum, specifically between 540 and 570 nm, instead of the red spectrum. It is a widely used vegetation index for assessing water and nitrogen absorption in crop canopies. GNDVI offers a more precise measurement of chlorophyll content compared to NDVI. The chlorophyll index, specifically CIgreen and CIred-edge, is used to determine the total chlorophyll content in leaves. This total chlorophyll content is linearly correlated with the difference between the inverse reflectance of green or red-edge bands and the near-infrared (NIR) band. Both CIgreen and CIred-edge values are responsive to minor variations in chlorophyll content and are applicable across most plant species. CIgreen, which encompasses broad NIR and green wavelengths, provides superior predictions of chlorophyll content, greater sensitivity, and an improved signal-to-noise ratio. In contrast, the CIred-edge band covers approximately 670-760 nanometers on the electromagnetic spectrum, situated between the visible red and near-infrared bands, where the spectral reflectance of green vegetation changes significantly.

3. Conclusion

High-throughput plant phenotyping (HTP) uses advanced imaging and sensor technologies to rapidly and non-destructively measure plant traits, enabling large-scale, precise assessment of crop growth, health, and stress responses. Combined with vegetation indices derived from spectral data, HTP allows for accurate monitoring of plant vigor, biomass, and nutrient status. This synergy accelerates crop improvement, supports precision agriculture, and fosters the development of resilient, resource-efficient crops vital for sustainable future farming.

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