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ANALYSIS OF VEGETATION INDEX VALUES AND SUGAR CONTENT IN SUGARCANE BASED ON PLANTING AGE USING SENTINEL-2 SATELLITE DATA

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ABSTRACT

This study the relationship between the age of sugarcane plants (Saccharum officinarum L.), vegetation indices, and sugar content using Sentinel-2 satellite imagery in Jember Regency. Vegetation indices such as NDVI, GNDVI, NDRE, and NDII were used to monitor the physiological condition of the plants, while sugar content was measured using a refractometer on the upper, middle, and lower sections of the sugarcane stalks. The results indicate that the highest sugar content was found in the lower stalk section, as this area serves as the primary storage site for sucrose. There is relationship that increasing plant age correlates with changes in vegetation index patterns, peaking during the maximum vegetative phase. These findings offer significant insights into technology-based sugarcane land management, supporting the optimization of harvest timing, irrigation, and fertilization.

Keywords: Sugarcane; Vegetation Indices; Sugar Content; Sentinel-2

INTRODUCTION

Sugarcane (Saccharum officinarum L.) is a plant belonging to the Gramineae family and has a characteristic stem that produces shoots from the base of the stem, forming clumps consisting of 3 to 7 stems. During its growth, sugarcane goes through 4 main phases, namely germination, sprouting, stem growth, and maturation [1-2]. The sugarcane industry is an important contributor to regional development, especially in Jember Regency. Sugarcane is a prominent agricultural commodity[3] and plays an important role in the Indonesian economy, serving as a source of food, industrial raw materials, and significant employment opportunities for the population[4].

Indonesia still imports sugar to meet its national demand. According to data from the Central Statistics Agency, Indonesia imported 1,796,221.9 ton of sugar in 2023[5]. To meet the growing national demand for sugar, efforts must be made to optimize sugarcane productivity through more efficient and effective technological approaches[6]. One method that has emerged in recent years for accurately monitoring plant conditions and growth is the use of remote sensing technology. Vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), Normalized Difference Red Edge Index (NDRE), and Normalized Difference Infrared Index (NDII), have demonstrated their effective in monitoring plant health using satellite data[7].

Remote sensing technology has become an important tool in monitoring the growth and productivity of sugarcane crops. One of the most widely used platforms is Sentinel-2, a satellite launched by the European Space Agency (ESA) as part of the Copernicus program[8-9]. Sentinel-2 consists of two twin satellites that provide imagery data with spatial resolution ranging from 10 to 60 meters and acquisition frequency every 5 days, enabling real-time vegetation monitoring[10-12].

According to Rekha et al.,[13]; Taravat et al.,[14] , agricultural yield estimation, particularly for sugarcane crops, has become a major focus in modern research utilizing remote sensing technology. One of the involved parameters of sugarcane yield is sugar content which can be measured using Brix meter from the sugarcane stalk segments that are top, middle, and bottom segments [15] . There is lack of information from the previous study which relate sugar content to predict sugarcane yield production through the vegetation indices and therefore this study proposed an analysis of sugarcane content and vegetation indices relationship. The use of satellite data enables broader and faster monitoring compared to field observation methods. Satellite imagery provides more accurate estimates through spectral information analysis. Sentinel-2 with its high resolution and rapid imaging frequency, has significant advantages, particularly in the red-edge index, which can address the saturation issues commonly encountered in traditional vegetation indices like NDVI. Meanwhile, a study by Liepa et al.,[16]; Morel et al.,[17] shows that time-series satellite-based remote sensing data offer great opportunities for analysing land cover dynamics and monitoring agricultural productivity at various temporal and spatial resolutions.

Several previous studies have also confirmed the close relationship between the age of sugarcane plants and variations in satellite image based vegetation indices[18] . Dengia et al.,[19] shows that the NDVI time series has a strong correlation with sugarcane yield, especially in the late growth phase, so it can be used as a phenological indicator. Similar findings were reported by Alemán-Montes et al., [20], who used Sentinel-2 and Landsat imagery to describe sugarcane growth dynamics and model yield and sugar content throughout the harvest cycle. Meanwhile, Maia et al., [21] confirmed that vegetation indices such as NDVI are quite sensitive in detecting changes in biomass at various stages of growth, thus having the potential to be used for classification of management zones based on differences in plant age. Although these studies have successfully demonstrated a strong correlation between sugarcane age and vegetation indices, they have not specifically investigated how these spectral dynamics are reflected in sugar distribution across different stem segments. This gap highlights the need for research that integrates vegetation indices with sugar distribution along stem segments.

This study aims to fill existing research gaps by integrating the Sentinel-2 vegetation index with sugar content measured in three stem segments (upper, middle, and lower). Unlike previous studies that focused on yield or total sugar content, this approach emphasizes the uneven distribution of sugar along the stem, where higher concentrations are generally found in the lower part and decrease towards the upper part. This variability has a direct impact on sugar recovery, milling efficiency, and harvest timing. By linking vegetation indices, plant age, and sugar distribution along the stem segments, this study offers a new perspective that combines remote sensing analysis with the physiological characteristics of sugarcane. The expected results are not only to enhance scientific understanding of sugarcane growth and quality but also to provide practical benefits for precision agriculture and sustainable sugarcane management in Jember Regency, thereby contributing to reducing dependence on sugar imports.

METHOD

This study focuses on the Jember Regency area. Geographically, Jember Regency is located at 113^{O}16’28” and 114^{O}03’42” East Longitude and 7^{O}59’6” to 8^{O}33’56” South Latitude and administratively within the Jember Regency area. Two types of data were used in this study Sentinel-2 satellite imagery data and sugarcane sugar content data. The satellite data used is Sentinel-2 data, which is optical data. The Sentinel-2 imagery data used was collected in a time series from May 2023 to June 2024 with a maximum cloud cover of 20%. Sentinel-2 data can be accessed through the Copernicus open access web portal (The Sentinels Scientific Data Hub). Information on the Sentinel-2 data bands is provided in Table 1 below.

Table 1. Sentinel-2 data bands

Band	Spatial Resolution	Wavelength	Description
1	60 m	443 nm	Coastal Aerosol
2	10 m	490 nm	Blue
3	10 m	560 nm	Green
4	10 m	665 nm	Red
5	20 m	705 nm	Red Edge
6	20 m	740 nm	Red Edge
7	20 m	783 nm	Red Edge
8	10 m	842 nm	NIR
8a	20 m	865 nm	NIR
9	60 m	940 nm	Water vapour
10	60 m	1375 nm	SWIR-Cirrus
11	20 m	1610 nm	SWIR
12	20 m	2190 nm	SWIR

Source : Kaplan & Avdan, [22]

Meanwhile, the sugarcane sugar content data was integrated with the age of the sugarcane and vegetation index variations, namely NDVI, GNDVI, NDRE, and NDII.

The Sentinel-2 image data was downloaded using the Google Earth Engine (GEE) platform to access the USGS website. The data was then cropped according to the research area, namely Jember Regency, using a shapefile containing administrative boundaries with map data for each regency in Indonesia. After the data was downloaded, the cropping process was continued according to the research area using ArcGIS v10.3 software.

The processing of vegetation index values was carried out on the GEE platform based on the following equation:

$$NDVI = \frac{NIR-RED}{NIR+RED} \quad [23] \qquad (1)$$

$$GNDVI = \frac{NIR-GREEN}{NIR+GREEN} \text{ [24]} \tag{2}$$

$$NDRE = \frac{NIR-RED\ EDGE}{NIR+RED\ EDGE} \text{ [25]} \tag{3}$$

$$NDII = \frac{NIR-SWIR}{NIR+SWIR} \text{ [26]} \tag{4}$$

Where: Red = Red band value (Band 4); Green = Green band value (Band 3); NIR = NIR band value (Band 8); Red Edge = RE band value (Band 5); SWIR = SWIR band value (Band 11)

Field measurements were conducted on 12 sugarcane plots representing various plant ages. Sugar content was measured in three stem segments (top, middle, and bottom) using a digital refractometer. Although the number of field plots is relatively small, they were carefully selected to capture representative variations in plant age and site conditions. All plots shared the same sugarcane variety and soil type, minimizing the influence of varietal or edaphic differences on the results. The limited sample size is acknowledged as a constraint that may reduce the generalizability of the findings; however, the dataset provides valuable empirical evidence for identifying preliminary patterns between spectral response and sugar accumulation. The relationship between vegetation index, plant age, and sugar content was evaluated using correlation coefficients to quantify the strength and direction of these associations. This approach enables a statistically supported interpretation of how vegetation indices reflect sugar accumulation across different stem segments, while recognizing that further validation with larger datasets would strengthen the conclusions.

The relationship between vegetation index, plant age, and sugar content was evaluated using correlation coefficients to measure the strength and direction of this relationship. In addition, the coefficient of determination (R^2) was calculated to assess the extent to which variations in sugar content corresponded to changes in vegetation index and plant age. The R^2 values shown in the Results section provide a quantitative measure of the relationship between these parameters. Similar approaches have been reported by Jamnani et al., [27] , who found a strong correlation between GNDVI and sucrose content $R^2 = 0.885$, supporting the use of spectral indices for monitoring sugar accumulation in sugarcane.

RESULTS AND DISCUSSION

Observations and data collection on sugarcane age and sugar content were conducted in 12 plots of sugarcane plantation. The data from these sugarcane plots were also used for image cropping and vegetation index processing based on plant age. Photos of the field observations are shown in Figure 1.

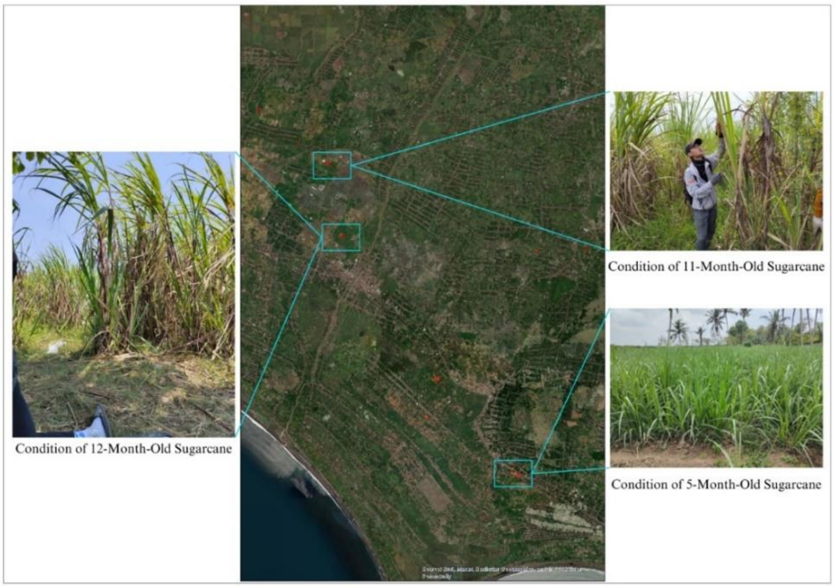

Figure 1. Photos taken during field observations of several sugarcane plots

The image above shows the research area, which is a sugarcane field where sugar content data was collected. The location consists of 12 sugarcane plots of varying ages. As shown in the image, the observation area is marked with a red box. The image shows direct documentation of the field and its varying ages. At 5 months old, the plants are still in the early stages of growth, with short leaves that are not yet dense. At 11 months, the stems are thicker, the leaves are longer, and the sugar content in the stems has increased. At 12 months, the stems are sturdy and the plants are significantly larger as they have reached maturity and are ready for harvest.

Based on the data regarding the age of the sugarcane plants and the results of processing the vegetation index values for the corresponding plots, a graph can be created showing the relationship between age and vegetation index, as illustrated in Figure 2.

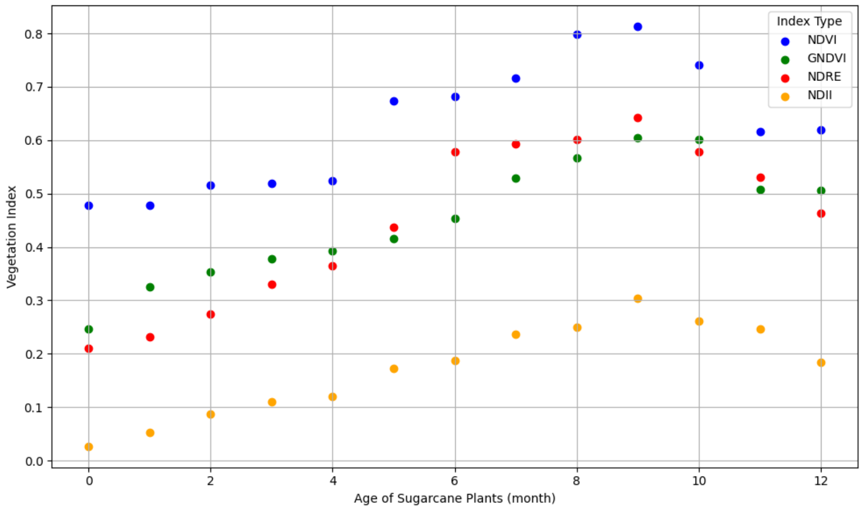

Figure 2. Graph of the relationship between sugarcane age and vegetation index

The results of the analysis of the relationship between sugarcane age and vegetation indices show a pattern of change that is consistent with the plant's growth phase. In the early growth phase, all indices increase in line with the accumulation of green biomass, increased chlorophyll, and photosynthetic activity. NDVI and GNDVI peak during the maximum vegetative phase, reflecting optimal plant conditions, before declining as the plant enters the reproductive or senescence phase. NDRE increases more slowly than NDVI because it is more sensitive to plant nitrogen conditions. Its value remains high longer before declining, making it relevant for monitoring plant health in the late vegetative phase. NDII, which reflects water content, increases from the early growth phase and peaks in the vegetative phase, then declines more sharply as the plant ages, reflecting natural water loss during the senescence phase.

Quantitatively, the correlation between plant age and each index shows an R^2 value of 0.49 for NDVI, 0.781 for GNDVI, 0.66 for NDRE, and 0.749 for NDII. These R^2 values indicate that GNDVI and NDII have a stronger ability to represent physiological changes in plants than NDVI, while NDRE is quite sensitive to nitrogen status and is useful for monitoring plant health in the late vegetative growth phase. The peak vegetation index occurs at 9–10 months of plant age, in line with the maximum vegetative phase of sugarcane, which is consistent with previous literature findings[28]. These results have direct applications in harvest scheduling, fertilizer management, and precision irrigation, as farmers can use NDRE and NDII trends to optimize timing and resource allocation.

Furthermore, to determine the relationship pattern between age and sugar content a graph plot of the relationship between the values of the two parameter was created, as shown in Figure 3.

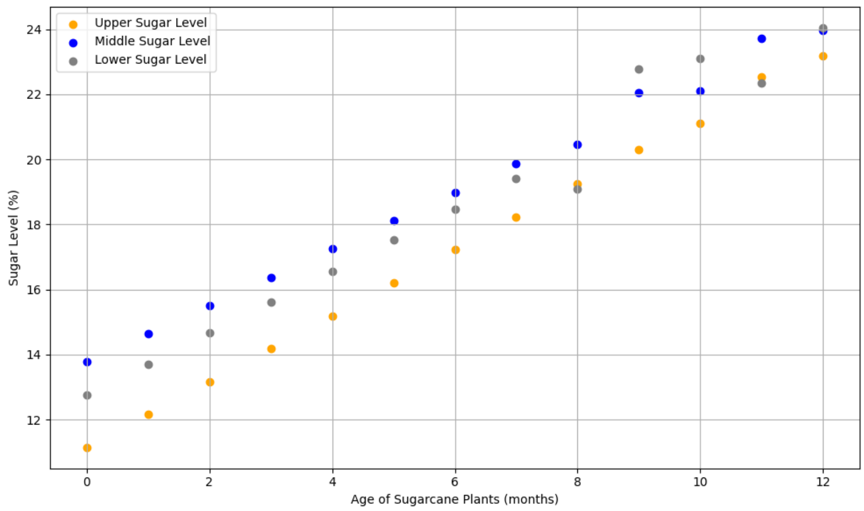

Figure 3. Graph showing the relationship between sugarcane age and sugar content

The graph in Figure 3 shows the relationship between the age of sugarcane plants and the sugar content in the stems, where the lower part of the stem has a higher sugar content than the middle and upper parts. This indicates that the lower part of the stem accumulates more sucrose than the middle and upper parts at a certain age. The distribution of sucrose in sugarcane stems is uneven, usually more concentrated in the lower part of the stem. This is related to the physiological processes of plants, where the products of photosynthesis in the form of sugar are transported through the phloem and tend to be stored first in the lower part of the stalk, which functions as the main storage site. The middle and upper parts of the stalk usually have lower sugar content because some of the energy is allocated for the growth of new tissues, such as leaves and young stalks[29].

Quantitative analysis indicates a very strong relationship between plant age and sugar content, with R^2 values of 0.999 for the upper, 0.995 for the middle, and 0.969 for the lower parts of the stalk. These high coefficients confirm that plant age serves as an excellent predictor of sugar accumulation in each stem segment. As shown in Figure 3, the increase in sugar content between the 11th and 12th months is noticeably smaller compared to the preceding months. This trend suggests that sugar accumulation begins to plateau after the 11th month, indicating that the optimal harvesting period may commence around that time.

These findings provide a strong basis for the use of vegetation indices from satellite data as a tool for estimating sugar distribution in sugarcane stems, and can be used as a practical guide in determining the optimal harvest time. To predict sugar content by calculating vegetation index values based on satellite data, it is necessary to analyse the relationship between vegetation index values and sugar content, as shown in Figure 4 to 7.

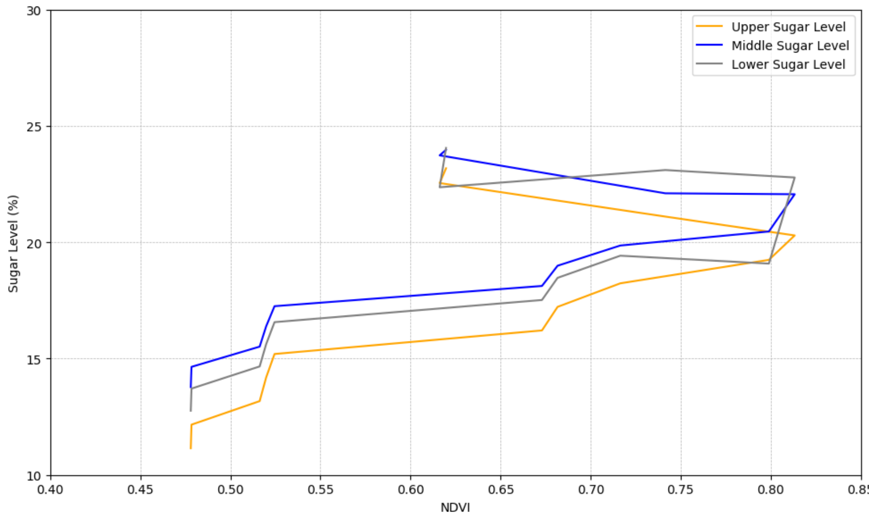

Figure 4. Graph showing the relationship between the NDVI index and sugar content

This graph illustrates the relationship between sugar content in sugarcane stalks and NDVI values, which are commonly used to measure vegetation health by utilizing differences in light reflection in the red and near-infrared spectrum. An increase in NDVI values generally reflects healthier plant conditions, which may correlate with increased photosynthesis and sugar production. Quantitative analysis shows a moderate relationship with an R^2 value of 0.493 for upper stalks, 0.494 for middle stalks, and 0.522 for lower stalks. These results indicate that NDVI has moderate predictive power for sugar content in various stalk segments, with little variation between locations. Similar findings were reported by Dimov et al., [30], who observed NDVI saturation in dense sugarcane canopies, resulting in reduced sensitivity to biomass variation compared to red edge indices such as NDRE (R^2 0.68). This comparison highlights that while NDVI can be used to monitor general plant health, alternative indices such as NDRE may provide more accurate predictions of sugar accumulation in dense or mature canopies.

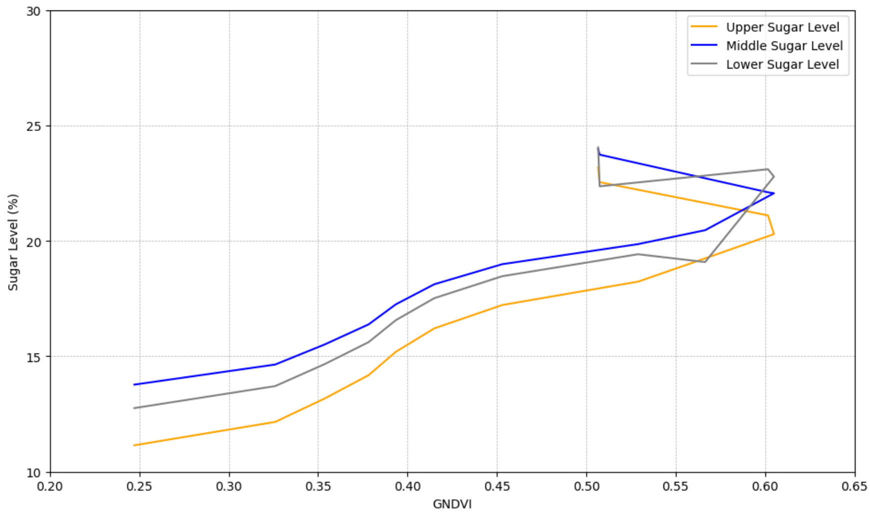

Figure 5. Graph showing the relationship between the GNDVI index and sugar content

GNDVI has a similar concept to NDVI, but is more sensitive to chlorophyll content in leaves because it uses the green band as one of its parameters. This graph shows a similar trend to NDVI, where sugar content increases along with an increase in GNDVI values. Quantitative analysis shows a fairly strong relationship with an R^2 value of 0.776 for the upper stem, 0.775 for the middle stem, and 0.807 for the lower stem. These results indicate that GNDVI is a more sensitive indicator of photosynthetic activity and sugar accumulation, especially in the lower stem. A similar study reported by Jamnani et al., [27], found R^2 0.885 for predicting sucrose content, confirming the superior sensitivity of GNDVI compared to NDVI in detecting chlorophyll, especially in dense canopies where NDVI tends to be saturated. These findings suggest that GNDVI can be used practically to estimate sugar accumulation more accurately along stem segments, aiding in determining the right harvest time and nutrient management.

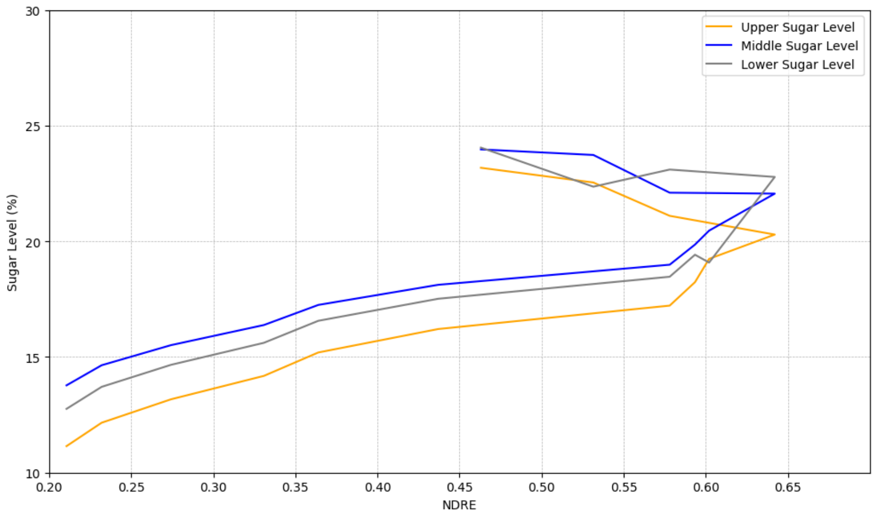

Figure 6. Graph showing the relationship between the NDRE index and sugar content

NDRE uses red-edge bands in its measurements, which are more sensitive to plant stress conditions and nitrogen content. The graph shows a positive trend, although with a narrower range of values compared to NDVI or GNDVI. Quantitative analysis shows a moderate relationship with R^2 values of 0.664 for upper stems, 0.669 for middle stems, and 0.671 for lower stems. These results indicate that plants with higher nitrogen content, which supports vegetative growth and photosynthetic efficiency, tend to produce higher sugar levels. Similar trends were reported by Akbarian et al., [31] and Canata et al., [32] , who observed R^2 values of 0.68–0.71 for NDRE in predicting nitrogen status during the late vegetative growth phase, confirming its effectiveness compared to NDVI, which tends to saturate in dense canopies. The specific trend of NDRE makes it a reliable indicator for detecting the relationship between plant physiological conditions and sugar accumulation, especially when plants are approaching the final growth phase. When NDRE reaches a plateau at 9–10 months of age, it indicates that the plants have accumulated sufficient nitrogen and are approaching optimal harvest maturity. Farmers can use this information to schedule harvests to maximize sugar yield, ensuring high sugar content and efficient resource management.

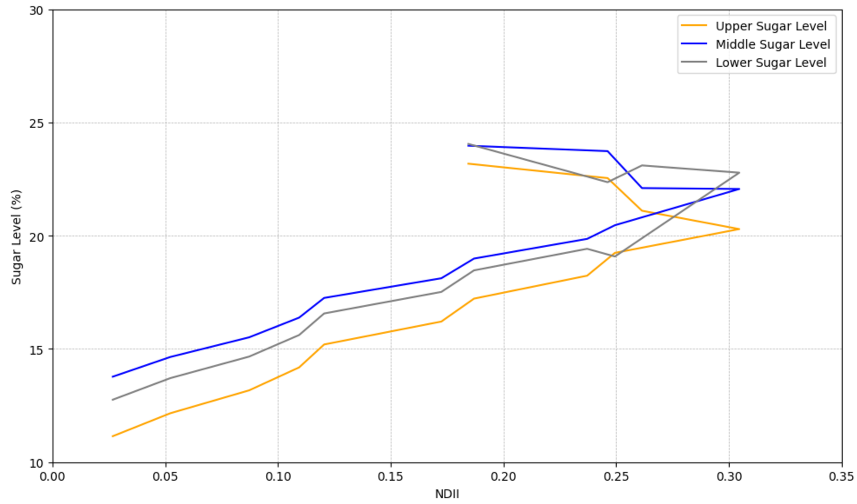

Figure 7. Graph showing the relationship between the NDII index and sugar content

NDII reflects the water content in plant leaves. The graph shows that sugar content increases along with an increase in NDII values, although this relationship is flatter than that of other indices. Quantitative analysis shows R^2 values of 0.751 for the upper stem, 0.763 for the middle stem, and 0.771 for the lower stem, indicating a moderate to strong relationship between water content and sugar accumulation. Water content is essential for supporting physiological processes such as photosynthesis and sugar transport in plants. The less pronounced correlation compared to other indices suggests that factors such as nutrient availability or environmental stress also influence sugar accumulation. A sharp decline in NDII values indicates water stress in plants[33], which can help farmers schedule precision irrigation to maintain plant health and optimize sugar content.

CONCLUSION

This study shows the relationship between the growth phase of sugarcane (Saccharum officinarum L.), sugar content, and vegetation indices, providing insights into sugarcane physiology. Analysis of 12 plots of different ages showed that sugar accumulated most in the lower stems, which function as the main storage site for sucrose. Vegetation indices such as GNDVI (R^2 0.775 – 0.807) and NDII (R^2 0.749 – 0.771) effectively monitor plant physiological conditions, while NDRE (R^2 0.664 – 0.671) is particularly useful for assessing harvest readiness based on nitrogen status. The patterns of relationship between the paint age and sugar content indicating that the optimal harvesting time may starting from the 11th month.

These findings support technology-based sugarcane management, enabling precision irrigation scheduling, fertilization planning, and optimal harvest timing. Future research could focus on the influence of the environment on these relationships or utilize drone and satellite technology to improve spatial accuracy and sustainability in the sugar industry.

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