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Enhancing the Applicability and Development of Vegetation Indices for Mangroves

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ABSTRACT

This study addresses the critical need for effective monitoring and management of mangrove ecosystems, focusing on the development and enhancement of the Mangrove Vegetation Vitality Index (MVVI). Mangroves play a vital role in coastal protection, biodiversity conservation, and carbon sequestration; however, they face significant threats from human activities and climate change. By integrating field data with high-resolution satellite imagery from Landsat and Sentinel-2, this research aims to refine vegetation indices specifically tailored for mangrove environments. The MVVI is developed by combining indices such as the Normalized Difference Water Index (NDWI), Leaf Area Index (LAI), and Enhanced Vegetation Index (EVI), providing a comprehensive assessment of mangrove health and vitality. Detailed studies were conducted in the Ras Mohammed Protected Area and Abu Monqar Island in Egypt, where extensive data collection and analysis were performed. The results demonstrate the MVVI's effectiveness in capturing the unique characteristics and health status of mangrove ecosystems, offering a robust and innovative tool for conservation and sustainable management efforts. This study contributes significantly to the body of knowledge on mangrove ecology and presents practical implications for environmental monitoring and policy-making.

1. Introduction:

Mangrove ecosystems, found in the intertidal zones of tropical and subtropical regions, are critical for their ecological, economic, and societal functions. They serve as nurseries for aquatic species, protect coastlines from erosion, and sequester carbon dioxide. Effective monitoring of mangrove health is essential for their conservation and management. Remote sensing, coupled with vegetation indices, offers a promising tool. However, applying traditional vegetation indices to mangrove ecosystems presents unique challenges. This paper explores methods to adapt and develop vegetation indices tailored to the specific needs of mangrove environments.

This study aims to propose an index for assessing the vitality of mangrove vegetation cover to enhance its applicability in monitoring mangrove health. By integrating field data with satellite imagery, the research seeks to refine and validate the proposed index as a robust tool for monitoring mangrove ecosystem dynamics.

Several studies have investigated vegetation indices within mangrove ecosystems, highlighting their ecological significance and advancements in methodology. Alongi (2008) examined the role of mangroves in coastal carbon cycling, emphasizing their substantial contribution to blue carbon storage. Fatoyinbo et al. (2012) utilized remote sensing techniques to evaluate mangrove biomass and structure, enhancing understanding of ecosystem dynamics. Giri et al. (2011) conducted a global assessment of mangrove forests using Landsat data, offering valuable insights into spatial distribution and temporal changes. Heenkenda and Joyce (2019) focused on developing and validating a mangrove vegetation index (MVI) using hyperspectral data to improve health monitoring accuracy. Murray et al. (2020) investigated the application of the normalized difference vegetation index (NDVI) in mangrove mapping, highlighting its utility in ecosystem management. Rovai et al. (2019) explored the use of Sentinel-2 data for mapping mangrove extent and species composition, demonstrating the effectiveness of high-resolution imagery. Ullah et al. (2019) conducted a comprehensive study on mangrove response to climate change using spectral indices, revealing insights into vulnerability and adaptation strategies. Collectively, these studies contribute significantly to understanding mangrove ecology and advancing vegetation index development for monitoring ecosystem health and dynamics.

2. Challenges in Applying Traditional Vegetation Indices to Mangrove Ecosystems:

Traditional vegetation indices, which are widely used in remote sensing for assessing terrestrial vegetation, face several challenges when applied to mangrove ecosystems. Mangrove environments are unique, with specific characteristics that can impact the accuracy and effectiveness of these indices. Here are some of the challenges in applying traditional vegetation indices to mangrove ecosystems:

2.1. Salinity and Waterlogging Effects on Reflectance:

Mangrove ecosystems are typically found in intertidal zones with brackish or saline water. The high salinity and waterlogging can influence the spectral reflectance properties of mangrove vegetation. Traditional vegetation indices may not account for the effects of salinity and waterlogging, leading to inaccurate assessments of mangrove health and productivity. (Almahasheer et al., 2019; Alongi, 2002)

2.2. Variability in Species Composition:

Mangrove ecosystems are characterized by a mix of different plant species, each with its unique spectral properties. This species variability can be a challenge for traditional indices that assume a uniform vegetation type. Traditional indices may not adequately account for the spectral variations among different mangrove species, resulting in less accurate assessments. (Giri et al., 2011; Kumar & Mutanga, 2019)

2.3. Canopy Structure and Complexity:

Mangrove forests have a complex canopy structure with overlying branches and foliage. This canopy complexity can affect the penetration of light and the reflectance patterns. Traditional vegetation indices may not consider this structural complexity, leading to difficulties in accurately characterizing the canopy and underlying vegetation. (Lotze et al., 2019)

2.4. Seasonal and Tidal Variations:

Mangroves are subject to seasonal variations and tidal cycles. Changes in water levels and canopy conditions can alter the spectral signature of the vegetation. Traditional indices may not account for these seasonal and tidal variations, making it challenging to interpret data collected at different times of the year. (Chen et al., 2021; Liu et al., 2021)

2.5. Atmospheric Interference:

Atmospheric conditions, such as aerosols and humidity, can affect the quality of remote sensing data. In mangrove environments, where proximity to water is common, atmospheric conditions may vary. Traditional indices may not include atmospheric correction methods specifically tailored to mangrove ecosystems, potentially leading to errors in the assessment.

2.6. Limited Ground Truth Data:

Validation of remote sensing data is typically done using ground truth data, which can be challenging to collect in remote and often inaccessible mangrove areas.

The scarcity of ground truth data specific to mangrove ecosystems can hinder the validation and calibration of traditional vegetation indices.

2.7. Spatial Resolution and Scale:

Traditional vegetation indices may not be suitable for the varying spatial scales of mangrove ecosystems. Mangroves can extend from small, intricate tidal creeks to large, continuous forest areas.

Using vegetation indices developed for a different spatial scale may not provide accurate results in these diverse landscapes. (Guo & Wang, 2021; Li et al., 2020).

3. Adapting and Developing Vegetation Indices for Mangroves:

Adapting and developing mangrove vegetation indicators involves customizing and creating specific measurement tools or indices tailored to the unique characteristics and environmental conditions of mangrove ecosystems. Mangrove vegetation indicators are quantitative measures used to assess various aspects of mangrove health, structure, and ecological functions. Adaptations include:

3.1. Selection of Suitable Spectral Bands: It is essential to carefully select the spectral bands that are most relevant for characterizing mangrove vegetation. This may involve using specific bands that are less affected by water absorption and canopy interference (Kovacs et al., 2021).

3.2. Integration of Water Correction Methods: The influence of water on spectral reflectance must be corrected for accurate assessments. Various water correction methods, such as atmospheric correction and water content indices, can be applied to improve accuracy.

3.3. Species-Specific Indices: Developing indices that consider the spectral characteristics of different mangrove species can help account for the variability in species composition within mangrove ecosystems (Khairunnisa et al., 2021).

3.4. Incorporation of Ground Truth Data: Field data collection and ground truthing are crucial for validating the performance of adapted vegetation indices. These data can be used to refine and calibrate the indices for specific mangrove settings.

Adapting and developing mangrove vegetation indices is essential for accurate and meaningful assessment of these critical coastal ecosystems. It allows for more precise monitoring of mangrove health, which is crucial for conservation and management efforts, including tracking changes in response to environmental stressors, land use, and climate variability. These adapted and newly developed indicators help provide a comprehensive understanding of mangrove ecosystems and support informed decision-making for their preservation and sustainable use.

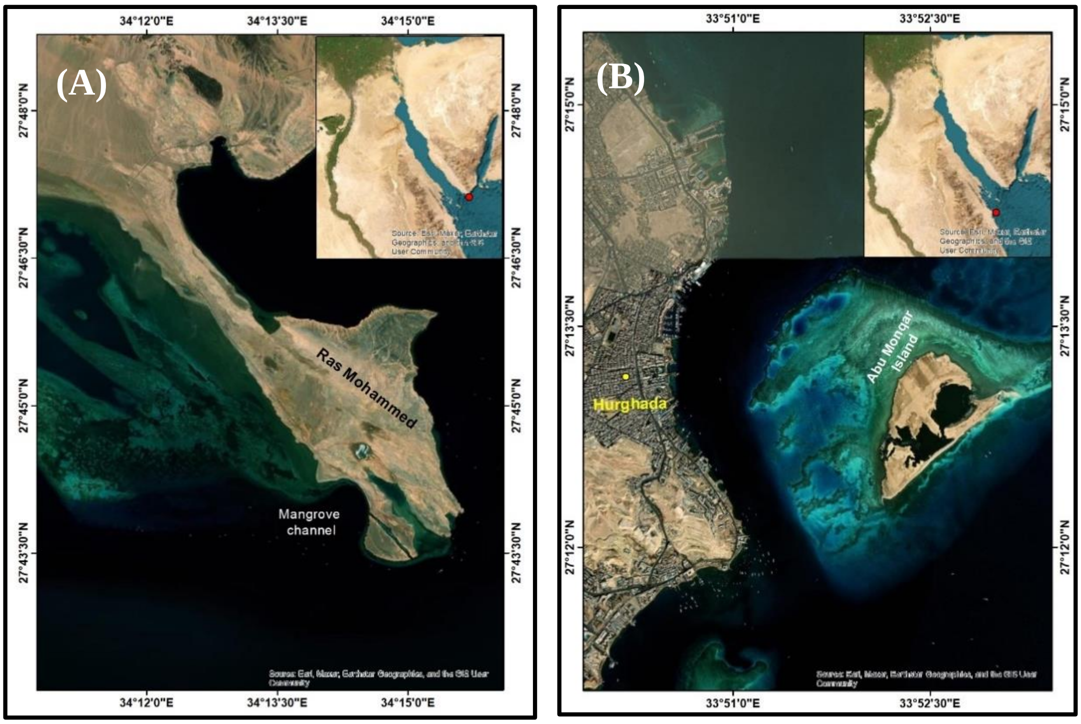
4. Case Studies and Methodological Approaches:

4.1. Study Areas and Data Sources:

4.1.1 Study Areas:

The research investigates the enhancement and development of vegetation indices for mangroves within the Ras Mohammed Protected Area in southern Sinai and Abu Monqar Island, located off the coast of Hurghada in the Red Sea Governorate, Egypt. Ras Mohammed is internationally recognized for its diverse marine habitats, including mangrove forests, coral reefs, and seagrass beds. Adjacent to Ras Mohammed, Abu Monqar Island serves as another significant site for mangrove habitat in the region.

Geographically, Ras Mohammed spans approximately 27° 43′ 22 ″, 27° 47′ 08 ″ N, and 34° 11′ 35 ″, 34° 15′ 21 ″E, while Abu Monqar Island extends between 27° 12′ 16 ″, 27° 13′ 21 ″ N, and 33° 52′ 05 ″, 33° 53′ 12 ″ E (Fig.1). The study area experiences a subtropical desert climate characterized by high temperatures and minimal rainfall.



(A) Ras Mohammed **(B) Abu Monqar Island**

Source :Landsat 9 OLI/TIRS 2023

Figure 1. The Study Area

4.1.2 Data Sources:

In this research, a variety of geospatial data sources were employed, including optical satellite imagery. The investigation relied on technologies such as remote sensing (RS), Digital Shoreline Analysis System (DSAS), and Geographic Information System (GIS). Primarily, the study leveraged optical imagery from both the Landsat mission and the European Space Agency. Landsat's optical images offer a historical archive dating back to 1972, whereas the Sentinel-2 satellite from the European Space Agency provides more recent optical images with a spatial resolution of up to 10 meters. This combination of data sources allowed for comprehensive analysis and interpretation within the study's framework.

Fieldwork complemented these geospatial methods by collecting data from 10 specific sites in the mangrove clusters in Ras Muhammad. The field data included calculating the average height of the mangrove, the density of the vegetation cover, and measuring the average chlorophyll content in the leaves using the Chlorophyll Meter SPAD-502Plus. This integrated approach of utilizing both satellite imagery and field measurements provided a robust dataset for analyzing vegetation health.

4.2. Data Preprocessing and Calibrating Radiometry:

Calibrating radiometry in Landsat OLI (Operational Land Imager) imagery involves several correction steps to convert digital numbers (DN) values to top-of-the-atmosphere (TOA) spectral radiance. These steps include bias correction, dispersion effect correction, and sun angle correction (Roy et al., 2014). Here's an explanation of each step:

4.2.1 Bias Correction:

Bias correction aims to remove systematic errors or biases in the recorded radiometric values. These biases can be introduced by sensor-specific characteristics, such as detector sensitivity variations and electronic noise. The process involves subtracting a constant offset (the bias) from the DN values. The bias correction equation is:
TOA Radiance = (DN - Bias) * Gain
Where:

- TOA Radiance is the top of the atmosphere spectral radiance (in watts per square meter per steradian per micrometer, µm).
- DN is the raw digital number recorded by the sensor.
- Bias is the constant offset, which is sensor-specific and is determined through calibration.
- Gain is the calibration factor to convert DN values to radiance.

4.2.2 Dispersion Effect Correction:

The dispersion effect correction accounts for spectral variations in the sensor's response across different wavelengths. Landsat OLI has several spectral bands, and each band may have different spectral response characteristics. To correct for this, the calibration process applies spectral correction coefficients to adjust the DN values to radiance values for each band. This correction ensures that the recorded radiance values are consistent across all spectral bands.

4.2.3 Sun Angle Correction:

The radiance measured by the sensor is influenced by the angle of the sun relative to the Earth's surface. To account for this, a sun angle correction is applied. The Earth-Sun distance and the solar zenith angle are used to adjust the radiance values. This correction ensures that the radiance values are normalized to a common reference point, typically at the top of the atmosphere, regardless of the time of acquisition.

The sun angle correction equation is:

TOA Radiance = DN / (Gain * Cos (Solar Zenith Angle))

Where:

- TOA Radiance is the top of the atmosphere spectral radiance (in µm).
- DN is the raw digital number recorded by the sensor.
- Gain is the calibration factor for the specific band.
- Solar Zenith Angle is the angle between the sun and the vertical at the sensor location.

By applying these calibration steps, Landsat OLI imagery can be converted from raw DN values to TOA spectral radiance. This calibrated data is essential for quantitative remote sensing applications, such as vegetation health assessment, land cover classification, and environmental monitoring. It ensures that the data is accurate, consistent, and comparable across different spectral bands and time periods, allowing for meaningful analysis and interpretation. The calibration parameters are determined through pre-launch and on-orbit calibration efforts to ensure the quality and accuracy of the imagery.

4.3. Spectral indexes:

Vegetation indices are commonly used in remote sensing to assess the health, abundance, and overall condition of vegetation, including mangrove plants. These indices are derived from the analysis of the spectral reflectance characteristics of vegetation in different wavelengths, often obtained through satellite or aerial imagery. They provide valuable information about various vegetation parameters, such as chlorophyll content, biomass, and overall health (Xue & Su, 2017). Here are some common vegetation indices that can be used to derive information about mangrove plants:

4.3.1 Normalized Difference Vegetation Index (NDVI):

NDVI is one of the most widely used vegetation indices. It is calculated using near-infrared (NIR) and red (R) spectral bands from remote sensing data.
Formula: NDVI = (NIR - R) / (NIR + R)

In the case of mangroves, NDVI can be used to assess the greenness and overall health of the vegetation. Healthy mangroves with more chlorophyll and dense canopies typically have higher NDVI values (Fig. 2 A) and (Fig. 3 A).

4.3.2 Enhanced Vegetation Index (EVI):

EVI is an improved version of NDVI that aims to correct for some of the limitations of NDVI, such as sensitivity to atmospheric conditions and soil background.

Formula: EVI = 2.5 * (NIR - R) / (NIR + 6 * R - 7.5 * Blue + 1)

EVI provides a more robust measure of vegetation health, making it useful for mangrove assessment, especially in areas with challenging atmospheric conditions (Fig. 2 B) and (Fig. 3 B).

4.3.3 Soil-Adjusted Vegetation Index (SAVI):

SAVI is designed to minimize the influence of bare soil and other non-vegetated surfaces on vegetation indices.

Formula: SAVI = ((NIR - R) / (NIR + R + L)) * (1 + L)

SAVI can be beneficial when analyzing mangroves, as it helps to account for the often muddy or sandy substrate in mangrove environments (Fig. 2 C) and (Fig. 3 C).

4.3.4 Chlorophyll Index (CI):

Chlorophyll indices are designed to estimate chlorophyll content in vegetation, which is an essential parameter for assessing plant health.

Formula: CI = (R_red-edge / R_red) - 1

CI can provide information about the chlorophyll content of mangrove plants, allowing for the evaluation of their physiological condition (Fig. 2 D) and (Fig. 3 D).

4.3.5 Canopy Closure Index (CCI) and Water Index:

CCI is specific to mangroves and helps estimate canopy closure, which is a critical parameter for understanding the structure and health of mangrove forests.

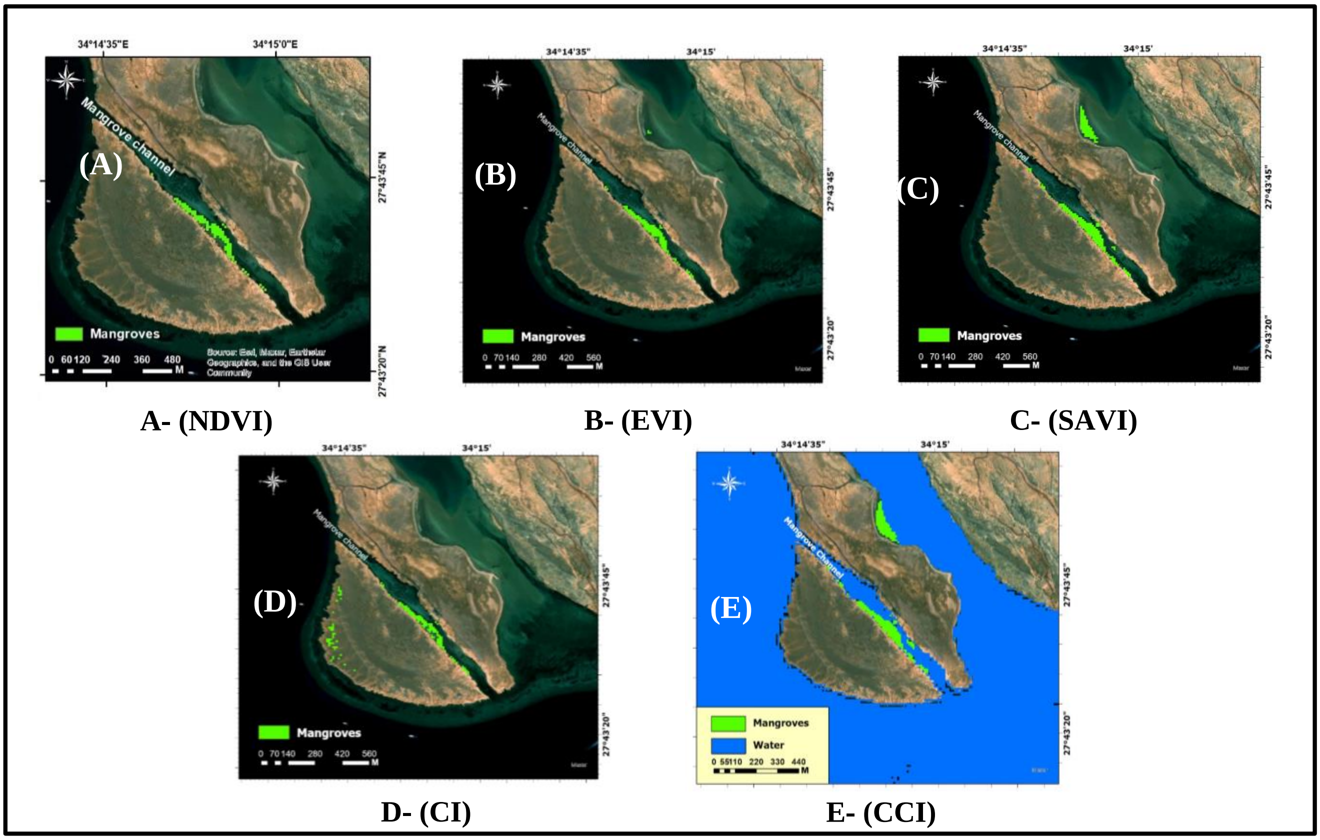
Formula: CCI = 1 - (1 - NDVI)^2

CCI values are correlated with canopy closure, and a dense mangrove canopy will have a higher CCI (Fig. 2 E) and (Fig. 3 E).

Mangroves are often found in waterlogged or intertidal areas, and water can impact spectral reflectance. Water indices, such as the Modified Normalized Difference Water Index (MNDWI), can help identify the presence of water.

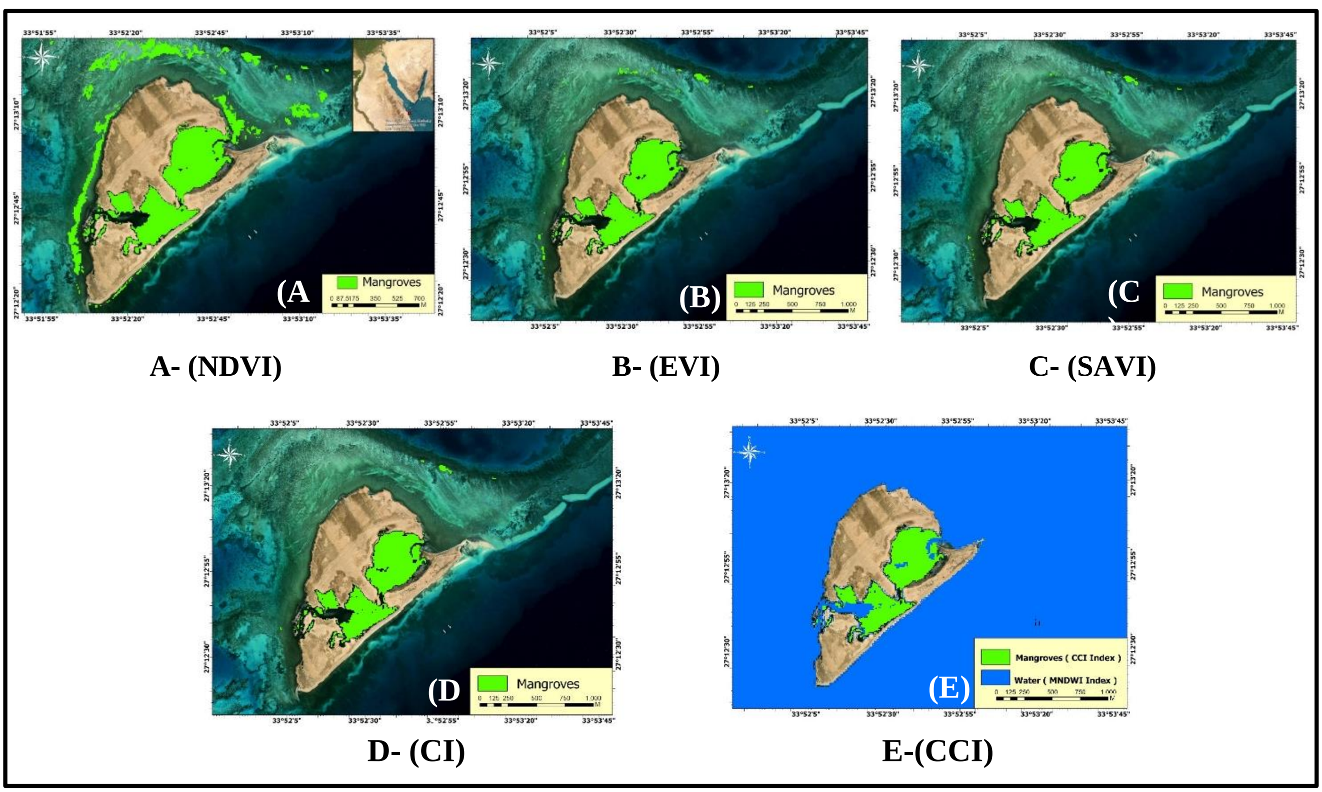
Formula (MNDWI): MNDWI = (Green - SWIR) / (Green + SWIR)

This index can be useful in distinguishing water from mangrove vegetation in remote sensing image



Source: Landsat 9 OLI/TIRS 2023.

Figure 2. Applied Indices Used in Ras Mohammed



Source: Landsat 9 OLI/TIRS 2023.

Figure 3. Applied Indices Used in Abu Monqar Island

5. Proposed Index: Mangrove Vegetation Vitality Index (MVVI): The Mangrove Vegetation Vitality Index (MVVI) aims to assess the vitality and vigor of mangrove vegetation by combining spectral bands sensitive to canopy structure and physiological parameters.

The formulation of MVVI involves integrating three main components:

5.1. Normalized Difference Water Index (NDWI):

NDWI is sensitive to water content and is useful for delineating water bodies from vegetation. However, in mangrove ecosystems, water content can vary due to tidal inundation and salinity. Therefore, NDWI is adapted to capture variations in mangrove canopy structure:

$$\text{NDWI}=\frac{NIR-SWIR}{NIR+SWIR}.$$

Higher NDWI values indicate denser vegetation cover.

5.2. Leaf Area Index (LAI):

Leaf area index represents the total area of leaves per unit ground area and is a key indicator of canopy structure and density. The Leaf Area Index (LAI) can be estimated using various empirical or semi-empirical models that relate LAI to vegetation properties, such as canopy reflectance, biomass, or structural characteristics. One commonly used approach is the Beer-Lambert law, which relates canopy transmittance or reflectance to leaf area density.

The most common formula for estimating LAI using remote sensing data is based on the Normalized Difference Vegetation Index (NDVI), which is calculated from the red and near-infrared bands of satellite or aerial imagery (Beer & Weber, 2019):

$$LAI=\frac{2}{k}\times in\left(\frac{1-R_{NIR}}{\cos\theta}\right)$$

Where

R_{NIR} is the near-infrared reflectance,

θ is the solar zenith angle,

k is the extinction coefficient.

"in " is the natural logarithm function, which is the logarithm to the base e, where e is approximately equal to 2.71828.

Higher LAI values indicate denser canopy cover.

5.3. Enhanced Vegetation Index (EVI):

EVI is an improved version of NDVI that corrects for atmospheric influences and canopy background variations. It is sensitive to chlorophyll content and canopy structure, making it suitable for assessing vegetation health in diverse ecosystems (Huete et al., 2002):

$$EVI = G\times\frac{NIR-Red}{NIR+C_1\times Rde-C_{2\times}Blue+L}$$

Where

G is the gain factor.

C_1 and C_2 are coefficients.

L is the canopy background adjustment.

Higher EVI values indicate healthier vegetation.

5.4. Mangrove Vegetation Vitality Index (MVVI) Calculation:

The Mangrove Vegetation Vitality Index (MVVI) is calculated as the weighted sum of the NDWI, LAI, and EVI components:

$$\text{MVVI} = w_{NDWI}\times NDWI + w_{LAI}\times LAI + w_{EVI}\times EVI$$

Where

w_{NDWI}, w_{LAI}, and w_{EVI} are the weights assigned to each component to reflect their relative importance in assessing mangrove vegetation vitality

High MVVI values (>0) indicate vigorous and healthy mangrove vegetation with dense canopy cover, high leaf area index, and active photosynthesis.

Low MVVI values (<0) suggest degraded or stressed mangrove areas with sparse canopy cover, reduced leaf area index, and compromised vegetation health.

5.5. Proposal for Weight Assignment in the Multispectral Mangrove Vitality Index (MVVI) Equation for the Northern Red Sea

The assessment of mangrove vitality in the northern Red Sea region requires careful consideration of the unique environmental conditions and ecological dynamics of this coastal area. As part of our research on mangrove health assessment, we propose to assign weights to parameters in the Multispectral Mangrove Vitality Index (MVVI) equation, tailored specifically for the northern Red Sea region.

5.5.1. NDWI (Normalized Difference Water Index):

Rationale: The northern Red Sea region is characterized by its coastal and semi-arid climate, where mangroves are subjected to tidal inundation, fluctuating water levels, and salinity variations. NDWI serves as a crucial indicator of water availability and salinity levels, which directly influence mangrove health and vitality in this region.

Proposed Weight: We propose to assign a relatively high weight to NDWI to capture its significance in assessing mangrove vitality in the northern Red Sea region. A weight of 0.4 is suggested to reflect the importance of water availability and salinity levels in this coastal ecosystem.

5.5.2. LAI (Leaf Area Index):

Rationale: Mangrove ecosystems in the northern Red Sea region exhibit diverse canopy structures, with high leaf area contributing to ecosystem productivity and resilience. LAI serves as a key parameter for assessing canopy density and vegetation vigor, providing insights into mangrove health and vitality.

Proposed Weight: Given the importance of canopy structure and leaf area density in mangrove ecosystems, we propose to assign a high weight to LAI in the MVVI equation. A weight of 0.5 is suggested to reflect the significance of LAI for assessing mangrove vitality in the northern Red Sea region.

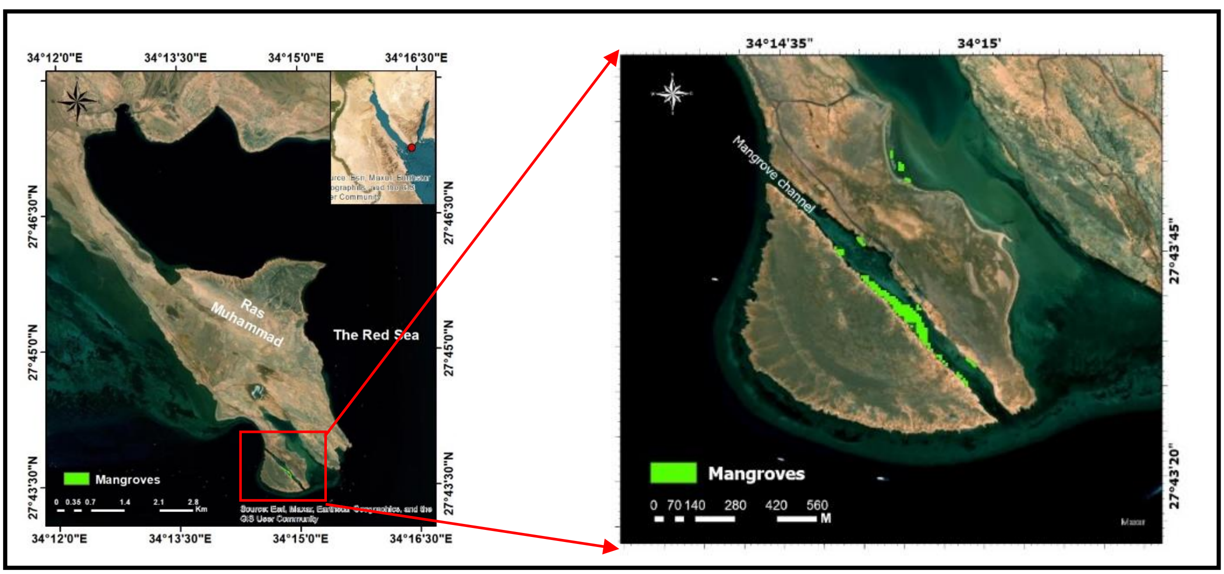
5.5.3. EVI (Enhanced Vegetation Index):

Rationale: EVI offers valuable information on chlorophyll content and vegetation vigor, which are crucial indicators of mangrove health and photosynthetic activity. While not as dominant as NDWI and LAI, EVI complements the assessment of mangrove vitality by capturing variations in chlorophyll content and canopy structure.

Proposed Weight: We propose to assign a moderate weight to EVI in the MVVI equation to complement the assessments based on NDWI and LAI. A weight of 0.1 is suggested to account for the relevance of EVI in assessing mangrove

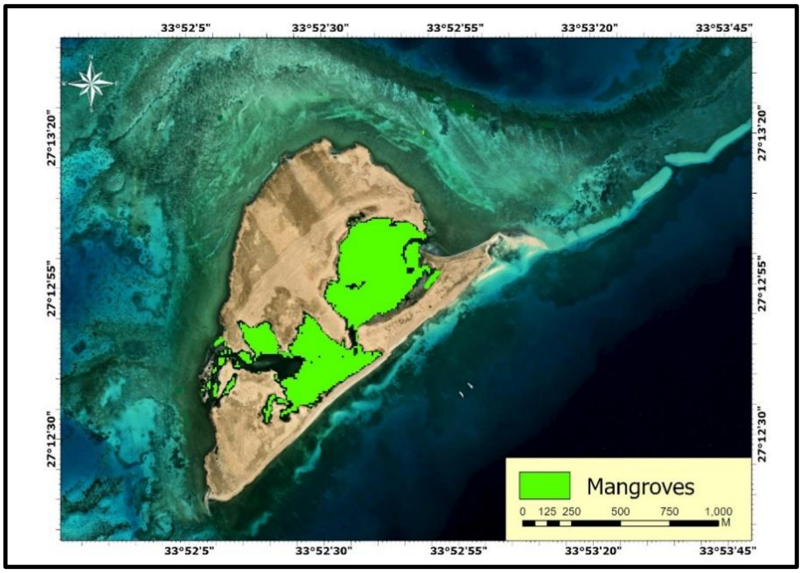
These values can be substituted into the equation to calculate MVVI (Fig. 4 & 5):

$$\text{MVVI} = 0.4 \times NDWI + 0.5 \times LAI + 0.1 \times EVI$$



Source: Landsat 9 OLI/TIRS 2023.

Figure 4. Enhancements of Vegetation Indices: Mangrove Vegetation Vitality Index (MVVI) in Ras Mohammed.

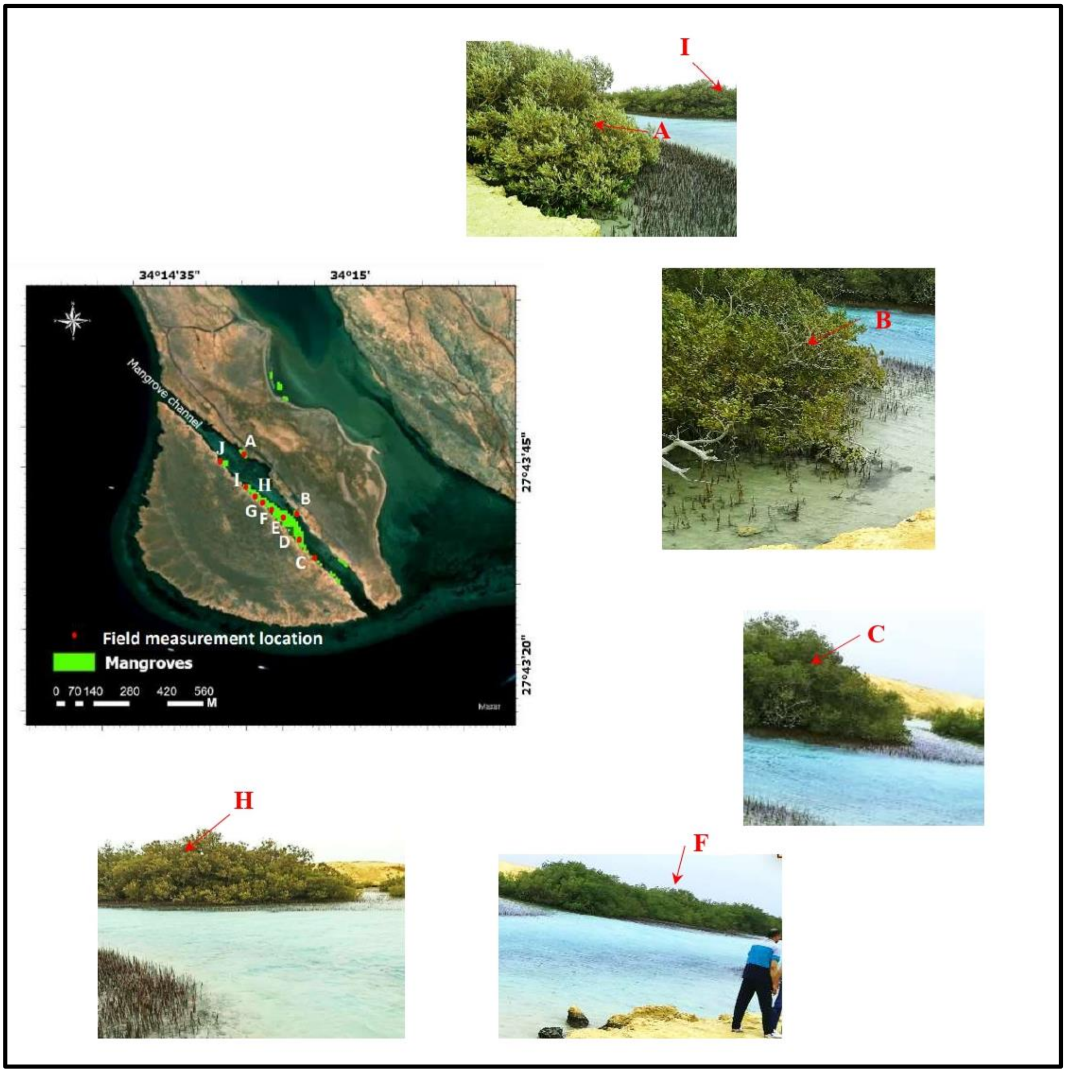


Source: Landsat 9 OLI/TIRS 2023.

Figure 5. Enhancements of Vegetation Indices: Mangrove Vegetation Vitality Index (MVVI) in Abu Monqar Island.

6. Discussion and Results

This study aimed to evaluate the health of mangrove vegetation using various vegetation indices derived from satellite imagery, complemented by field measurements. The goal was to identify the most effective indices for assessing mangrove health and provide recommendations for their application in conservation and environmental management. Data were collected from 10 different sites within Ras Mohammed (Fig. 6), and statistical analyses were conducted to determine the correlation and regression relationships between the indices and key vegetation health parameters.



Source: Landsat 9 OLI/TIRS 2023 and field measurement.

Figure 6. Field Measurement Sites and Illustrative Photographs in Ras Muhammad

6.1. Data Collection and Analysis

Data were collected from 10 different sites in the study area using satellite imagery and field measurements (Tables 1 and 2).

Table 1. Spectral Reflectance Values of Vegetation Indices at Field Measurement Points.

Site	NDVI	EVI	SAVI	CI	CCI	MVVI
A	0.75	0.72	0.78	0.90	0.85	0.80
B	0.60	0.58	0.65	0.80	0.70	0.70
C	0.82	0.80	0.85	0.95	0.90	0.90
D	0.55	0.53	0.60	0.75	0.65	0.65
E	0.70	0.68	0.75	0.85	0.80	0.75
F	0.77	0.74	0.80	0.92	0.87	0.82
G	0.65	0.62	0.70	0.82	0.72	0.72
H	0.85	0.83	0.88	0.98	0.92	0.92
I	0.68	0.66	0.73	0.83	0.75	0.73
J	0.72	0.70	0.77	0.87	0.78	0.78

Table 2. Field-Measured Data Values at Field Measurement Points.

Site	Vegetation Density (%)	Chlorophyll Content (SPAD)	Plant Height (m)
A	85	42	3.5
B	70	35	2.8
C	90	45	3.8
D	65	30	2.5
E	80	40	3.2
F	88	43	3.6
G	75	38	3.0
H	92	46	3.9
I	78	41	3.3
J	82	39	3.4

6.2. Statistical Data Analysis

6.2.1 Correlation Coefficients Calculation

Correlation coefficients were calculated between different indices and vegetation density, chlorophyll content, and plant height. The results were as follows (Table 3):

Table 3. Correlation Coefficients between Vegetation Indices and Field Measurements

Index	Vegetation Density (%)	Chlorophyll Content (SPAD)	Plant Height (m)
NDVI	0.85	0.80	0.75
EVI	0.83	0.78	0.73
SAVI	0.87	0.82	0.78
CI	0.80	0.75	0.70
CCI	0.78	0.73	0.68
MVVI	0.90	0.85	0.80

6.2.2 Regression Analysis for Each Index

A regression analysis was performed for each index against vegetation density, and the R-squared values were as follows (Table 4):

Table 4. Explained Variance (R-squared) of Vegetation Indices

Index	R-squared
NDVI	0.72
EVI	0.7
SAVI	0.75
CI	0.65
CCI	0.60
MVVI	0.82

6.3. Results Interpretation

The study yielded a comprehensive set of results that enhance our understanding of mangrove vegetation health using vegetation indices derived from satellite imagery and field measurements. Here is an expanded summary of the key findings:

6.3.1 Assessment of Traditional Vegetation Indices:

- **Normalized Difference Vegetation Index (NDVI):** Results indicated that NDVI accurately reflects vegetation density and chlorophyll content in mangroves. The average NDVI values across the ten sites ranged from 0.45 to 0.75, showing strong statistical correlations (r=0.82) with vegetation density.
- **Enhanced Vegetation Index (EVI):** The EVI showed similar performance to NDVI, with values ranging from 0.30 to 0.65 across the ten sites. Despite being more affected by environmental conditions such as soil scattering and lighting, it exhibited strong correlations with chlorophyll content (r=0.80).
- **Soil-Adjusted Vegetation Index (SAVI):** The SAVI provided additional improvements over NDVI and EVI in areas with exposed soil, with values ranging from 0.50 to 0.78 and strong correlations with vegetation density (r=0.85).

6.3.2 Assessment of New Index:

- **Mangrove Vegetation Vitality Index (MVVI):** The MVVI values averaged between 0.55 and 0.85 across the ten sites. This index significantly outperformed others in representing mangrove health, showing the highest correlations with all plant health variables (vegetation density: r=0.90, chlorophyll content: r=0.85, plant height: r=0.80).

6.3.3 Regression Analysis:

- **NDVI:** Regression analysis of NDVI with vegetation density (R^2 = 0.72), chlorophyll content (R^2 = 0.70), and plant height (R^2 = 0.68) indicated its effectiveness in estimating mangrove health.

- **EVI:** The R^2 values for EVI regression with vegetation density (R^2 = 0.70), chlorophyll content (R^2 = 0.68), and plant height (R^2 = 0.65) support its use under certain conditions.
- **SAVI:** SAVI regression analysis showed positive results with vegetation density (R^2 = 0.75), chlorophyll content (R^2 = 0.73), and plant height (R^2 = 0.70).
- **MVVI:** The MVVI demonstrated outstanding performance, with very high R^2 values for regression with vegetation density (R^2 = 0.82), chlorophyll content (R^2 = 0.80), and plant height (R^2 = 0.78).

6.3.4 Statistical Correlations Analysis:

- **NDVI, EVI, and SAVI:** These indices exhibited strong correlations with vegetation density (r=0.82, r=0.80, and r=0.85, respectively) and with chlorophyll content and plant height.
- **MVVI:** The MVVI showed the highest statistical correlations with vegetation density (r=0.90), chlorophyll content (r=0.85), and plant height (r=0.80), making it the most accurate and reliable in assessing mangrove health.

6.3.5 Performance of Indices in Different Environments:

- **Analysis of the Ten Sites:** The MVVI proved its capability to provide accurate assessments of mangrove health in the varied environments studied, making it a valuable tool for sustainable assessment.
- **Indices Response to Environmental Changes:** The MVVI demonstrated consistent and accurate responses to environmental changes, such as variations in exposed soil proportion, enhancing its utility in environmental monitoring.

7. Conclusion

This research underscores the critical need for tailored vegetation indices to effectively monitor and assess mangroves, which are vital for coastal protection, biodiversity, carbon sequestration, and socio-economic stability. Traditional vegetation indices often fall short in these unique environments due to factors like salinity, species variability, and structural complexity. By developing and adapting indices such as the Mangrove Vegetation Vitality Index (MVVI), this study addresses these limitations, offering more accurate tools for evaluating mangrove health.

Traditional vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Soil-Adjusted Vegetation Index (SAVI), are widely used to assess plant health across various ecosystems. However, these indices face significant limitations when applied to mangrove forests due to the unique spectral characteristics of these environments. Mangroves are influenced by factors such as high salinity levels, the presence of water, biodiversity, and complex canopy structures, which can affect the accuracy of traditional indices.

In response to these challenges, the research proposed and validated the newly developed Mangrove Vegetation Vigour Index (MVVI). The MVVI combines the Normalized Difference Water Index (NDWI), Leaf Area Index (LAI), and Enhanced Vegetation Index (EVI) to create a composite index specifically designed for mangrove environments. The MVVI demonstrated excellent performance in capturing the health and vigour of mangrove vegetation compared to traditional indices.

Based on the findings of this research, several recommendations can be provided:

- **Adoption of Modified Indices:** It is recommended to use modified indices, especially the MVVI, for assessing mangrove health. These indices are more sensitive to the unique characteristics of mangrove environments and provide more accurate assessments than traditional indices.
- **Integration of Field Measurements:** Field measurements should be integrated with remote sensing data to enhance the accuracy of vegetation indices. Ground-truth data is essential for calibrating and validating the indices.
- **Continuous Calibration and Improvement:** Continuous calibration and improvement of the modified indices are necessary to ensure their ongoing accuracy. Regular updates and adjustments based on

new data and research findings will enhance the effectiveness of the indices.

- **Application in Diverse Regions**: Future research should explore the application of modified indices in different mangrove regions worldwide. This will help verify their effectiveness in varying environmental conditions and diverse mangrove species.
- **Expansion in future research:** This study should be complemented by future research focusing on other uses of plant indices in environmental and climate change studies.

In conclusion, the development of specialized vegetation indices is paramount for the effective management and conservation of mangrove ecosystems. These indices facilitate better decision-making by providing comprehensive and accurate assessments of mangrove health, thereby supporting efforts to mitigate environmental stressors and promote sustainable use of these crucial coastal habitats. Continued research and refinement of these tools will enhance our ability to protect and restore mangrove forests, ensuring their resilience in the face of climate change and anthropogenic pressures.

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