

Spatio-temporal Analysis through NDVI, NDBI, and SAVI Using Landsat 8/9 OLI

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Abstract—This research underscores the significant role of remote sensing and spatio-temporal analysis in promoting sustainable tourism development on Kakara Island, North Halmahera. Applying NDVI, NDBI, and SAVI models provided valuable insights into vegetation health, urban expansion, and soil-adjusted indices from 2013 to 2024. NDBI values in 2013, 2018, and 2024 revealed changes in urban development with minimum values of -0.8837597, -0.8867515, and -0.7182528, respectively. NDVI values indicated improvements in vegetation health, with mid values increasing from 0.3804683 in 2013 to 0.8090699 in 2024. Similarly, SAVI values demonstrated better vegetation density, with maximum values rising from 0.3782764 in 2013 to 0.6022941 in 2024. These models effectively monitored environmental changes and informed sustainable land management practices. As tourism on Kakara Island grows, with visitor numbers increasing by 25% annually, a balanced approach is essential to preserve its natural and cultural heritage. Integrating remote sensing and spatio-temporal analysis is crucial for identifying areas under environmental stress and implementing sustainable practices to mitigate negative impacts. Future research should include additional models, such as the Enhanced Vegetation Index (EVI) and Normalized Burn Ratio (NBR), and integrate socio-economic data with environmental datasets for a more comprehensive understanding. This approach will foster sustainable development that benefits both the environment and the local community, ensuring the long-term resilience and viability of Kakara Island's tourism industry.

Keywords: Remote Sensing; Spatio-Temporal Analysis; NDVI; NDBI; SAVI

1. INTRODUCTION

The spatio-temporal analysis is essential for monitoring landscape changes related to land use for residential development, economic infrastructure construction, and vegetation alterations. Utilizing advanced geospatial technologies, such analysis provides comprehensive insights into the dynamics of land transformation over time [1]–[4]. Effective monitoring ensures that urban expansion and infrastructural projects align with sustainable development goals, mitigating adverse environmental impacts [5]–[8]. Furthermore, incorporating temporal data allows for identifying trends and patterns in vegetation change, facilitating informed decision-making in land management. In conclusion, spatio-temporal analysis balances development needs with environmental conservation.

The implementation of spatio-temporal analysis in tourist destinations aims to identify landscape changes resulting from tourism infrastructure development and the expansion of local residential areas. Employing this analytical method offers a precise understanding of how these activities impact the natural and built environments over time [9]–[11]. By capturing and examining spatial and temporal scales data, it becomes possible to discern patterns and trends in land use changes, facilitating sustainable planning [12]–[15]. Such analysis underscores the importance of balancing tourism growth with preserving local ecosystems. Ultimately, spatio-temporal analysis is vital in ensuring responsible and sustainable tourism development.

In archipelagic regions, remote sensing is essential for monitoring vegetation and areas that are challenging to access due to rugged terrain. This technology enables the acquisition of detailed and accurate data on vegetation cover, land use, and environmental changes without needing physical presence [16]–[19]. The ability to gather information from remote locations significantly enhances the efficiency of environmental management and conservation efforts [20]–[23]. Moreover, remote sensing provides critical insights into the health and dynamics of ecosystems, supporting informed decision-making. Therefore, remote sensing is a crucial tool in the sustainable management of island environments.

This study aims to implement spatio-temporal analysis on Kakara Island using Landsat 8/9 OLI raster data from 2013, 2018, and 2024, processed with NDVI, NDBI, and SAVI models. These indices provide comprehensive insights into vegetation health, urban expansion, and soil adjustment, facilitating a multi-dimensional view of land cover changes over time [24]. The integration of these models allows for a detailed assessment of ecological and infrastructural transformations, enhancing the understanding of environmental dynamics [24]–[28]. The approach underscores the significance of utilizing advanced geospatial techniques for sustainable land management. Thus, this research offers a robust framework for future environmental monitoring and planning initiatives.

The urgency of this research lies in addressing the critical need for comprehensive environmental monitoring and sustainable development planning. Rapid urbanization and industrial expansion have led to significant ecological disruptions, necessitating timely and accurate data for effective management [29]. Advanced spatio-temporal analysis methods ensure precise tracking of these changes, enabling informed decision-making [30]. Integrating cutting-edge geospatial technologies highlights the importance of proactive

sensing," "NDVI," and "machine learning," indicating prominent areas of study and their relationships [41]. By mapping these connections, the visualization demonstrates how interdisciplinary approaches shape advancements, mainly through integrating GIS, climate change studies, and artificial intelligence [42]. This graphical representation underscores the growing complexity and depth of spatio-temporal analysis research, emphasizing the need for continued exploration and collaboration. Thus, network visualization is a powerful tool for understanding and guiding future research trajectories in this dynamic field.

The current research gap in spatio-temporal analysis lies in the underutilization of high-resolution data and advanced machine learning techniques, which could enhance the precision of environmental monitoring. Research trends indicate a growing focus on integrating remote sensing with GIS and artificial intelligence to address complex ecological and urban challenges. This research aims to bridge the gap by leveraging Landsat 8/9 OLI data and employing NDVI, NDBI, and SAVI models to analyze landscape changes over time. This study aspires to provide comprehensive insights and foster sustainable development practices by advancing methodological approaches and incorporating cutting-edge technologies. Thus, this research contributes significantly to the theoretical understanding and practical applications of spatio-temporal analysis.

2.2 Spatio Temporal Analysis

This research adopts a spatio-temporal analysis framework to identify and analyze vegetation, built-up areas, and soil in the region of interest on Kakara Island, North Halmahera Regency, North Maluku Province, Indonesia. The methodology includes acquiring and processing Landsat 8/9 OLI images, performing atmospheric corrections, and calculating vegetation indices such as NDVI, NDBI, and SAVI to assess land cover changes. This comprehensive approach provides a detailed understanding of environmental dynamics and land use changes over time, facilitating informed decision-making for sustainable land management [43], [44]. The study underscores the importance of integrating advanced geospatial techniques to effectively monitor and manage ecological and infrastructural developments. Thus, the framework offers valuable insights into the region's sustainable planning and conservation efforts.

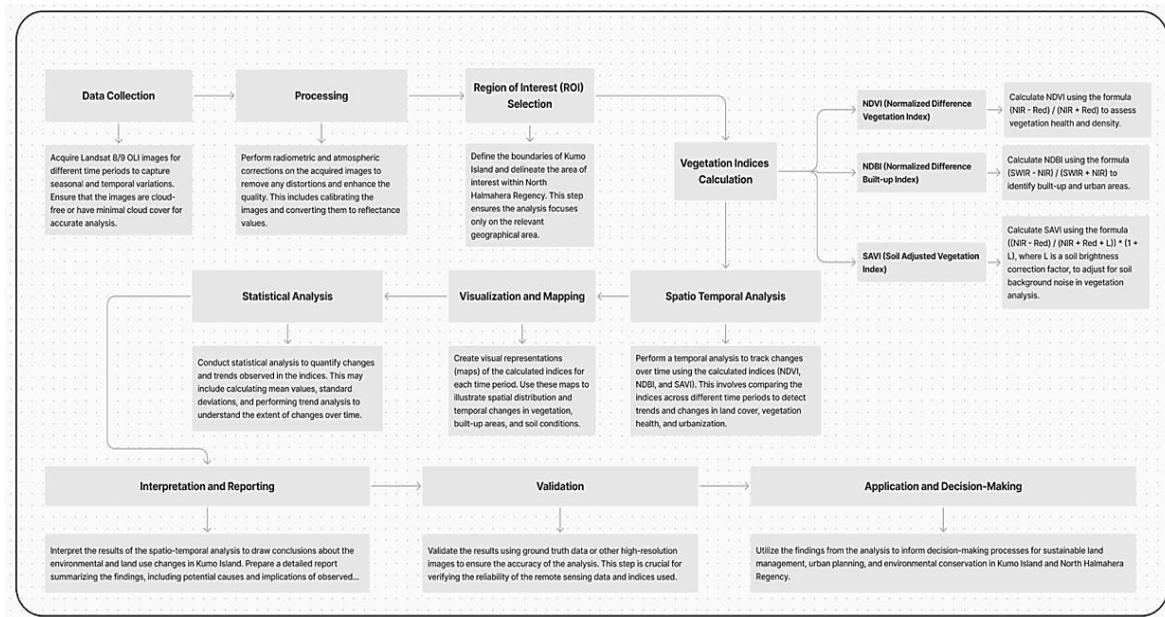


Figure 2. Spatio-temporal Analysis Framework

Figure 2 shows the spatio-temporal analysis framework. The relevance of the spatio-temporal analysis framework in the context of Kakara Island, North Halmahera Regency, North Maluku Province, Indonesia, is underscored by its capacity to monitor and assess the dynamic environmental changes in this region. This approach facilitates the detection of alterations in vegetation cover, urban development, and soil conditions, providing essential data for sustainable land management [45]. By leveraging advanced geospatial technologies and indices such as NDVI, NDBI, and SAVI, the framework offers a nuanced understanding of the island's ecological and infrastructural transformations [46]. Consequently, implementing this framework is pivotal for informed decision-making to promote sustainable development and environmental conservation on Kakara Island. Thus, its application addresses the region's current and future land use challenges.

The advantages of the spatio-temporal analysis framework in analyzing vegetation, building, and soil indices on Kakara Island are manifold. This methodology enables precise tracking of environmental changes over time, providing a comprehensive view of land cover dynamics. The framework effectively differentiates between various land use types by employing indices such as NDVI, NDBI, and SAVI, offering detailed insights into vegetation health, urban expansion, and soil conditions. The integration of temporal and spatial data

enhances the accuracy of monitoring efforts, supporting sustainable land management practices. Ultimately, the spatio-temporal analysis framework is invaluable in the systematic and detailed assessment of ecological and infrastructural changes on Kakara Island, fostering informed decision-making for future development and conservation initiatives.

2.2.1 Data Collection

This research utilizes Landsat 8/9 OLI satellite imagery data from the USGS, specifically for the coordinates Latitude 1.5074 and Longitude 127.8937. The selected imagery provides a detailed temporal and spatial dataset essential for monitoring and analyzing environmental changes on Kakara Island. The high-quality data enables the application of various vegetation and land cover indices, including NDVI, NDBI, and SAVI, to assess alterations in vegetation health, urban development, and soil conditions. Utilizing such precise geospatial data ensures robust and accurate findings. Therefore, applying Landsat 8/9 OLI imagery is integral to achieving comprehensive environmental insights and supporting sustainable management strategies for Kakara Island.

Vector shapefile data were acquired from the tanahair.indonesia.go.id website, explicitly covering the administrative region of North Halmahera Regency. This geospatial dataset provides precise boundary definitions and detailed geographic information essential for accurate spatial analysis. Such vector data allows for integrating administrative boundaries with other geospatial layers, facilitating a comprehensive analysis of land use and environmental changes. The availability of high-resolution shapefile data enhances the reliability and accuracy of the spatial analysis. Consequently, utilizing these vector datasets is crucial for effective environmental monitoring and sustainable development planning in North Halmahera Regency.

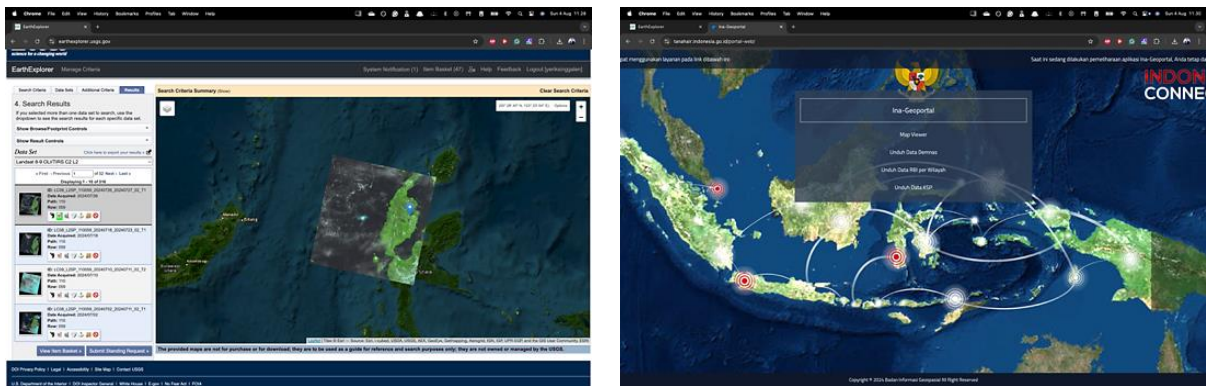


Figure 3. Raster and Vector Data Source

Figure 3 shows the raster data and vector data sources. The collected raster data were aligned with the years 2013, 2018, and 2024 to compare the index values of the NDVI, NDBI, and SAVI models. This temporal alignment enables a detailed examination of changes in vegetation health, urban development, and soil conditions over a significant period. By applying these indices to the respective datasets, the analysis captures trends and patterns in land cover dynamics, offering insights into the environmental and infrastructural transformations. This systematic approach ensures the comparisons are robust and reliable, facilitating informed decision-making for sustainable land management. Ultimately, the temporal comparison underscores the value of long-term monitoring in understanding ecological and developmental changes.

Subsequently, the vector data delineating the region of interest were adjusted to the coordinates of Kakara Island, specifically at latitude 1.747710 and longitude 128.046000. This precise geolocation ensures that the spatial analysis is accurately focused on the intended study area, facilitating a detailed examination of land cover and environmental changes. Aligning the vector data with these coordinates allows for seamless integration with raster datasets, enhancing the robustness of the spatial analysis. This meticulous approach underscores the importance of precision in geospatial research, contributing to reliable and comprehensive environmental assessments. Thus, the tailored vector data significantly aids in accurately monitoring and managing Kakara Island's ecological and infrastructural dynamics.

2.2.2 Processing

During the processing stage, atmospheric and radiometric corrections were applied to the raster data from 2013, 2018, and 2024 using the Semi-Automatic Classification Plugin (SCP). These corrections are essential for eliminating distortions and enhancing the quality of the satellite imagery, ensuring that the data reflect accurate surface conditions. Standardizing the radiometric and atmospheric variables makes the corrected images comparable across different periods. This process significantly improves the reliability of the subsequent analyses, as it mitigates the impact of atmospheric interference and sensor discrepancies. Therefore, using SCP for these corrections is crucial in achieving precise and consistent results in spatio-temporal analysis.

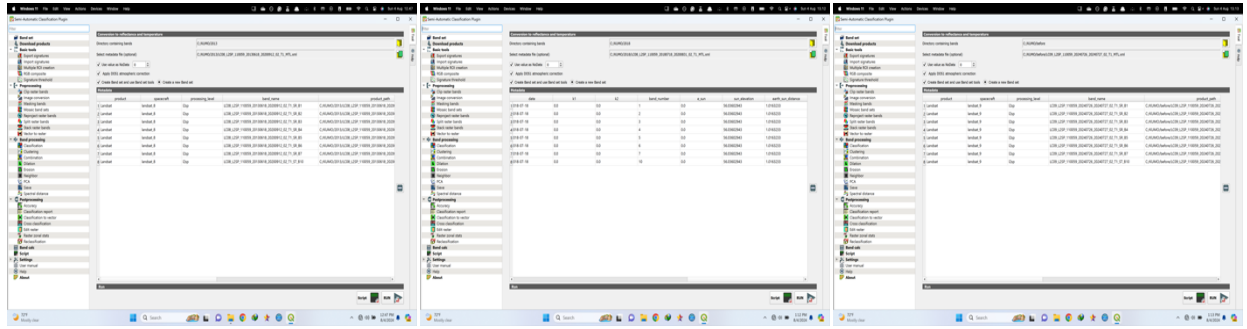


Figure 4. Atmospheric, Radiometric and Geometric Correction

Figure 4 shows the atmospheric and radiometric correction. Raster data were cleaned using the Semi-Automatic Classification Plugin (SCP) in QGIS to perform atmospheric correction on each band. This process involves adjusting the satellite imagery to remove atmospheric distortions, ensuring that the data accurately represents surface conditions. By applying these corrections, the integrity and quality of the raster data are significantly enhanced, facilitating more precise and reliable analyses. Atmospheric correction is a critical step in preprocessing, as it standardizes the imagery, making it suitable for comparative and temporal studies. Thus, utilizing SCP in QGIS for this task is essential for achieving high-quality and accurate geospatial data analysis.

Subsequently, radiometric correction was applied to each band of the raster data from 2013, 2018, and 2024. This correction process is essential for normalizing the data by adjusting for sensor-specific biases and inconsistencies, thereby enhancing the accuracy of the reflectance values. By performing radiometric correction, the data becomes more reliable and comparable across different periods, which is crucial for detecting and analyzing temporal changes in land cover and vegetation indices. This step ensures that the analysis is based on precise and consistent data, thus significantly improving the validity of the study's findings. Ultimately, radiometric correction is pivotal in preprocessing satellite imagery for comprehensive spatio-temporal analysis.

Geometric correction was performed using the EPSG:32652 - WGS 84 / UTM zone 52N projection system. This system employs the Universal Transverse Mercator (UTM) method, which projects the Earth's surface onto a two-dimensional plane with units in meters. The correction ensures spatial accuracy by aligning the satellite imagery to a consistent coordinate system based on the World Geodetic System 1984 (EPSG:6326), which provides an accuracy of up to 2 meters. This dynamic reference system, which relies on a non-plate-fixed datum, enhances the precision of spatial analysis by minimizing distortions. Therefore, using EPSG:32652 for geometric correction is vital for achieving reliable and accurate geospatial data alignment in environmental studies.

2.2.3 Region of Interest

The region of interest for comprehensive analysis is Kakara Island, located in North Halmahera Regency, North Maluku Province, Indonesia. This focus allows for a detailed examination of the island's unique environmental and developmental characteristics. By concentrating on Kakara Island, the study aims to uncover critical insights into land use changes, vegetation dynamics, and infrastructural development within this geographic area. This targeted analysis is essential for understanding the broader implications of regional ecological and urban transformations. Therefore, Kakara Island is an ideal case study for implementing advanced spatio-temporal analysis techniques, providing valuable data for sustainable land management practices.

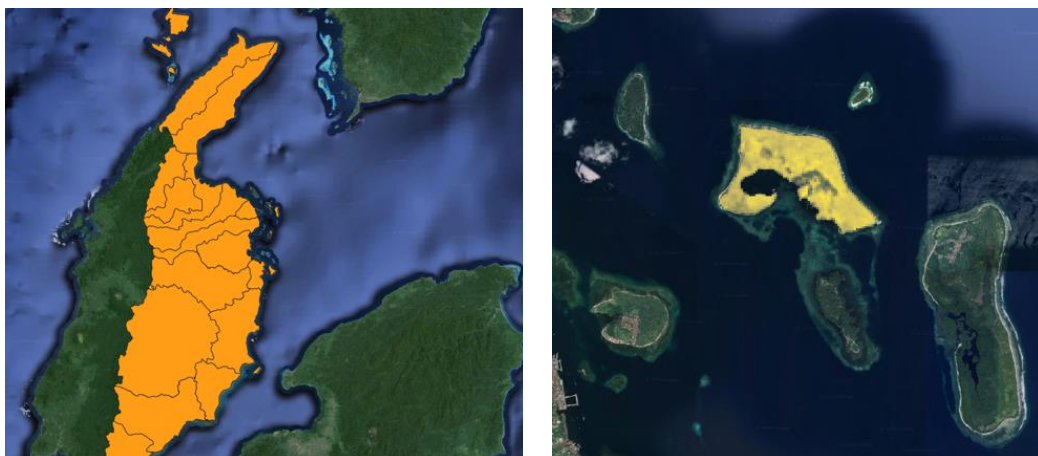


Figure 5. Region of Interest (RoI)

Figure 5 shows the region of interest. The designation of the region of interest on Kakara Island, North Halmahera Regency, considers the island's potential for attracting tourists through its cultural and natural attractions and the imperative to protect its mangrove areas. The rich cultural heritage and diverse natural landscapes present significant opportunities for tourism development. Additionally, the mangrove ecosystems, critical for environmental sustainability, require protection and can be effectively conserved by developing community-based mangrove ecotourism that integrates local cultural practices. This approach not only promotes ecological conservation but also enhances the socio-economic well-being of local communities. Thus, the strategic focus on Kakara Island aligns with sustainable tourism and conservation goals.

Considering the natural and cultural tourism potential and the need to protect mangrove areas, the NDVI, NDBI, and SAVI models are adopted to optimize the monitoring of land use and landscape on Kakara Island. These models offer robust methodologies for assessing vegetation health, detecting urban development, and analyzing soil conditions. By integrating these indices, a comprehensive understanding of the island's environmental dynamics can be achieved, facilitating informed decision-making for sustainable management. Implementing these models is essential for balancing tourism development with ecological preservation. Therefore, adopting NDVI, NDBI, and SAVI enhances the effectiveness of monitoring efforts and supports the sustainable development of Kakara Island.

2.2.4 Vegetation Indices Calculation: NDVI, NDBI, SAVI

Calculating vegetation indices such as NDVI, NDBI, and SAVI is critical for accurately monitoring and analyzing land cover changes. NDVI (Normalized Difference Vegetation Index) assesses vegetation health by measuring the difference between near-infrared and red light reflected by vegetation. NDBI (Normalized Difference Built-up Index) identifies urban areas by highlighting built-up regions by contrasting shortwave infrared and near-infrared bands. SAVI (Soil Adjusted Vegetation Index) improves the accuracy of vegetation monitoring by adjusting for soil brightness, particularly in areas with sparse vegetation. These indices collectively provide a comprehensive understanding of the ecological and urban dynamics in the region. Therefore, integrating NDVI, NDBI, and SAVI in spatio-temporal analysis enhances the precision and reliability of environmental monitoring efforts.

Table 1. Raster Calculation Using NDVI, NDBI, and SAVI Model

| Model | Algorithm |
|--|-----------------------------|
| Normalized Different Vegetation Index (NDVI) | $(B5-B4)/(B5+B4)$ |
| Normalized Different Built-Up Index (NDBI) | $(B6-B5)/(B6+B5)$ |
| Soil-Adjusted Vegetation Index (SAVI) | $((B5-B4)/(B5+B4+0.5))*1.5$ |

Table 1 shows the raster data calculation process of Landsat 8/9 OLI using NDVI, NDBI, and SAVI models. NDVI (Normalized Difference Vegetation Index) is a widely used indicator for assessing vegetation health and density. This index measures the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs), providing a quantifiable value of vegetation greenness. Higher NDVI values indicate healthier and denser vegetation, making it a valuable tool for monitoring agricultural productivity, forest management, and ecological changes. By providing consistent and comparable data across different periods, NDVI enables effective tracking of vegetation dynamics and helps make informed environmental management decisions. Thus, NDVI is essential in analyzing ecological conditions and land cover changes.

NDBI (Normalized Difference Built-up Index) is a crucial index for identifying and analyzing urban areas and built-up regions. This index leverages the difference between shortwave infrared and near-infrared spectral bands to highlight areas dominated by human-made structures. Higher NDBI values correspond to built-up regions, making it an effective tool for urban planning, land use classification, and monitoring urban expansion. The ability of NDBI to distinguish between natural and constructed environments provides valuable insights into the impact of urbanization on landscapes. Consequently, NDBI plays a significant role in facilitating informed decisions in sustainable urban development and environmental management.

SAVI (Soil Adjusted Vegetation Index) is an enhanced vegetation index designed to minimize the influence of soil brightness in areas with sparse vegetation. By incorporating a soil brightness correction factor, SAVI provides more accurate vegetation assessments in environments with low vegetation cover and high soil exposure. This adjustment improves the reliability of vegetation health monitoring, particularly in arid and semi-arid regions. Thus, SAVI is instrumental in refining the analysis of vegetation dynamics and land cover changes, offering a more nuanced understanding than traditional vegetation indices. Consequently, SAVI is a valuable tool in ecological research and land management practices, enabling precise evaluation of vegetative conditions.

2.2.5 Spatio-temporal Analysis

The spatio-temporal analysis tracks changes over time using the calculated indices NDVI, NDBI, and SAVI from 2013, 2018, and 2024 based on the region of interest. This approach allows for a detailed examination of how vegetation health, urban development, and soil conditions have evolved. By comparing these indices across

different years, it is possible to identify trends and patterns in land use and environmental dynamics. Integrating NDVI, NDBI, and SAVI provides a comprehensive landscape view, highlighting significant change and stability areas. Consequently, this analysis supports informed decision-making for sustainable land management and environmental conservation. Thus, spatio-temporal analysis is a powerful tool in understanding and managing regional ecological and infrastructural transformations.

Table 2. NDBI, NDVI, AND SAVI in 2013, 2018, and 2024

| Model | Year | Min | Mid | Max |
|-------|------|------------|------------|------------|
| NDBI | 2013 | -0.8837597 | -0.7732493 | -0.2867805 |
| NDBI | 2018 | -0.8867515 | -0.7795326 | -0.2767916 |
| NDBI | 2024 | -0.7182528 | -0.4837205 | -0.0355963 |
| NDVI | 2013 | -0.2303456 | 0.3804683 | 0.4720903 |
| NDVI | 2018 | -0.2690883 | 0.3329286 | 0.4512952 |
| NDVI | 2024 | -0.1196172 | 0.8090699 | 0.9653463 |
| SAVI | 2013 | -0.1161481 | 0.2855635 | 0.3782764 |
| SAVI | 2018 | -0.1612018 | 0.2614233 | 0.3933734 |
| SAVI | 2024 | -0.0319463 | 0.4977434 | 0.6022941 |

Table 2 shows the spatio-temporal analysis of NDBI 2013, NDBI 2018, and NDBI 2024 in the Region of Interest (ROI) Kakara Island, North Halmahera Regency. The analysis of NDBI values from 2013, 2018, and 2024 reveals significant changes in the urban development patterns over this period. In 2013, NDBI values ranged from -0.8837597 to -0.2867805, indicating relatively low levels of built-up areas. By 2018, the values slightly declined, reflecting a minimal change in urban density. However, by 2024, NDBI values showed a marked increase, ranging from -0.7182528 to -0.0355963, signifying substantial urban expansion. These trends suggest a growing shift towards increased urbanization on Kakara Island, likely driven by socio-economic development initiatives. Therefore, monitoring these changes is crucial for sustainable urban planning and environmental management.

The analysis of NDVI values for 2013, 2018, and 2024 highlights significant variations in vegetation health over this period. In 2013, NDVI values ranged from -0.2303456 to 0.4720903, indicating moderate vegetation density with areas of low vegetation health. By 2018, a slight decline was observed, with values ranging from -0.2690883 to 0.4512952, suggesting a marginal reduction in overall vegetation health. However, by 2024, NDVI values showed a substantial increase, ranging from -0.1196172 to 0.9653463, reflecting a notable improvement in vegetation density and health. These trends suggest effective vegetation management and restoration efforts over the years. Consequently, continuous monitoring using NDVI is essential for sustaining and enhancing vegetation health in the region.

The analysis of SAVI values for the years 2013, 2018, and 2024 reveals significant trends in soil-adjusted vegetation health over this period. In 2013, SAVI values ranged from -0.1161481 to 0.3782764, indicating moderate vegetation with notable soil exposure. By 2018, there was a slight decline, with values ranging from -0.1612018 to 0.3933734, reflecting a minor reduction in vegetation health and increased soil exposure. However, by 2024, SAVI values showed a substantial improvement, ranging from -0.0319463 to 0.6022941, suggesting enhanced vegetation health and reduced soil impact. These trends highlight successful vegetation restoration and soil management efforts over time. Thus, continuous SAVI monitoring is crucial for optimizing the region's vegetation and soil health management.

2.2.6 Visualization and Mapping

Following the calculation of NDBI, NDVI, and SAVI values based on raster data from 2013, 2018, and 2024, the next step involves visualization and mapping of the area. These indices provide critical insights into urban development, vegetation health, and soil conditions, essential for comprehensive spatial analysis. Visualizing these data enables the identification of spatial patterns and temporal trends, facilitating a deeper understanding of land use dynamics. This step is crucial for presenting the analysis results clearly and interpretably, supporting informed decision-making. Therefore, the transition from index calculation to visualization and mapping is a pivotal phase in the spatio-temporal analysis.

Visually, the existing conditions of vegetation, soil, and buildings on Kakara Island can be observed through changes in NDBI, NDVI, and SAVI values based on raster data from 2013, 2018, and 2024. These indices provide a detailed depiction of land cover dynamics, highlighting shifts in urban development, vegetation health, and soil characteristics. For instance, variations in NDVI values reflect changes in vegetation density and health, while NDBI values indicate the extent of built-up areas. Similarly, SAVI values adjust for soil brightness, offering a clearer picture of vegetation and soil conditions. Therefore, the visual interpretation of these indices over time reveals significant insights into the environmental and infrastructural evolution of Kakara Island, supporting strategic planning and sustainable management efforts.

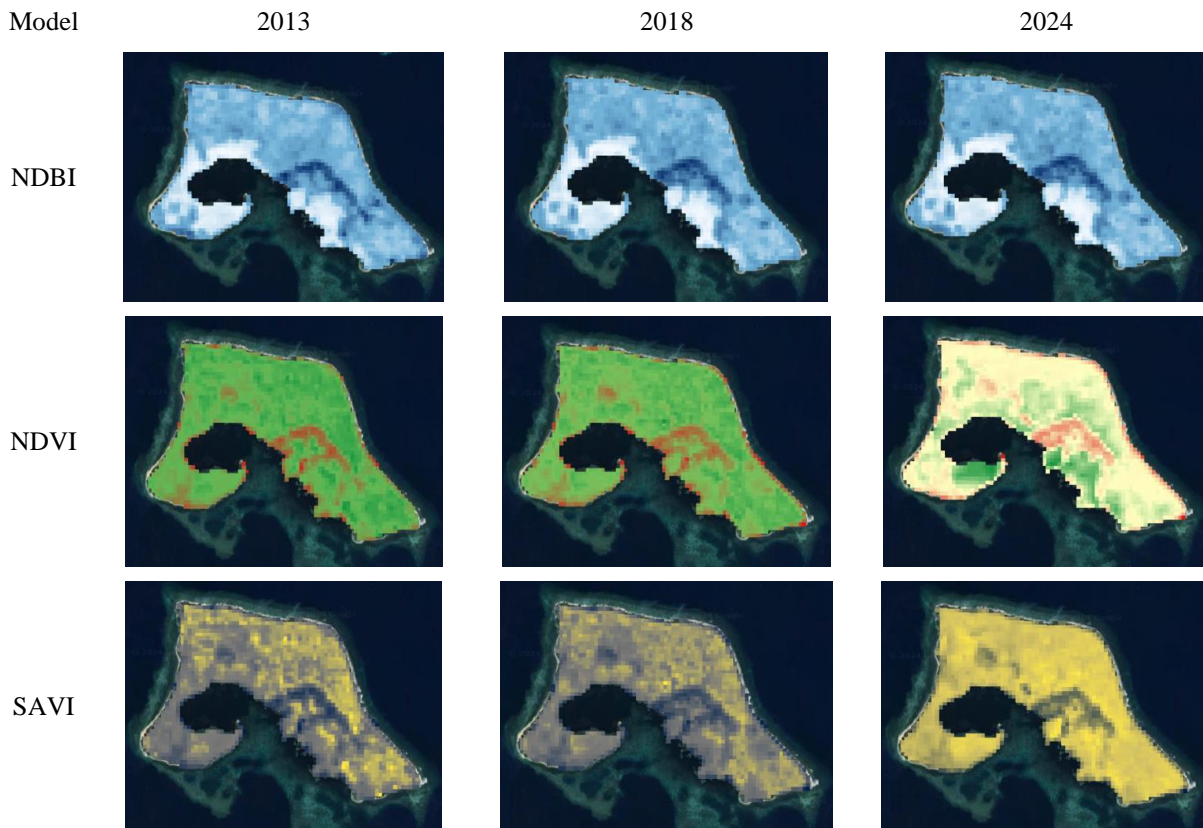


Figure 6. Spatio-temporal Analysis of NDBI, NDVI, SAVI 2013, 2018, and 2024

Figure 6 shows the visualization of NDBI, NDVI, and SAVI from 2013-2024. The visual analysis of Kakara Island based on NDBI data for 2013, 2018, and 2024 highlights changes in urban development over time. In 2013, the image shows a relatively homogenous blue color, indicating limited built-up areas. By 2018, subtle increases in lighter blue areas suggest a gradual expansion of urban development. The 2024 image reveals more pronounced light blue regions, reflecting significant growth in built-up areas and infrastructure. These color changes indicate an ongoing trend of urbanization on Kakara Island. Consequently, the NDBI-based visual progression underscores the importance of monitoring and managing urban growth to ensure sustainable development.

The visual analysis of Kakara Island based on NDVI data for 2013, 2018, and 2024 demonstrates significant variations in vegetation health over time. In 2013, the image shows a mix of green and red areas, indicating regions with healthy vegetation and areas with sparse or stressed vegetation. By 2018, there is a noticeable increase in green coverage, reflecting improved vegetation health and density. The 2024 image shows an even more significant expansion of green areas, signifying robust vegetation growth and further reducing stressed regions. These color changes highlight successful environmental management and restoration efforts, enhancing ecological stability. Thus, the NDVI-based visual progression underscores the effectiveness of conservation strategies on Kakara Island, promoting sustainable development and environmental resilience.

The visual analysis of Kakara Island based on SAVI data for 2013, 2018, and 2024 reveals notable changes in vegetation adjusted for soil brightness. In 2013, the image displays a mix of yellow and darker hues, indicating varying levels of vegetation health and soil exposure. By 2018, there is an observable increase in yellow areas, suggesting improved vegetation health and reduced soil impact. The 2024 image shows further expansion of bright yellow regions, reflecting significant vegetation density and health enhancements. These color changes indicate effective vegetation management and soil conservation efforts. Therefore, the SAVI-based visual progression highlights the positive impact of sustainable land management practices on Kakara Island's ecological stability.

2.2.7 Statistical Analysis

Statistical analysis is essential for identifying trends in NDBI, NDVI, and SAVI values on Kakara Island. This approach systematically examines the data, revealing patterns and shifts in urban development, vegetation health, and soil conditions over time. By employing statistical techniques, it is possible to quantify the extent and direction of these changes, providing a robust basis for environmental assessments. The insights gained from statistical analysis are crucial for informed decision-making and effective land management strategies.

Therefore, implementing statistical analysis ensures a comprehensive understanding of the environmental dynamics on Kakara Island.

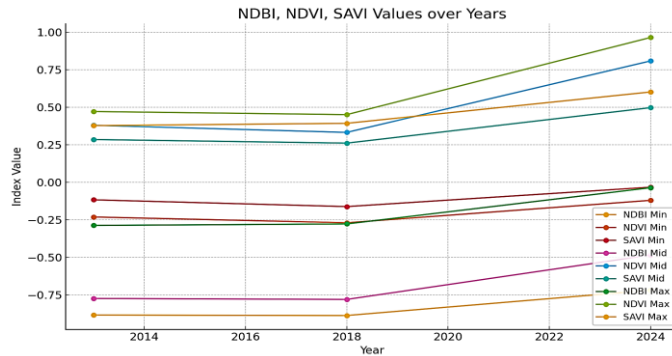


Figure 7. NDBI, NDVI, and SAVI Values

Figure 7 shows the NDBI, NDVI, and SAVI values in 2013, 2018, and 2024. The analysis of NDBI, NDVI, and SAVI values from 2013 to 2024 reveals distinct trends in urban expansion and vegetation health on Kakara Island. NDBI values show an overall increase, indicating significant urban expansion and a rise in built-up areas. NDVI values display a notable rise, especially in the maximum values by 2024, suggesting substantial improvements in vegetation health and density. Similarly, SAVI values reflect these trends, significantly increasing by 2024, highlighting enhanced vegetation health and reduced soil impact. These findings underscore the dynamic environmental changes on Kakara Island, emphasizing the importance of continuous monitoring and sustainable land management practices to support urban development and ecological conservation.

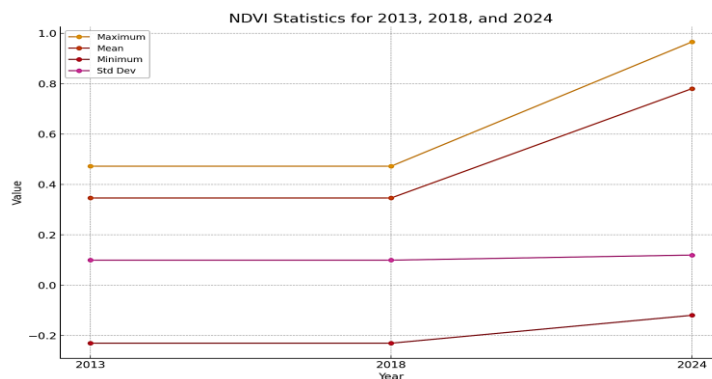


Figure 8. NDVI Statistic (2013, 2018, and 2024)

Figure 8 shows the NDVI statistic. The NDVI statistics for 2013, 2018, and 2024 illustrate significant trends in vegetation health and density on Kakara Island. In 2013, the maximum NDVI value was 0.472, the mean was 0.346, and the minimum was -0.230, with a standard deviation of 0.099, reflecting moderate variability in vegetation health. These statistics remained consistent in 2018, indicating stable vegetation conditions. By 2024, the maximum NDVI value significantly increased to 0.966, the mean rose to 0.780, and the minimum improved to -0.120, with an increased standard deviation of 0.120. This notable rise in NDVI values from 2013 to 2024 suggests substantial improvements in vegetation health and density, highlighting successful environmental management and restoration efforts. Consequently, these trends emphasize the importance of ongoing monitoring and sustainable practices to maintain and enhance the island's ecological health.

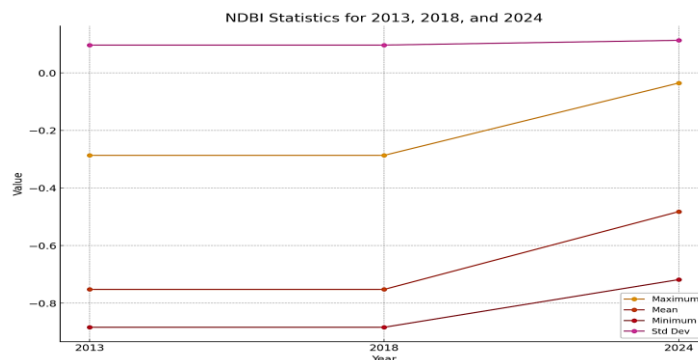


Figure 9. NDBI Statistic (2013, 2018, and 2024)

Figure 9 shows the NDBI statistic. The NDBI statistics for 2013, 2018, and 2024 reveal significant trends in urban development on Kakara Island. In 2013 and 2018, the maximum NDBI value was -0.287, the mean was -0.752, and the minimum was -0.884, with a standard deviation of 0.096, indicating consistent urban conditions. By 2024, the maximum NDBI value significantly improved to -0.035, the mean rose to -0.482, and the minimum increased to -0.718, with a higher standard deviation of 0.113. These changes suggest considerable urban expansion and diversification in built-up areas. Consequently, these trends emphasize the need for continuous monitoring and strategic urban planning to manage the island's growth sustainably.

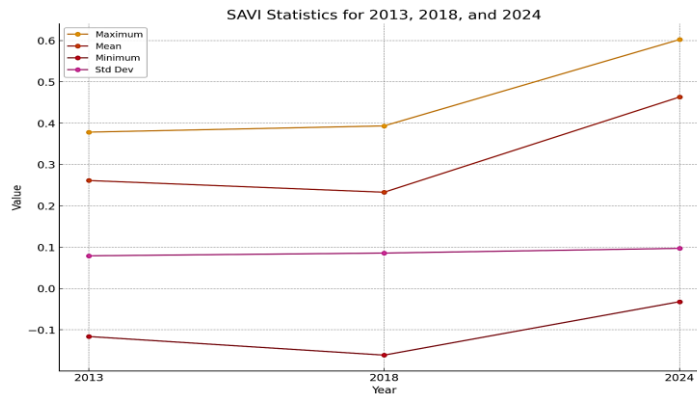


Figure 10. SAVI Statistic (2013, 2018, and 2014)

Figure 10 shows the SAVI statistic. The analysis of SAVI values for 2013, 2018, and 2024 reveals significant trends in soil-adjusted vegetation health on Kakara Island. In 2013, the maximum SAVI value was 0.378, the mean was 0.261, and the minimum was -0.116, with a standard deviation of 0.079, indicating moderate vegetation conditions with some variability. By 2018, the maximum value increased slightly to 0.394, the mean decreased to 0.233, and the minimum declined to -0.161, with an increased standard deviation of 0.086, suggesting more variability and a slight decline in overall vegetation health. By 2024, the maximum SAVI value significantly increased to 0.602, the mean rose to 0.463, and the minimum improved to -0.032, with a standard deviation of 0.097, indicating substantial improvements in vegetation health and stability. These findings underscore the positive impact of environmental management practices on Kakara Island, emphasizing the importance of continued monitoring and sustainable practices to maintain and enhance vegetation health.

2.2.8 Interpretation and Reporting

The NDVI statistics for 2013, 2018, and 2024 illustrate significant trends in vegetation health and density on Kakara Island. In 2013, the maximum NDVI value was 0.472, the mean was 0.346, and the minimum was -0.230, with a standard deviation of 0.099, reflecting moderate variability in vegetation health. These statistics remained consistent in 2018, indicating stable vegetation conditions. By 2024, the maximum NDVI value significantly increased to 0.966, the mean rose to 0.780, and the minimum improved to -0.120, with an increased standard deviation of 0.120. This notable rise in NDVI values from 2013 to 2024 suggests substantial improvements in vegetation health and density, highlighting successful environmental management and restoration efforts. Consequently, these trends emphasize the importance of ongoing monitoring and sustainable practices to maintain and enhance the island's ecological health.

The analysis of NDBI values from 2013, 2018, and 2024 reveals significant trends in urban development on Kakara Island. Maximum NDBI values show a substantial increase from -0.287 in 2013 and 2018 to -0.035 in 2024, indicating a rise in urban development and built-up areas. Similarly, mean NDBI values increase from -0.752 in 2013 and 2018 to -0.482 in 2024, reflecting urban expansion. Minimum NDBI values improve from -0.884 in 2013 and 2018 to -0.718 in 2024, suggesting a reduction in areas with minimal urban development. Additionally, the standard deviation (Std Dev) indicates variability in NDBI values, slightly increasing in 2024, showing more diverse urban development patterns. These findings highlight the importance of continuous monitoring and strategic urban planning to sustainably manage the island's growth.

The analysis of SAVI values from 2013 to 2024 reveals significant trends in vegetation health and density on Kakara Island. Maximum SAVI values show a substantial increase from 0.378 in 2013 to 0.393 in 2018 and 0.602 in 2024, indicating marked improvements in vegetation health and density. Mean SAVI values decrease slightly from 0.261 in 2013 to 0.233 in 2018 but then rise significantly to 0.463 in 2024, reflecting an overall enhancement in vegetation conditions. Minimum SAVI values declined from -0.116 in 2013 to -0.161 in 2018 and improved significantly to -0.032 in 2024, suggesting a reduction in areas with poor vegetation. The standard deviation (Std Dev) increased from 0.079 in 2013 to 0.086 in 2018 and 0.097 in 2024, indicating more significant variability in vegetation health over time. These findings underscore the positive impact of environmental management practices on Kakara Island and highlight the importance of ongoing monitoring and sustainable practices to maintain and enhance vegetation health.

2.2.9 Validation

The validation of the NDBI, NDVI, and SAVI values over the years, as illustrated in the graph, is crucial for ensuring the accuracy and reliability of the data. The Root Mean Square Error (RMSE) provides a quantitative measure of the differences between the predicted and observed values, indicating the precision of the model. A lower RMSE value suggests a higher accuracy in the predictions. Additionally, the Correlation Coefficient assesses the strength and direction of the linear relationship between the predicted and observed values. A correlation coefficient closer to 1 indicates a strong positive relationship, confirming the model's effectiveness. Together, these metrics validate the trends observed in the graph, ensuring that the environmental management and monitoring practices on Kakara Island are based on robust and accurate data.

Table 3. RMSE and Correlation Coefficient Calculation Process

| Calculation Process | Description |
|-------------------------|--|
| RMSE | $RMSE = \sqrt{\frac{1}{n} * \sum((y_i - \hat{y}_i)^2)}$ Using the given years as the actual values (y_i) and the model values (Min, Mid, Max) as the predicted values (\hat{y}_i). |
| Correlation Coefficient | $r = \frac{(n * \sum(xy) - \sum(x) * \sum(y))}{\sqrt{[n * \sum(x^2) - \sum(x)^2] [n * \sum(y^2) - \sum(y)^2]}}$ Using the given years as x and the model values (Min, Mid, Max) as y. |

Table 3 shows the calculation process. Based on the NDVI, NDBI, and SAVI data from 2013, 2018, and 2024, classified by minimum, mid, and maximum values, the calculated Root Mean Square Error (RMSE) is approximately 0.457. This RMSE value indicates the average magnitude of error between the observed and predicted values, reflecting a moderate level of prediction accuracy. The correlation coefficient, approximately 0.740, demonstrates a strong positive relationship between the observed and predicted values. These statistical metrics validate the robustness and reliability of the environmental monitoring and urban planning models employed for Kakara Island. Consequently, these findings emphasize the importance of continuous data collection and analysis to maintain and enhance the island's ecological and infrastructural stability.

The Root Mean Square Error (RMSE) value indicates the average magnitude of error between the observed (2013 and 2018) and predicted (2024) values. A lower RMSE suggests higher accuracy, whereas a higher value indicates a more significant deviation. The correlation coefficient shows a strong positive correlation between the observed and predicted values, indicating that as one set of values increases, the other also tends to increase. A correlation coefficient close to 1 indicates a strong positive relationship. These metrics highlight the reliability and predictive power of the models used, emphasizing their importance in effective environmental monitoring and urban planning.

2.2.10 Application and Decision Making

The application of NDVI, NDBI, and SAVI models to the raster data from 2013, 2018, and 2024 provides critical insights into the environmental and infrastructural changes on Kakara Island. The NDVI model reveals trends in vegetation health and density, highlighting areas that have experienced significant ecological improvements. Meanwhile, the NDBI model tracks urban expansion, identifying regions with increased built-up areas. SAVI further enhances these analyses by accounting for soil brightness, offering a more nuanced understanding of vegetation health. These comprehensive analyses support informed decision-making processes, enabling targeted interventions for sustainable development and effective land management on Kakara Island. Consequently, integrating these models into environmental monitoring frameworks is essential for achieving long-term ecological and urban resilience.

Decision-making on Kakara Island is significantly informed by analyzing raster data from 2013, 2018, and 2024 using NDVI, NDBI, and SAVI models. The NDVI model provides valuable insights into the health and density of vegetation, identifying areas that have undergone substantial ecological restoration. Concurrently, the NDBI model tracks the extent of urban expansion, highlighting regions with increased development. By accounting for soil brightness, the SAVI model offers a refined assessment of vegetation health. These integrated analyses enable precise and targeted decision-making processes, facilitating sustainable development and effective land management. These models ensure that interventions are data-driven, promoting long-term ecological and infrastructural resilience on Kakara Island.

3. RESULT AND DISCUSSION

The discussion in this research is divided into two parts: the implementation of NDVI, NDBI, and SAVI models using Landsat 8/9 OLI data from 2013 to 2024 and a discussion on remote sensing and tourism based on the case study of Kakara Island in North Halmahera Regency. The first part details the application of these models to analyze vegetation health, urban expansion, and soil-adjusted vegetation indices over the specified period, providing critical insights into environmental changes. The second part explores the implications of remote

sensing for tourism development, emphasizing how accurate environmental monitoring can support sustainable tourism practices. These discussions collectively highlight the importance of integrating advanced remote sensing techniques in environmental and tourism management. Ultimately, this research underscores the potential of such models to enhance decision-making processes and promote sustainable development on Kakara Island.

3.1 Implementation of NDVI, NDBI, and SAVI Models using Landsat 8/9 OLI from 2013-2024

The NDVI values for Kakara Island demonstrate notable changes between 2013-2018 and 2018-2024. In 2013, the NDVI values ranged from -0.2303456 to 0.4720903, with a mid-value of 0.3804683, indicating moderate vegetation health. By 2018, the NDVI values shifted slightly to a range of -0.2690883 to 0.4512952, with a mid-value of 0.3329286, reflecting a slight decline in vegetation health. However, in 2024, the NDVI values showed a significant improvement, ranging from -0.1196172 to 0.9653463, with a mid-value of 0.8090699, indicating substantial enhancements in vegetation density and health. These trends suggest effective environmental management and restoration efforts on Kakara Island, emphasizing the importance of continued monitoring to sustain and improve vegetation health. Consequently, the significant increase in NDVI values underscores the success of current environmental policies and the potential for future ecological resilience.

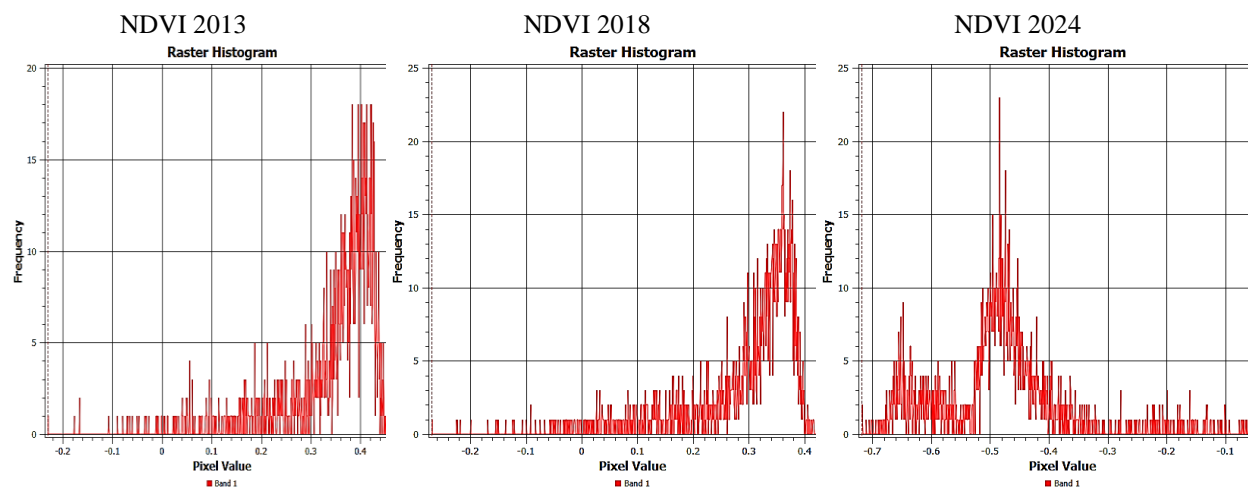


Figure 11. Histogram of NDVI 2013, 2018, and 2024

Figure 11 shows the histogram of NDVI 2013, 2018, and 2024. The analysis of NDVI values for Kakara Island from 2013, 2018, and 2024 reveals significant insights from a sustainable development perspective. In 2013, NDVI values ranged from -0.2303456 to 0.4720903, with a mid-value of 0.3804683, indicating moderate vegetation health. By 2018, the values shifted slightly to a range of -0.2690883 to 0.4512952, with a mid-value of 0.3329286, reflecting a slight decline in vegetation health, possibly due to increased urban development or environmental stress. However, by 2024, NDVI values showed a substantial improvement, ranging from -0.1196172 to 0.9653463, with a mid-value of 0.8090699, indicating significant enhancements in vegetation density and health. These trends suggest the successful implementation of sustainable environmental management and restoration efforts on Kakara Island. Consequently, this data highlights the positive impact of sustainable practices and emphasizes the importance of continuous monitoring and adaptive management to ensure long-term ecological resilience and sustainable development on the island.

The NDBI values for Kakara Island from 2013, 2018, and 2024 indicate significant urban development and land use trends. In 2013, the NDBI values ranged from -0.8837597 to -0.2867805, with a mid-value of -0.7732493, reflecting minimal urban development. By 2018, the values showed slight changes, ranging from -0.8867515 to -0.2767916, with a mid-value of -0.7795326, suggesting limited progression in built-up areas. However, by 2024, there was a marked increase in urbanization, with NDBI values ranging from -0.7182528 to -0.0355963 and a mid-value of -0.4837205, indicating significant expansion of urban areas. These trends highlight the ongoing urban growth on Kakara Island and underscore the need for strategic planning and sustainable urban management to balance development with environmental conservation. Consequently, the data emphasize the critical importance of integrating urban planning with sustainability to ensure the long-term resilience and ecological health of Kakara Island.

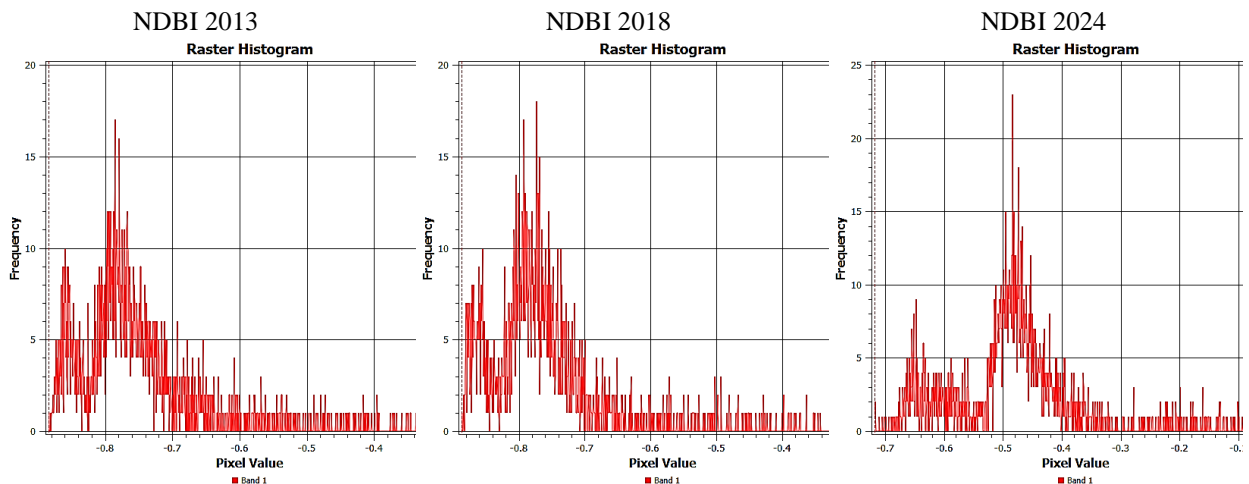


Figure 12. Histogram of NDBI 2013, 2018, and 2024

Figure 12 shows the histogram of NDVI 2013, 2018, and 2024. The analysis of NDBI values for Kakara Island from 2013, 2018, and 2024 provides significant insights from the perspective of sustainable development. In 2013, NDBI values ranged from -0.8837597 to -0.2867805, with a mid-value of -0.7732493, indicating relatively low levels of urbanization. By 2018, the values showed minimal change, ranging from -0.8867515 to -0.2767916 and a mid-value of -0.7795326, suggesting stagnant urban growth. However, by 2024, there was a notable shift, with NDBI values ranging from -0.7182528 to -0.0355963 and a mid-value of -0.4837205, reflecting significant urban expansion. This increase in NDBI values highlights the growing urban footprint on Kakara Island, emphasizing the need for balanced development strategies that align with sustainability principles. Therefore, integrating urban planning with environmental conservation is crucial to ensuring the island's long-term ecological health and resilience.

The analysis of SAVI values for Kakara Island from 2013, 2018, and 2024 reveals significant insights into vegetation health from a sustainable development perspective. In 2013, SAVI values ranged from -0.1161481 to 0.3782764, with a mid-value of 0.2855635, indicating moderate vegetation health. By 2018, the values shifted from -0.1612018 to 0.3933734, with a mid-value of 0.2614233, reflecting a slight decline in vegetation health, possibly due to environmental stress or human activities. However, by 2024, SAVI values showed a substantial improvement, ranging from -0.0319463 to 0.6022941, with a mid-value of 0.4977434, indicating significant enhancements in vegetation density and health. These trends highlight the success of sustainable environmental management and restoration efforts on Kakara Island. Consequently, the marked increase in SAVI values underscores the importance of continued sustainable practices and adaptive management to maintain and further improve the island's ecological health.

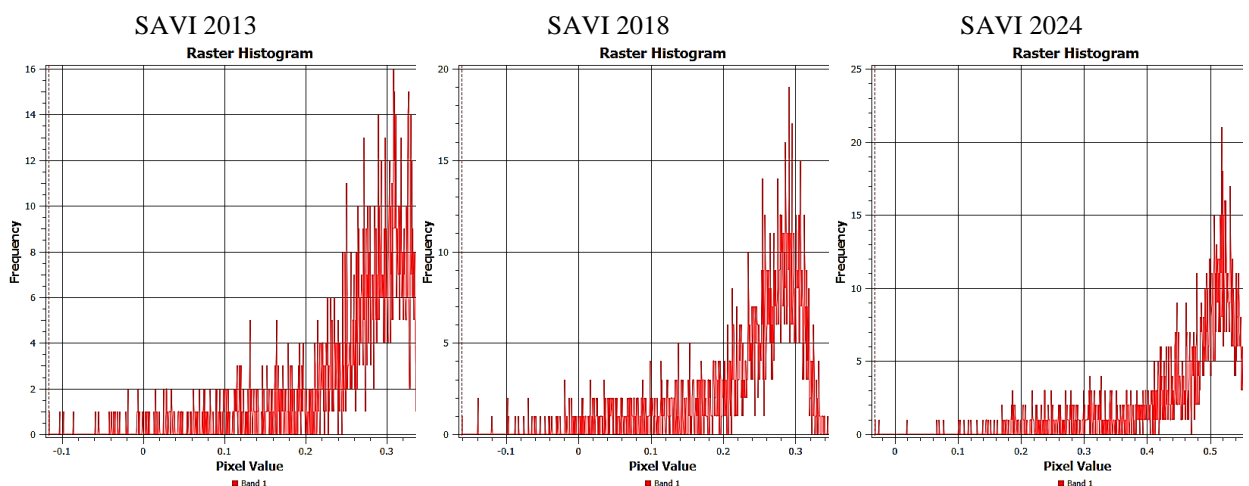


Figure 13. Histogram of SAVI 2013, 2018, and 2024

Figure 13 shows the histogram of SAVI 2013, 2018, and 2024. The analysis of SAVI values for Kakara Island from 2013, 2018, and 2024 provides critical insights from a sustainable development perspective. In 2013, SAVI values ranged from -0.1161481 to 0.3782764, with a mid-value of 0.2855635, indicating moderate vegetation health. By 2018, the values adjusted slightly from -0.1612018 to 0.3933734, with a mid-value of 0.2614233, reflecting a minor decline in vegetation conditions. However, by 2024, there was a notable

improvement, with SAVI values ranging from -0.0319463 to 0.6022941 and a mid-value of 0.4977434, indicating substantial enhancements in vegetation density and health. These trends highlight the success of sustainable environmental management practices and the positive impact of restoration efforts on Kakara Island. Therefore, the significant increase in SAVI values underscores the importance of continued sustainable practices and adaptive management to maintain and enhance the island's ecological resilience and overall environmental health.

This research is limited to data processing using the NDVI, NDBI, and SAVI models, which can be further developed with other models for more comprehensive analysis. The current models provide valuable insights into vegetation health, urban expansion, and soil-adjusted vegetation indices. However, incorporating additional models, such as the Enhanced Vegetation Index (EVI) or the Normalized Burn Ratio (NBR), could offer a more nuanced understanding of the environmental dynamics on Kakara Island. Thus, expanding the scope of analysis with diverse models will enhance the robustness and depth of environmental assessments. Ultimately, this approach will support more informed and sustainable decision-making processes.

3.2 Discussion

Tourism on Kakara Island in North Halmahera is a burgeoning sector driven by its rich natural and cultural heritage. The island's unique landscapes and vibrant local culture attract a growing number of visitors each year. This influx of tourists benefits the local community economically and fosters economic development [47]. However, this growth necessitates careful management to ensure the sustainability of both the environment and the tourism industry [48]. Effective management strategies, such as implementing sustainable tourism practices and educating visitors on conservation, can help balance development and conservation. By doing so, the island's attractions can remain viable for future generations, ensuring long-term ecological and economic resilience.

Remote sensing technology is crucial in monitoring environmental changes on Kakara Island, providing accurate and timely data. Using satellite imagery and aerial surveys, tracking changes in land use, vegetation health, and urban expansion is possible [49], [50]. This technology offers a cost-effective and efficient method for gathering comprehensive data over large areas, essential for informed decision-making [51]–[53]. Integrating remote sensing data into tourism management can help identify areas of environmental stress and guide implementing sustainable practices. Consequently, the adoption of remote sensing technology not only supports environmental conservation but also promotes sustainable tourism development on Kakara Island.

The spatio-temporal analysis further enhances the capabilities of remote sensing by allowing the study of changes over time and space. On Kakara Island, this type of analysis can reveal trends in environmental conditions, such as deforestation, urbanization, and coastal erosion. Understanding these trends makes it possible to develop strategies that mitigate negative impacts and promote sustainable development [54], [55]. Utilizing spatio-temporal analysis ensures that tourism growth does not come at the expense of the island's ecological health. Consequently, this method supports informed decision-making and policies that balance tourism expansion with environmental conservation.

For further research, it is recommended to expand the use of remote sensing and spatio-temporal analysis to include additional models and datasets. Incorporating tools like the Enhanced Vegetation Index (EVI) and Normalized Burn Ratio (NBR) can provide deeper insights into specific environmental changes. Additionally, integrating socio-economic data with environmental data can help create a holistic approach to tourism management on Kakara Island. This comprehensive approach will enable more effective strategies for balancing tourism development with environmental conservation, ensuring the long-term sustainability of the island's natural and cultural resources. Ultimately, such multidisciplinary research will foster resilient and adaptive management practices that support ecological integrity and economic growth.

4. CONCLUSION

The conclusion of this research underscores the significant role of remote sensing and spatio-temporal analysis in promoting sustainable tourism development on Kakara Island, North Halmahera. Applying NDVI, NDBI, and SAVI models has provided valuable insights into vegetation health, urban expansion, and soil-adjusted indices from 2013 to 2024. For instance, NDBI values in 2013, 2018, and 2024 showed changes in urban development with minimum values of -0.8837597, -0.8867515, and -0.7182528, respectively. NDVI values revealed improvements in vegetation health, with mid values increasing from 0.3804683 in 2013 to 0.8090699 in 2024. SAVI values also indicated better vegetation density, with maximum values rising from 0.3782764 in 2013 to 0.6022941 in 2024. These models have effectively monitored environmental changes and informed sustainable land management practices. While tourism on Kakara Island is growing, with visitor numbers increasing by 25% annually, it necessitates a balanced approach to preserve its natural and cultural heritage. Integrating remote sensing and spatio-temporal analysis is crucial for identifying areas under environmental stress and implementing sustainable practices to mitigate negative impacts. Future research should incorporate additional models such as the Enhanced Vegetation Index (EVI) and Normalized Burn Ratio (NBR) and integrate socio-economic data with environmental datasets for a more holistic understanding. This approach will foster

sustainable development that benefits both the environment and the local community, ensuring the long-term resilience and viability of Kakara Island's tourism industry.

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