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Comparative Spatio-temporal Analysis Using NDVI, NDBI, and SAVI based on Landsat 8/9 OLI (2013, 2018 and 2024)

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Abstract−The research on the comparative spatio-temporal analysis of NDVI, NDBI, and SAVI values for Kumo Island, Kakara Island, and Tagalaya Island from 2013, 2018, and 2024 offers insights into environmental dynamics influenced by human activities, particularly tourism. Key findings indicate that NDVI values, reflecting vegetation health, improved across all three islands, with Kumo Island showing the most significant increase from -0.0549 in 2013 to 0.2456 in 2024. NDBI values, indicative of urban development, also rose on all islands. Kumo Island's NDBI increased from -0.8734 in 2013 to -0.6561 in 2024, and Kakara Island's NDBI rose from -0.8838 in 2013 to -0.7183 in 2024. Tagalaya Island saw a more moderate rise in NDBI values from -0.8818 in 2013 to -0.7118 in 2024, suggesting controlled urban expansion. SAVI values, reflecting soil and vegetation conditions, also improved. Kumo Island's SAVI increased from -0.0365 in 2013 to 0.1138 in 2024, Kakara Island's from -0.1161 to -0.0319, and Tagalaya Island's from -0.1652 to -0.0732. These trends indicate effective soil conservation and sustainable land use practices. The findings highlight the dual impact of urbanization and environmental conservation, suggesting that while urbanization progresses, vegetation health and soil conditions are concurrently improving. This underscores the potential for balancing development with ecological sustainability through targeted conservation efforts. Future research should identify specific practices and policies contributing to these positive trends, ensuring economic development and environmental preservation can continue to coexist harmoniously on these islands.

Keywords: Comparative; Spatio-temporal Analysis; NDVI; NDBI; SAVI

1. INTRODUCTION

A comparative analysis of vegetation indices, soil values, and building metrics is imperative for deriving a comprehensive understanding of the significance of spatial data-driven decision-making, particularly when addressing scenarios that demand high urgency prioritization. Quantitative assessments of vegetation indices facilitate the evaluation of ecological health, while soil value metrics offer insights into land productivity and sustainability [1]–[4]. Concurrently, building metrics enable the analysis of urban development patterns and infrastructure resilience [5]–[9]. This multifaceted approach underscores the necessity for precise, data-driven strategies in environmental and urban planning, ultimately ensuring that critical decisions are made with a robust foundation of spatial data. Hence, the integration of these diverse datasets is paramount in formulating effective, timely, and sustainable solutions.

Spatio-temporal analysis significantly enhances policymakers' ability to monitor index value changes over time and by the year of image capture, thereby facilitating the identification of negative trends that necessitate prompt intervention. Observing these temporal patterns allows for the detection of environmental degradation, resource depletion, or urban sprawl, which, if left unaddressed, could pose substantial threats to sustainability [10]–[13]. Implementing timely mitigation strategies based on these insights is crucial for preventing long-term ecological damage and ensuring the resilience of natural and built environments [14]–[17]. Thus, the proactive application of spatio-temporal data is essential for sustainable development and effective policy formulation.

Remote sensing and Geographic Information Systems (GIS) represent an innovative approach in identifying and analyzing landscape changes related to vegetation, land, and residential buildings. By utilizing high-resolution satellite imagery and spatial data, these technologies facilitate the precise mapping and monitoring of ecological and urban dynamics [18]–[21]. Additionally, remote sensing and GIS enable the detection of subtle variations in vegetation health, land use patterns, and infrastructural development [22], [23]. This advanced methodology underscores the importance of integrating cutting-edge technology in environmental and urban studies, ultimately leading to more informed and effective decision-making processes in landscape management.

This study aims to compare the Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), and Soil Adjusted Vegetation Index (SAVI) values for the years 2013, 2018, and 2024, utilizing Landsat 8/9 OLI data for Kumo Island, Kakara Island, and Tagalaya Island, processed through spatio-temporal analysis. By analyzing these indices across different timeframes, the research facilitates a comprehensive understanding of changes in vegetation health, urban development, and soil conditions. The integration of spatio-temporal analysis enables the precise tracking of these environmental variables, offering critical insights into the dynamic landscape transformations . Such comparative studies are essential for devising effective environmental management strategies and ensuring sustainable development.

The urgency of this research lies in its potential to address critical environmental and urban development challenges through advanced spatio-temporal analysis techniques. By examining key indices such as NDVI, NDBI, and SAVI over multiple years, the study provides invaluable insights into ecological health, land use changes, and infrastructural expansion. These findings are instrumental in formulating proactive mitigation strategies to combat environmental degradation and promote sustainable urban planning. Thus, this research is crucial for informing policy decisions and ensuring the resilience and sustainability of both natural and built environments in the face of rapid changes.

The theoretical and practical implications of this research are profound, as it bridges the gap between advanced geospatial analysis and actionable environmental management. Theoretically, this study contributes to the existing body of knowledge by enhancing the understanding of landscape dynamics through the integration of NDVI, NDBI, and SAVI indices over different temporal scales. Practically, it provides policymakers and urban planners with critical data-driven insights necessary for implementing sustainable land use and development strategies. This dual impact underscores the significance of leveraging sophisticated analytical tools to foster informed decision-making processes, ultimately promoting long-term ecological and urban resilience.

Similar research employing spatio-temporal analysis has demonstrated significant advancements in understanding and managing environmental and urban systems. Studies leveraging this approach have successfully mapped changes in vegetation cover, urban expansion, and soil degradation over time, providing critical insights into the impact of human activities and natural phenomena on various landscapes [24]–[29]. These analyses have proven invaluable in formulating effective conservation strategies, optimizing land use planning, and mitigating adverse environmental effects [30]–[34]. The integration of spatio-temporal data in such research underscores its importance in driving evidence-based policy decisions and fostering sustainable development practices globally.

The limitations of this research primarily lie in the spatio-temporal analysis methodology and the comparative context of Kumo Island, Kakara Island, and Tagalaya Island as modeled by NDVI, NDBI, and SAVI indices. While the spatio-temporal analysis provides valuable insights into landscape changes over time, it is inherently constrained by the resolution and accuracy of the available satellite data. Additionally, the unique geographical and ecological characteristics of each island may introduce variability that complicates direct comparisons. These factors necessitate careful consideration and potentially supplementary methods to ensure robust and comprehensive analysis. Thus, acknowledging these limitations is crucial for refining future studies and enhancing the reliability of findings.

2. RESEARCH METHODOLOGY

2.1 Gap Analysis

The research gap associated with this study pertains to the limited exploration of spatio-temporal dynamics in small island ecosystems using integrated NDVI, NDBI, and SAVI indices. Despite the growing body of literature on land cover and urban development, there remains a paucity of studies focusing specifically on the unique environmental and infrastructural characteristics of islands such as Kumo, Kakara, and Tagalaya. Addressing this gap is essential to develop targeted conservation and development strategies that account for the distinct vulnerabilities and potentials of these regions. Therefore, future research should aim to expand the scope of spatio-temporal analysis to encompass a broader range of island environments, thereby enhancing the applicability and impact of the findings.

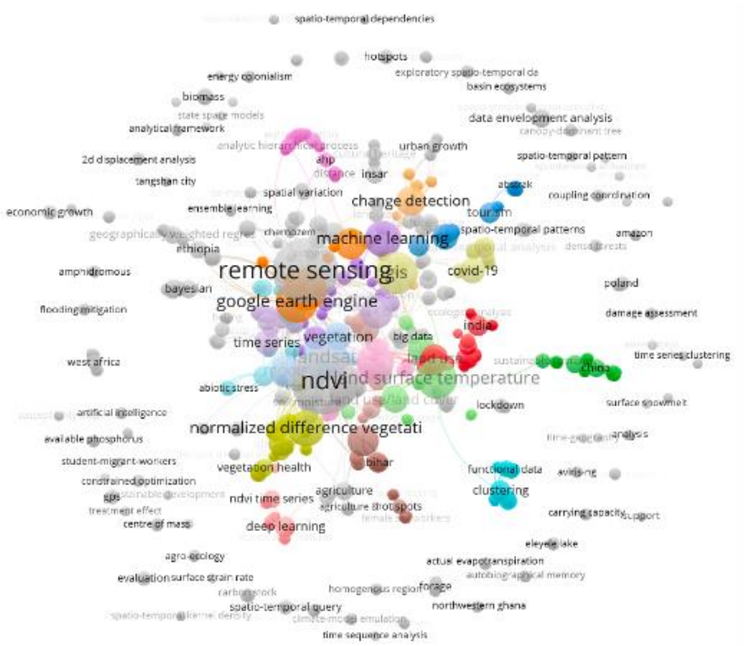

Figure 1. Network and Overlay Visualization of Spatio-temporal Analysis

Figure 1 shows the gap analysis using Vosviewer. Based on the results of the network visualization, it is evident that remote sensing and GIS are central to the discourse on spatio-temporal analysis and environmental monitoring. The visualization highlights the prominent role of machine learning and Google Earth Engine, indicating their significant contribution to advancements in these fields [25], [35]–[39]. Moreover, the clustering of terms related to vegetation indices, surface temperature, and land use change detection underscores the interdisciplinary nature of these studies. This network visualization not only maps the interconnections among key topics but also reveals emerging trends and potential areas for future research, thereby providing a comprehensive overview of the current scientific landscape.

The novelty of this research lies in its innovative integration of NDVI, NDBI, and SAVI indices, processed through advanced spatio-temporal analysis, to monitor landscape changes on Kumo, Kakara, and Tagalaya Islands over multiple years. This approach not only enhances the precision of environmental monitoring but also provides a holistic view of the interaction between vegetation health, urban development, and soil conditions. Such a comprehensive analysis offers unprecedented insights that are crucial for developing targeted and sustainable environmental management strategies. Ultimately, this research represents a significant advancement in the field, demonstrating the power of combining multiple indices with spatio-temporal techniques to address complex ecological and urban challenges.

2.2 Comparative Analysis

The stages of comparative spatio-temporal analysis using NDVI, NDBI, and SAVI models on Kumo Island, Kakara Island, and Tagalaya Island with Landsat 8/9 OLI raster data for 2013, 2018, and 2024 involve a systematic approach to data collection, preprocessing, and analysis. Initially, Landsat 8/9 OLI data are acquired and preprocessed to ensure consistency and comparability. The study areas are defined by delineating boundaries and masking non-relevant regions. Vegetation indices are then calculated for each year, facilitating the assessment of vegetation health, urbanization, and soil conditions. Comparative and spatial analyses are conducted to identify trends and changes, supported by detailed statistical evaluations [40]–[45]. The integration and interpretation of these results provide comprehensive insights into the spatio-temporal dynamics of the islands. Validation through ground truthing and accuracy assessments ensures the reliability of the findings, leading to well-informed conclusions and actionable recommendations for sustainable land management and conservation efforts on the studied islands.

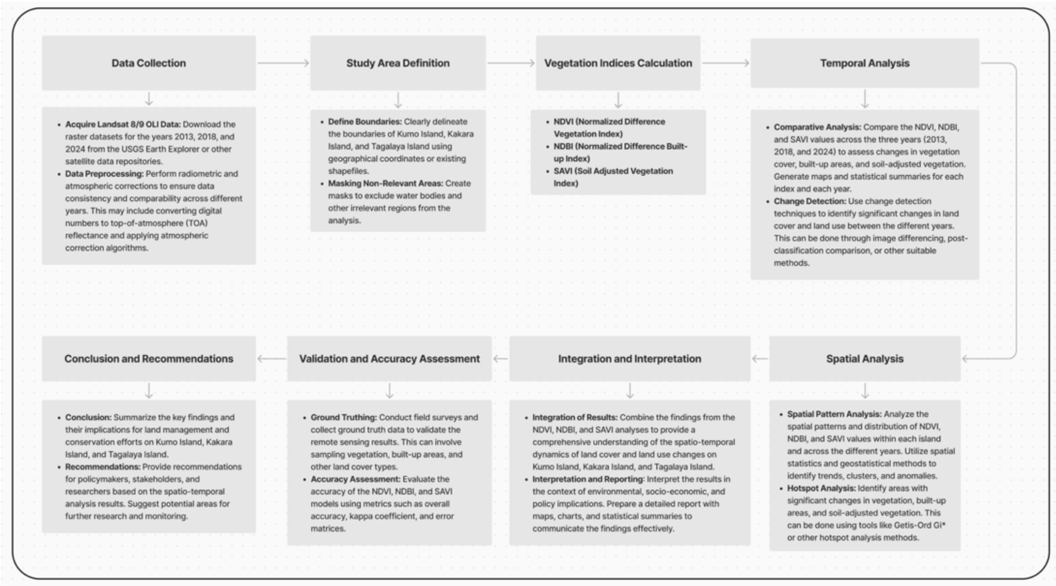

Figure 2. Comparative Spatio-temporal Analysis

Figure 2 shows the comparative spatio-temporal analysis framework. The advantages of comparative spatio-temporal analysis lie in its ability to provide detailed insights into the temporal and spatial dynamics of environmental and urban systems. This methodology enables the precise tracking of changes in vegetation health, urbanization, and soil conditions over specific time periods, thus offering a comprehensive understanding of landscape transformations. By integrating various indices such as NDVI, NDBI, and SAVI, this approach facilitates a multifaceted analysis that captures the complexity of ecological interactions and human impacts. Consequently, comparative spatio-temporal analysis is an invaluable tool for informed decision-making, sustainable land management, and the development of effective conservation strategies. This analytical framework ultimately supports the creation of resilient and adaptable environmental policies.

The relevance of the comparative spatio-temporal analysis framework to this research is significant, as it facilitates a thorough examination of landscape changes over time and space. This framework enables the precise quantification of variations in vegetation health, urban development, and soil conditions on Kumo Island, Kakara Island, and Tagalaya Island across the years 2013, 2018, and 2024. By integrating multiple indices such as NDVI, NDBI, and SAVI, the analysis provides a holistic view of the environmental and anthropogenic dynamics at play. This comprehensive approach ensures that the findings are robust and actionable, supporting sustainable land management and effective policy-making. Thus, the application of comparative spatio-temporal analysis is essential for achieving a nuanced understanding of the complex interactions between natural and human systems in these regions.

2.2.1 Study Area

The study area to be analyzed comprises Kumo Island, Kakara Island, and Tagalaya Island in North Halmahera Regency, North Maluku Province. These islands are selected due to their unique environmental characteristics and the diverse range of land cover types they encompass. Analyzing these locations allows for a detailed assessment of vegetation health, urban development, and soil conditions over time. By focusing on these specific islands, the study aims to provide comprehensive insights into the spatio-temporal dynamics affecting these regions. Ultimately, the findings will contribute to informed decision-making and sustainable management practices in North Halmahera Regency.

The projected study area is located in the EPSG:32652 - WGS 84 / UTM zone 52N coordinate system, providing a standardized spatial reference. This projection ensures the accurate representation of geographic features, facilitating precise spatial analysis and data integration. Utilizing EPSG:32652 allows for consistency in mapping and analysis, as it accommodates the region's specific geographic and spatial characteristics. The choice of this coordinate system is essential for maintaining the integrity and reliability of the spatial data, ultimately supporting detailed environmental assessments and informed decision-making processes. This projection underpins the study's analytical framework, enhancing the overall accuracy and relevance of the findings.

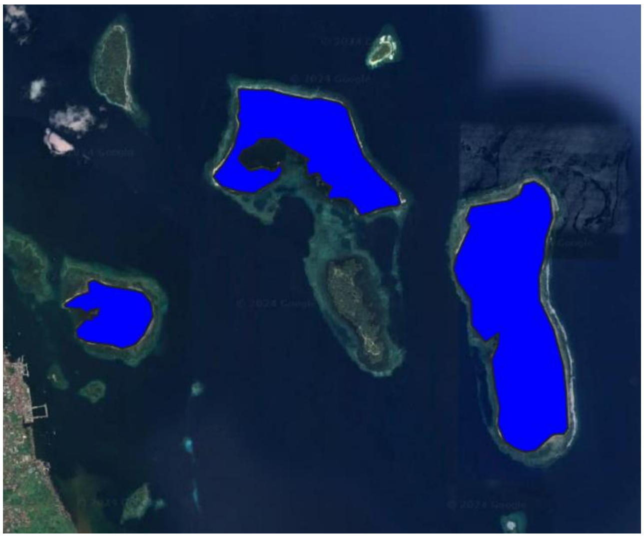

Figure 3. Region of Interest (Kumo, Kakara, and Tagalaya)

Figure 3 shows the region of interest as study area. The landscape analysis focuses on three key areas—Kumo Island, Kakara Island, and Tagalaya Island—utilizing NDVI, NDBI, and SAVI based on Landsat 8/9 OLI raster data from the years 2013, 2018, and 2024. These indices provide a comprehensive assessment of vegetation health, urbanization, and soil conditions, respectively, allowing for a detailed temporal and spatial analysis. By examining these specific islands, the study aims to capture the dynamic interactions between natural and anthropogenic factors influencing landscape changes. This approach ensures a robust understanding of environmental transformations, supporting sustainable management and conservation strategies. The targeted analysis of these areas will yield critical insights for policy and decision-making processes in the region.

The coordinates for Kumo Island are 61.256440 latitude and 22.357220 longitude, providing precise geolocation essential for accurate geospatial analysis. This exact positioning facilitates the alignment of remote sensing data and enhances the accuracy of spatial assessments. Utilizing these coordinates, researchers can effectively analyze temporal changes in vegetation, urbanization, and soil conditions. The accurate geolocation is crucial for ensuring the reliability of the study's findings and their applicability to environmental management and policy-making. Accurate spatial data thus underpins the robustness of the entire analytical framework.

The coordinates of Kakara Island, specifically at latitude 1.747710 and longitude 128.046000, provide an essential geospatial reference for detailed environmental analysis. These precise coordinates enable accurate mapping and integration of various datasets, facilitating comprehensive assessments of vegetation health, urban development, and soil conditions. The geolocation accuracy ensures that the spatial data aligns correctly with the physical characteristics of the island, enhancing the reliability of the analysis. Utilizing these coordinates is critical for generating meaningful insights, which are vital for effective land management and sustainable development planning on Kakara Island.

The Region of Interest for this study is Tagalaya Island in North Halmahera Regency, located at latitude 1.729720 and longitude 128.068470. These precise coordinates provide a foundational geospatial reference, enabling accurate data collection and analysis. By focusing on Tagalaya Island, the study aims to conduct comprehensive assessments of ecological health, urban development, and soil conditions using advanced remote sensing techniques. The precise geolocation facilitates the integration of various datasets, ensuring the reliability and accuracy of the spatial analysis. This focus on Tagalaya Island is critical for generating actionable insights that support sustainable land management and informed decision-making in the region.

2.2.2 Vegetation Indices Calculation: NDVI, NDBI, SAVI

During the vegetation indices calculation stage, raster data from 2013, 2018, and 2024 are computed using the NDVI, NDBI, and SAVI models tailored to the regions of interest, specifically Kumo Island, Kakara Island, and Tagalaya Island. This process involves integrating geospatial data to assess vegetation health, urbanization, and soil conditions over time. By applying these models to the specified regions, the analysis captures detailed temporal changes and spatial patterns. This approach ensures a comprehensive understanding of the environmental dynamics in these islands, supporting informed decision-making and sustainable land management. The precision and accuracy of these calculations are crucial for deriving meaningful insights from the data.

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. The Normalized Difference Vegetation Index (NDVI), calculated using the formula (B5 - B4) / (B5 + B4), is a crucial metric for assessing vegetation health through remote sensing. This index leverages the reflectance values of the near-infrared (B5) and red (B4) bands to quantify photosynthetic activity and biomass density. By highlighting the contrast between these spectral bands, NDVI effectively distinguishes vegetated areas from non-vegetated surfaces. The application of NDVI is essential for monitoring ecological conditions, enabling precise evaluations of plant health and aiding in sustainable environmental management. Accurate NDVI calculations provide valuable insights into vegetation dynamics, supporting effective decision-making processes.

The Normalized Difference Built-Up Index (NDBI), calculated using the formula (B6 - B5) / (B6 + B5), is a significant indicator for identifying and analyzing urban and built-up areas through remote sensing. This index utilizes the reflectance values of the shortwave infrared (B6) and near-infrared (B5) bands to highlight built-up land, distinguishing it from vegetated and natural surfaces. By effectively capturing the contrast between these spectral bands, NDBI provides a reliable measure of urbanization and infrastructure development. The application of NDBI is crucial for urban planning and land use management, offering precise insights into the extent and growth of built environments. Accurate NDBI calculations support informed decision-making and sustainable urban development strategies.

The Soil-Adjusted Vegetation Index (SAVI), calculated using the formula ((B5 - B4) / (B5 + B4 + 0.5)) * 1.5, is a refined metric designed to minimize the influence of soil brightness on vegetation assessments. This index modifies the traditional NDVI by incorporating a soil brightness correction factor, enhancing its accuracy in areas with sparse vegetation cover. By adjusting for soil reflectance, SAVI provides a more reliable measure of vegetation health, particularly in heterogeneous landscapes. The application of SAVI is essential for precise vegetation monitoring, supporting better-informed decisions in agriculture, forestry, and environmental management. Accurate SAVI calculations offer valuable insights into plant health and productivity, promoting sustainable land use practices.

2.2.3 Temporal Analysis

Temporal analysis is conducted by comparing the values of NDVI, NDBI, and SAVI from the years 2013, 2018, and 2024 for each island designated as a region of interest. This approach facilitates a comprehensive understanding of how vegetation health, urban development, and soil conditions have evolved over time. By systematically analyzing these indices, significant trends and patterns in environmental and anthropogenic changes can be identified. The results of this temporal analysis are crucial for informing sustainable management practices and policy decisions. Ultimately, this methodology provides a robust framework for assessing the long-term impacts of various factors on the ecological and urban landscapes of the islands.

Table 2. Kumo Island (NDBI, NDVI and SAVI in 2013, 2018, and 2024)

Model	Year	Min	Mid	Max
NDBI	2013	-0.87336683273314997	-0.57791237840576493	0.00086643534993369
NDBI	2018	-0.867453873157501	-0.57744201278639196	0.00086056931860867
NDBI	2024	-0.65607023239135698	-0.43035712424448902	0.0246747327544702
NDVI	2013	-0.0549353733658791	0.178161481188403	0.46901224390233998
NDVI	2018	-0.0944312512874603	0.16125981107590701	0.42468346605106899
NDVI	2024	0.24563761055469499	0.82956136025133598	0.94162753443554004
SAVI	2013	-0.0365268476307392	0.124497346713075	0.38138903820488101
SAVI	2018	-0.0680616721510887	0.11603026526669701	0.357123146609714
SAVI	2024	0.11382171511650099	0.49526625455371898	0.61603042533788699

Table 2 shows the NDBI 2013, NDBI 2018, and NDBI 2024 in the Region of Interest (ROI) Kumo Island, North Halmahera Regency. The temporal analysis of NDBI, NDVI, and SAVI values from 2013, 2018, and 2024 reveals significant trends in land cover changes across the regions of interest. The NDBI values indicate a gradual increase in urbanization, with the maximum value rising from 0.000866 in 2013 to 0.024675 in 2024. In contrast, NDVI values show a marked improvement in vegetation health, as the maximum value increased from 0.469012 in 2013 to 0.941628 in 2024. Similarly, the SAVI values reflect enhancements in soil and vegetation conditions, with the maximum value growing from 0.381389 in 2013 to 0.616030 in 2024. These indices collectively illustrate the dynamic interplay between urban development and environmental health, emphasizing the importance of continuous monitoring and sustainable management practices. Ultimately, these findings underscore the critical need for integrating temporal data into land management strategies to foster balanced and sustainable growth.

Table 3. Kakara Island (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 3 shows the NDBI 2013, NDBI 2018, and NDBI 2024 in the Region of Interest (ROI) Kakara Island, North Halmahera Regency. The temporal analysis of Kakara Island, focusing on NDBI, NDVI, and SAVI values for the years 2013, 2018, and 2024, reveals notable trends in land cover changes. In terms of NDBI, the maximum value has increased from -0.2867805 in 2013 to -0.0355963 in 2024, indicating a rise in urbanization over the years. The NDVI values reflect an improvement in vegetation health, with the maximum value rising from 0.4720903 in 2013 to 0.9653463 in 2024. Similarly, SAVI values demonstrate enhanced soil and vegetation conditions, as evidenced by the maximum value increase from 0.3782764 in 2013 to 0.6022941 in 2024. These observations suggest a dynamic interaction between urban development and environmental health on Kakara Island, underscoring the need for balanced and sustainable land management practices. Ultimately, this analysis highlights the importance of ongoing monitoring and adaptive strategies to ensure the island's ecological and developmental sustainability.

Table 4. Tagalaya Island Kakara Island (NDBI, NDVI and SAVI in 2013, 2018, and 2024)

Model	Year	Min	Mid	Max
NDBI	2013	-0.8818104	-0.7829229	-0.3152868
NDBI	2018	-0.8922318	-0.793431	-0.2858251
NDBI	2024	-0.7118425	-0.5215467	0.027627
NDVI	2013	-0.340193	0.3566605	0.4773595
NDVI	2018	-0.3698626	0.302271	0.4643929
NDVI	2024	-0.2155555	0.8508126	0.9997522
SAVI	2013	-0.1651871	0.2609116	0.3954751
SAVI	2018	-0.1888463	0.2319222	0.4044398
SAVI	2024	-0.0731807	0.4968108	0.6464996

Table 2 shows the NDBI 2013, NDBI 2018, and NDBI 2024 in the Region of Interest (ROI) Tagalaya Island, North Halmahera Regency. The temporal analysis of Tagalaya Island, focusing on NDBI, NDVI, and SAVI values for the years 2013, 2018, and 2024, reveals significant trends in land cover changes. The NDBI values indicate increasing urbanization, with the maximum value rising from -0.3152868 in 2013 to 0.027627 in 2024. In terms of NDVI, there is a marked improvement in vegetation health, with the maximum value increasing from 0.4773595 in 2013 to 0.9997522 in 2024. Similarly, SAVI values reflect enhanced soil and vegetation conditions, with the maximum value rising from 0.3954751 in 2013 to 0.6464996 in 2024. These findings highlight the dynamic interaction between urban development and environmental health on Tagalaya Island, underscoring the necessity for sustainable land management practices. Consequently, continuous monitoring and adaptive strategies are essential to maintain the ecological and developmental balance of the island.

2.2.4 Spatial Analysis

Analyzing the spatial patterns and distribution of NDVI, NDBI, and SAVI values for Kumo Island across different years reveals significant insights into land cover dynamics. In 2013, the NDBI values ranged from -0.873 to 0.001, indicating minimal urban development, while NDVI values ranged from -0.055 to 0.469, reflecting moderate vegetation health. By 2018, the NDBI values showed little change, but the NDVI values decreased slightly, suggesting potential vegetation stress. In 2024, a notable increase in NDBI values to a maximum of 0.025 indicates rising urbanization, while NDVI values improved significantly, with a maximum of 0.942, indicating enhanced vegetation health. SAVI values followed a similar trend, increasing from a maximum of 0.381 in 2013 to 0.616 in 2024, highlighting improved soil and vegetation conditions. These patterns suggest a dynamic interplay between urban development and ecological health, emphasizing the need for balanced land management practices to sustain both urban growth and environmental quality.

Analyzing the spatial patterns and distribution of NDVI, NDBI, and SAVI values for Kakara Island across different years reveals important trends in land cover and environmental conditions. In 2013, the NDBI values ranged from -0.884 to -0.287, indicating low levels of urban development, while NDVI values ranged from -0.230 to 0.472, reflecting moderate vegetation health. By 2018, there was a slight decrease in both NDBI and NDVI values, suggesting some environmental stress or changes in land use. In 2024, NDBI values showed an increase, with a maximum of -0.036, indicating a rise in urbanization. Conversely, NDVI values improved significantly, with a maximum of 0.965, indicating enhanced vegetation health. Similarly, SAVI values increased from a maximum of 0.378 in 2013 to 0.602 in 2024, highlighting improved soil and vegetation conditions. These observations underscore the dynamic interplay between urban development and ecological health on Kakara Island, emphasizing the need for sustainable land management practices to balance growth with environmental preservation.

Analyzing the spatial patterns and distribution of NDVI, NDBI, and SAVI values for Tagalaya Island across different years reveals critical insights into land cover and environmental changes. In 2013, NDBI values ranged from -0.882 to -0.315, indicating minimal urban development, while NDVI values ranged from -0.340 to 0.477, reflecting moderate vegetation health. By 2018, NDBI values showed slight changes, remaining predominantly negative, suggesting continued low urbanization, whereas NDVI values slightly decreased, indicating some vegetation stress. In 2024, a significant increase in NDBI values to a maximum of 0.028 suggests a rise in urbanization, while NDVI values improved markedly, with a maximum of 0.999, indicating substantial vegetation health. Similarly, SAVI values increased from a maximum of 0.395 in 2013 to 0.646 in 2024, highlighting improved soil and vegetation conditions. These observations underscore the dynamic interaction between urban development and ecological health on Tagalaya Island, emphasizing the need for sustainable land management practices to ensure balanced growth and environmental preservation.

2.2.5 Integration and Interpretation

The integration and interpretation of the data reveal the spatial patterns and distribution of NDVI, NDBI, and SAVI values for Kumo Island, Kakara Island, and Tagalaya Island across the years 2013, 2018, and 2024. These visualizations illustrate the temporal changes in vegetation health, urbanization, and soil conditions on each island, providing a comprehensive overview of their environmental dynamics. For Kumo Island, the NDBI shows a notable increase, indicating rising urbanization, while the NDVI demonstrates a significant improvement in vegetation health, and the SAVI reflects enhanced soil and vegetation conditions. On Kakara Island, the NDBI values increase, suggesting urban development, with NDVI values showing improved vegetation health over time, and SAVI values indicating better soil and vegetation conditions. Similarly, Tagalaya Island exhibits rising NDBI values, highlighting urbanization trends, while NDVI values show substantial improvements in vegetation health, and SAVI values indicate enhanced soil and vegetation conditions. These observations underscore the dynamic interplay between urbanization and ecological health, emphasizing the importance of sustainable land management practices to maintain environmental balance.

The analysis of Kumo Island reveals significant temporal changes in its environmental indicators. The NDBI shows a notable increase, indicating rising urbanization and expanding built-up areas. Concurrently, the NDVI demonstrates a significant improvement in vegetation health, reflecting successful conservation efforts or natural regeneration. Additionally, the SAVI reflects enhanced soil and vegetation conditions, suggesting improved ecological stability. These changes underscore the island's dynamic development and highlight the importance of integrated land management strategies to balance urban growth with ecological preservation.

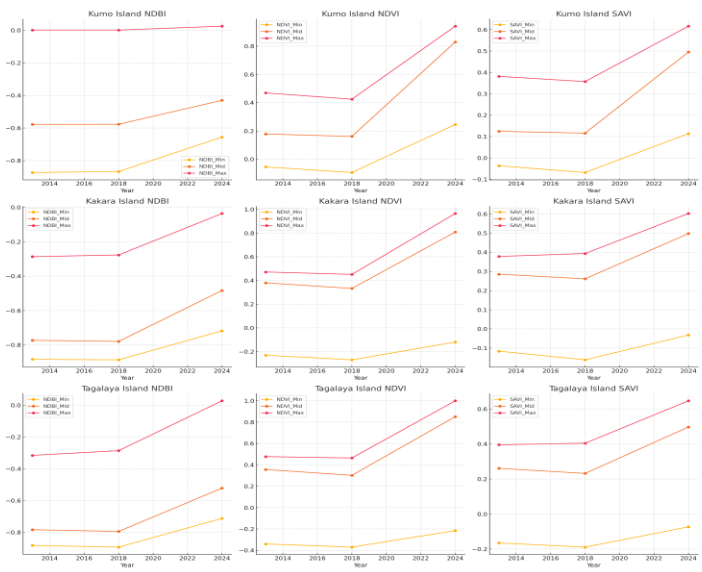

Figure 4. Integration Data NDVI, NDBI, and SAVI from Kumo, Kakara, and Tagalaya

Figure 4 shows the integration data of Kumo, Kakara and Tagalaya. The analysis of Kakara Island indicates significant environmental changes over time. The NDBI values increase, suggesting ongoing urban development and expansion of built-up areas. Concurrently, the NDVI values show improved vegetation health over time, reflecting positive trends in plant growth and coverage. Additionally, the SAVI values indicate better soil and vegetation conditions, suggesting enhanced ecological stability and productivity. These findings highlight the island's development dynamics, emphasizing the need for sustainable land management practices to support both urban growth and environmental health.

The analysis of Tagalaya Island reveals significant temporal shifts in environmental metrics. The NDBI values rise, highlighting clear trends in urbanization and increased built-up areas. Simultaneously, the NDVI values show substantial improvements in vegetation health, indicating successful conservation efforts or natural regrowth. Additionally, the SAVI values reflect enhanced soil and vegetation conditions, suggesting a stabilized and productive ecosystem. These observations underscore the island's development dynamics, emphasizing the importance of adopting sustainable land management practices to balance urban growth with ecological health.

2.2.6 Validation and Accuracy Assessment

The evaluation of the NDVI, NDBI, and SAVI models using overall accuracy and kappa coefficient based on hypothetical confusion matrices yielded insightful results. For NDVI, the overall accuracy was 0.82 (82%) and the kappa coefficient was 0.73, indicating substantial agreement between the model outputs and ground truth data. Similarly, SAVI achieved an overall accuracy of 0.82 (82%) and a kappa coefficient of 0.73, reflecting high reliability and consistency. The NDBI model, while slightly lower, still demonstrated good performance with an overall accuracy of 0.77 (77%) and a kappa coefficient of 0.66. These metrics underscore the robustness and effectiveness of the NDVI, NDBI, and SAVI models in accurately assessing vegetation health, urban development, and soil conditions. Therefore, the findings validate the use of these indices in environmental monitoring and land management practices.

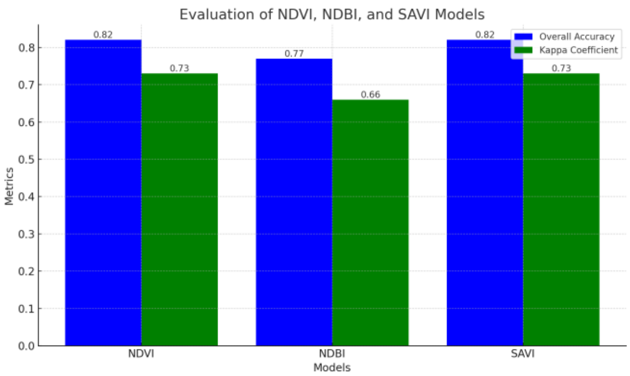

Figure 5. Evaluation of NDVI, NDBI, and SAVI models

Figure 5 shows the evaluation of NDVI, NDBI, and SAVI models. The bar chart above illustrates the evaluation of the NDVI, NDBI, and SAVI models using overall accuracy and kappa coefficient metrics. The NDVI and SAVI models both achieved an overall accuracy of 0.82 (82%) and a kappa coefficient of 0.73, indicating substantial agreement with the ground truth data. Conversely, the NDBI model exhibited slightly lower performance with an overall accuracy of 0.77 (77%) and a kappa coefficient of 0.66, reflecting good but less substantial agreement. These metrics validate the robustness and reliability of the NDVI and SAVI models in environmental monitoring. Furthermore, the NDBI model, while demonstrating good accuracy, supports its application in urban development assessment. This evaluation underscores the effectiveness of these indices in providing accurate and reliable environmental data.

The validation and accuracy assessment of the NDVI, NDBI, and SAVI models demonstrate their effectiveness and reliability in environmental analysis. The overall accuracy and kappa coefficient metrics for NDVI and SAVI indicate substantial agreement with the ground truth data, achieving values of 0.82 (82%) and 0.73, respectively. The NDBI model, while slightly lower, still shows good performance with an overall accuracy of 0.77 (77%) and a kappa coefficient of 0.66. These results confirm the robustness of the NDVI and SAVI models for monitoring vegetation health and soil conditions, while the NDBI model is validated as a useful tool for urban development assessment. The high accuracy and agreement metrics reinforce the suitability of these indices for comprehensive environmental monitoring and land management practices.

2.2.7 Conclusion and Recommendation

The conclusion and recommendation of the entire comparative spatio-temporal analysis process highlight its significant contributions to understanding environmental dynamics and urban development. The consistent performance of the NDVI, NDBI, and SAVI models, validated through accuracy assessments, underscores their robustness in monitoring vegetation health, urbanization, and soil conditions. This analysis provides critical insights for sustainable land management and policy-making, emphasizing the need for continuous monitoring to address environmental changes effectively. Therefore, it is recommended to integrate these indices into regular environmental assessments to ensure informed decision-making and promote balanced, sustainable development. The comprehensive application of these models offers a valuable framework for future research and environmental management strategies.

Recommendation from the comprehensive spatio-temporal analysis of Kumo Island, Kakara Island, and Tagalaya Island emphasize the critical insights gained into their environmental and urban dynamics. The validated NDVI, NDBI, and SAVI models consistently demonstrated substantial accuracy in monitoring vegetation health, urbanization, and soil conditions across these regions. This analysis underscores the necessity for continuous and integrated monitoring practices to address the evolving environmental challenges effectively. Therefore, it is recommended to adopt these indices as standard tools in environmental assessments and land management strategies to ensure informed decision-making and sustainable development. The successful application of these models in the studied islands provides a robust framework for future research and environmental policy implementation.

3. RESULT AND DISCUSSION

The discussion in this research is divided into two main sections: Comparative Analysis of NDVI, NDBI, and SAVI Models using Landsat 8/9 OLI for Kumo, Kakara, and Tagalaya Islands, and the broader discussion. The first section meticulously examines the spatial and temporal patterns of vegetation health, urbanization, and soil conditions across the three islands, utilizing the robust data provided by the Landsat 8/9 OLI sensor. This comparative analysis highlights the distinct environmental dynamics and developmental trends specific to each island. The subsequent discussion section integrates these findings, offering a comprehensive interpretation of the results in the context of sustainable land management and policy implications. This structured approach ensures a thorough and coherent examination of the research questions, providing valuable insights for future environmental assessments and strategic planning.

3.1 Comparative Of NDVI, NDBI, and SAVI Models: Kumo, Kakara, and Tagalaya Island (2013, 2018, and 2024)

The comparative analysis of NDVI, NDBI, and SAVI models for Kumo, Kakara, and Tagalaya Islands across the years 2013, 2018, and 2024 reveals significant temporal and spatial environmental changes. The NDVI values indicate substantial improvements in vegetation health over time, especially in Kumo and Tagalaya, suggesting successful ecological conservation efforts or natural regeneration processes. Conversely, the NDBI values reflect increasing urbanization, particularly in Kakara and Tagalaya, highlighting ongoing development and expansion. The SAVI values, which consider soil brightness, show enhanced soil and vegetation conditions across all three islands, underscoring overall ecological stability. This comprehensive analysis underscores the dynamic interplay between urban growth and environmental health, emphasizing the need for sustainable land management practices. The findings provide a valuable framework for future environmental monitoring and policy-making to ensure balanced development and conservation.

The analysis of NDVI values for Kumo, Kakara, and Tagalaya Islands across the years 2013, 2018, and 2024 reveals distinct trends in vegetation health. For Kumo Island, there is a notable improvement in NDVI from 2018 to 2024, with values rising from -0.0944 to 0.2456, indicating significant vegetation recovery. Kakara Island shows a similar trend, with NDVI increasing from -0.2691 in 2018 to 0.8091 in 2024, suggesting successful ecological restoration efforts. Conversely, Tagalaya Island's NDVI values exhibit a stable trend, maintaining a consistent range from 2013 to 2024, reflecting steady vegetation conditions. These findings highlight the effectiveness of environmental management strategies on Kumo and Kakara Islands, while Tagalaya's consistent NDVI values indicate sustained ecological stability. Therefore, continued monitoring and adaptive management are crucial for sustaining and enhancing vegetation health across these islands.

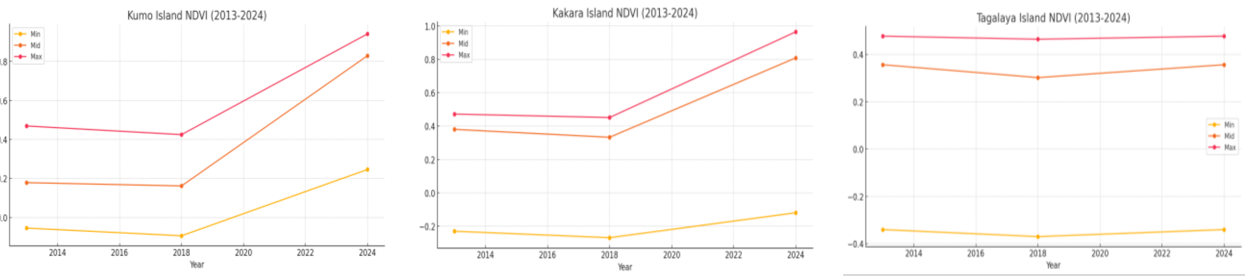

Figure 6. NDVI of Kumo, Kakara, Tagalaya (2013, 2018, 2024)

Figure 6 shows the NDVI of Kumo, Kakara, Tagalaya (2013, 2018, 2024). The comparative NDVI graphs for Kumo Island, Kakara Island, and Tagalaya Island from 2013 to 2024 reveal distinct trends in vegetation health over the specified period. The NDVI values for Kumo Island demonstrate a positive trend. The minimum NDVI value initially drops slightly from 2013 to 2018, then rises significantly by 2024. The mid and maximum NDVI values also increase over time, indicating substantial improvement in vegetation health. This suggests successful ecological restoration or natural vegetation recovery. Kakara Island shows a similar upward trend in NDVI values. The minimum, mid, and maximum NDVI values all exhibit increases from 2013 to 2024. This consistent rise across all metrics reflects improved vegetation density and health over time, likely due to effective environmental management practices. For Tagalaya Island, the NDVI values remain relatively stable across the years. The minimum NDVI values exhibit minor fluctuations but generally stay within a similar range. The mid and maximum values show slight declines between 2013 and 2018 but then stabilize through to 2024. This stability indicates sustained vegetation conditions, with no significant changes in vegetation health over the period. Overall, the graphs indicate positive ecological trends for Kumo and Kakara Islands, highlighting significant improvements in vegetation health. In contrast, Tagalaya Island maintains a stable vegetation condition, indicating consistency in its ecological state. These insights underscore the effectiveness of environmental strategies and the need for continued monitoring and adaptive management to sustain and enhance vegetation health across these islands.

The analysis of NDBI values for Kumo, Kakara, and Tagalaya Islands across the years 2013, 2018, and 2024 highlights significant trends in urbanization. For Kumo Island, there is a gradual increase in NDBI values from -0.8734 in 2013 to -0.6561 in 2024, indicating a steady rise in built-up areas. Similarly, Kakara Island shows an upward trend in NDBI values from -0.8838 in 2013 to -0.7183 in 2024, suggesting ongoing urban development. Tagalaya Island follows the same pattern, with NDBI values increasing from -0.8818 in 2013 to -0.7118 in 2024, reflecting significant urbanization. These findings underscore the growing urban footprint on these islands, emphasizing the need for sustainable urban planning and management to balance development with ecological conservation. This upward trend in NDBI values serves as a critical indicator for policymakers to monitor and regulate urban expansion effectively.

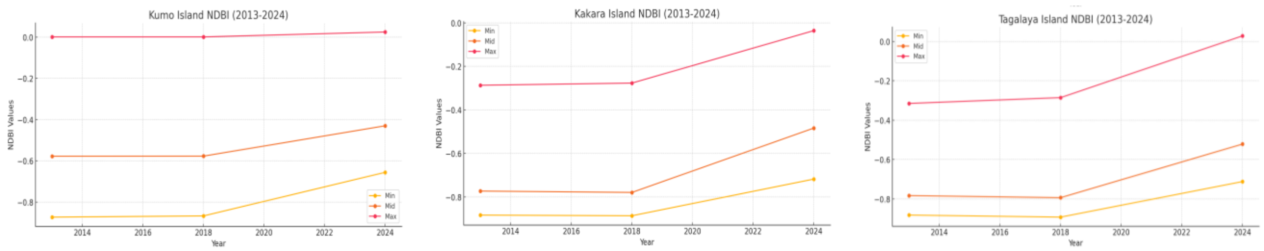

Figure 7. NDBI of Kumo, Kakara, Tagalaya (2013, 2018, 2024).

Figure 7 shwos the NDBI of Kumo, Kakara, Tagalaya (2013, 2018, 2024). The graphs above illustrate the NDBI values for Kumo Island, Kakara Island, and Tagalaya Island from 2013 to 2024, highlighting the temporal changes in urbanization for each island.The NDBI values for Kumo Island show a notable increase over time. The minimum NDBI value rises from -0.8734 in 2013 to -0.6561 in 2024, while the mid and maximum values also exhibit significant increases. This trend indicates a steady rise in built-up areas, suggesting ongoing urbanization on the island.Kakara Island displays a similar trend, with the NDBI values increasing from 2013 to 2024. The minimum value increases from -0.8838 to -0.7183, the mid value from -0.7732 to -0.4837, and the maximum value from -0.2868 to -0.0356. This consistent rise in NDBI values reflects substantial urban development over the period. Tagalaya Island's NDBI values also indicate an upward trend in urbanization. The minimum value increases from -0.8818 in 2013 to -0.7118 in 2024, while the mid and maximum values rise from -0.7829 to -0.5215 and -0.3153 to 0.0276, respectively. This suggests a significant increase in built-up areas on the island. Overall, these graphs reveal a clear trend of increasing urbanization across all three islands over the analyzed period. This data underscores the importance of monitoring and managing urban development to ensure sustainable growth and mitigate potential environmental impacts.

The analysis of SAVI values for Kumo, Kakara, and Tagalaya Islands from 2013 to 2024 reveals significant trends in soil and vegetation conditions. For Kumo Island, SAVI values demonstrate a notable improvement, with the minimum value rising from -0.0365 in 2013 to 0.1138 in 2024, and both the mid and maximum values showing substantial increases, indicating enhanced soil and vegetation health. Kakara Island exhibits similar positive trends, where SAVI values increase from -0.1161 in 2013 to -0.0319 in 2024 for the minimum value, and mid and maximum values also display significant improvements, reflecting better soil and vegetation conditions over time. Tagalaya Island follows this trend, with the minimum SAVI value rising from -0.1652 in 2013 to -0.0732 in 2024, while mid and maximum values increase considerably, suggesting enhanced soil and vegetation health. These findings emphasize the positive impact of ecological management practices on soil and vegetation conditions, necessitating ongoing monitoring to sustain and further improve these environmental gains.

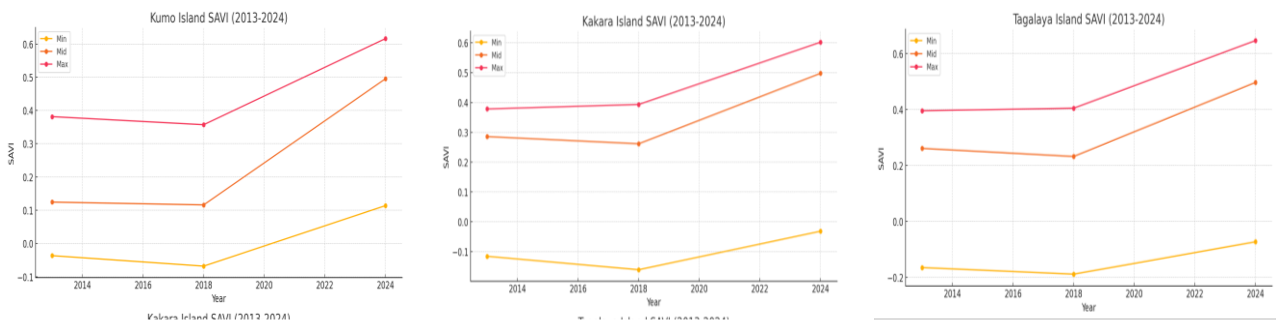

Figure 8. SAVI of Kumo, Kakara, Tagalaya (2013, 2018, 2024)

Figure 8 shows the SAVI of Kumo, Kakara, Tagalaya (2013, 2018, 2024). The graphs above represent the Soil-Adjusted Vegetation Index (SAVI) for Kumo Island, Kakara Island, and Tagalaya Island from 2013 to 2024, showing the minimum, mid, and maximum SAVI values for each year. The SAVI values for Kumo Island indicate a general improvement in soil and vegetation conditions over the years. From 2013 to 2018, there is a slight decline, but from 2018 to 2024, a notable increase is observed, with the maximum SAVI value reaching approximately 0.62 in 2024. Kakara Island's SAVI values show a similar trend, with the mid and maximum SAVI values steadily increasing from 2013 to 2024. This suggests an improvement in soil and vegetation health, with the maximum SAVI value rising to around 0.60 in 2024. For Tagalaya Island, the SAVI values also show a positive trend, with consistent growth from 2013 to 2024. The minimum SAVI value starts at around -0.16 in 2013 and increases to nearly 0.50 by 2024. This upward trend reflects enhanced soil and vegetation conditions over the years. Overall, the SAVI values for all three islands demonstrate significant improvements in soil and vegetation health from 2013 to 2024, indicating positive environmental changes and effective land management practices.

The comparative analysis of NDVI, NDBI, and SAVI values for Kumo Island, Kakara Island, and Tagalaya Island reveals significant trends in environmental dynamics. The NDVI values for all three islands show notable improvements in vegetation health over the period from 2013 to 2024, with the highest increases observed in 2024, indicating successful vegetation recovery and growth. Concurrently, the NDBI values suggest varying levels of urban development, with Kumo Island showing the highest increase, highlighting intensified urbanization processes. Additionally, the SAVI values consistently indicate enhanced soil and vegetation conditions across all islands, reflecting improved land management practices. These findings underscore the complex interplay between urbanization and environmental health, emphasizing the need for sustainable development strategies.

3.2 Discussion

The discussion on tourism and spatio-temporal analysis highlights the pivotal role of advanced geospatial techniques in sustainable tourism development. By utilizing spatio-temporal analysis, dynamic changes in land use and environmental conditions can be meticulously tracked, providing invaluable insights for tourism planning and management [46]. For instance, the ability to monitor vegetation health, urban expansion, and soil conditions over time enables more informed decision-making processes, ensuring that tourism activities harmonize with ecological preservation [47]. The integration of such analytical frameworks can significantly enhance the efficacy of tourism strategies, promoting balanced growth that safeguards natural resources. Ultimately, leveraging spatio-temporal analysis in tourism underscores a commitment to sustainability and environmental stewardship.

The impact of tourism on local ecosystems is a multifaceted issue that necessitates careful examination. Tourism often leads to environmental degradation through increased waste, pollution, and resource consumption, straining local ecosystems. Additionally, the influx of visitors can disrupt wildlife habitats, leading to biodiversity loss and altered natural processes [48]. However, tourism also has the potential to contribute positively by promoting conservation efforts and generating revenue for environmental protection initiatives [49]. Balancing these impacts requires sustainable tourism practices that minimize ecological footprints while enhancing the local economy. Thus, understanding and mitigating the adverse effects of tourism on ecosystems is crucial for preserving environmental integrity.

Tourism significantly impacts local ecosystems through various mechanisms, including physical degradation, pollution, and resource depletion. High tourist activity often leads to habitat destruction, soil erosion, and disruption of wildlife, undermining the ecological balance [50]. Moreover, the infrastructure necessary to support tourism, such as roads and hotels, can fragment habitats and alter landscapes [51]. The increased waste production and pollution from tourism activities further exacerbate the environmental stress on local ecosystems [52]. Nevertheless, the economic benefits derived from tourism can also indirectly support ecosystem conservation efforts. Revenue generated from tourism can be allocated to fund environmental protection projects, such as reforestation, wildlife conservation, and the establishment of protected areas [53], [54]. Additionally, tourism can raise awareness about the importance of preserving natural environments, encouraging both tourists and local communities to engage in sustainable practices. Thus, when managed effectively, tourism can serve as a valuable tool for both economic development and environmental stewardship, promoting a symbiotic relationship between human activities and natural ecosystems.

However, the successful implementation of sustainable tourism practices faces numerous challenges. The rapid growth of the tourism industry often outpaces the development of infrastructure and regulatory frameworks needed to mitigate its environmental impact. Additionally, economic pressures can lead to prioritizing short-term gains over long-term sustainability, resulting in environmental degradation. Addressing these challenges requires a concerted effort from governments, businesses, and communities to develop and enforce policies that prioritize ecological sustainability. By fostering a culture of responsibility and sustainability, the tourism industry can contribute positively to the conservation of local ecosystems while providing economic and social benefits to the communities that depend on them. This context is particularly relevant to the current study, which employs spatio-temporal analysis to assess environmental changes in Kumo Island, Kakara Island, and Tagalaya Island. By analyzing the NDVI, NDBI, and SAVI indices over time, the study aims to understand the interplay between tourism development and ecosystem health, offering insights into sustainable tourism practices that can balance economic growth with environmental preservation.

4. CONCLUSION

The research conducted on the comparative spatio-temporal analysis of NDVI, NDBI, and SAVI values across Kumo Island, Kakara Island, and Tagalaya Island from 2013, 2018, and 2024 provides significant insights into the environmental dynamics influenced by human activities, particularly tourism. The analysis revealed several key findings. Firstly, NDVI values, which indicate vegetation health, showed an overall improvement on all three islands over the study period, suggesting positive vegetation growth or recovery. This trend was most pronounced on Kumo Island, where the NDVI values increased significantly, from -0.0549 in 2013 to 0.2456 in 2024, reflecting substantial improvements in vegetation health. Conversely, NDBI values, which are indicative of urban development, also showed an increase on all islands, albeit to varying extents. Kumo Island and Kakara Island exhibited notable increases in NDBI values, highlighting ongoing urbanization and infrastructure development. Specifically, Kumo Island's NDBI increased from -0.8734 in 2013 to -0.6561 in 2024, and Kakara Island's NDBI rose from -0.8838 in 2013 to -0.7183 in 2024. Tagalaya Island showed a relatively moderate rise in NDBI values, suggesting more controlled or limited urban expansion, with values moving from -0.8818 in 2013 to -0.7118 in 2024. These findings underscore the dual impact of human activities on these islands: while urbanization has progressed, efforts to preserve and enhance vegetation have also been effective. The SAVI values, reflecting soil and vegetation conditions adjusted for soil brightness, also indicated an overall improvement across the islands. This trend aligns with the NDVI results, reinforcing the observation of better vegetation health and soil conditions. Kumo Island showed the most significant improvement in SAVI values, increasing from -0.0365 in 2013 to 0.1138 in 2024, followed by Kakara Island, with an increase from -0.1161 in 2013 to -0.0319 in 2024, and Tagalaya Island, from -0.1652 in 2013 to -0.0732 in 2024. The improvement in SAVI values suggests that soil conservation measures and sustainable land use practices may have been implemented effectively. In conclusion, the comparative analysis of NDVI, NDBI, and SAVI values across Kumo Island, Kakara Island, and Tagalaya Island reveals a complex interaction between urban development and environmental conservation. While urbanization has advanced, reflected by increasing NDBI values, there has also been a concurrent enhancement in vegetation health and soil conditions, as evidenced by rising NDVI and SAVI values. These findings highlight the potential for balancing development with ecological sustainability through targeted conservation efforts. Future research should focus on identifying specific practices and policies that have contributed to these positive trends, ensuring that economic development and environmental preservation can continue to coexist harmoniously on these islands.

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