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Geospatial Assessment of Land Use and Land Cover Change in Alappuzha District, Western Kerala, India.

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Abstract
Rapid urbanization has altered land use and land cover, leading to a decline in environmental quality. Monitoring these changes with LULC analysis is, therefore, indispensable. This study looks at LULC changes in Alappuzha district, Kerala, for the years 2000, 2015, and 2025 using Remote Sensing and GIS. LULC maps were generated from Landsat images using Maximum Likelihood Classification for five categories: agriculture, built-up land, mixed vegetation, uncultivable land, and water bodies. The results indicate substantial reductions in mixed vegetation (35.63%), agricultural land (23.88%), water bodies (20.25%), and uncultivable land (14.32%) between 2000 and 2025. Conversely, built-up land expanded by 344.61%, indicating rapid urban growth. Socioeconomic changes, population growth, climate change, and shifts in employment patterns have contributed to the decline in agricultural areas. The observed decreases in mixed vegetation and water bodies highlight ecological stress and underscore the urgent need for restoration initiatives. The study highlights the need for well-planned land-use strategies that prioritise resource sustainability and ecological protection. Further research into the effects of LULC Changes on surface temperatures, hydrology and biodiversity is recommended to inform environmental planning in the ecologically sensitive Alappuzha district.

Keywords: Alappuzha, Ecological Stress, Land Use Land Cover Changes, Landsat, Remote Sensing and GIS

Abbreviations

Abbreviations	Full Form
CE	Commission Error
DN	Digital Number
ERDAS	Earth Resources Data Analysis System (ERDAS IMAGINE software)
ETM+	Enhanced Thematic Mapper Plus
GIS	Geographic Information System
KLU	Kerala Land Utilisation (Order)
LC	Land Cover
LST	Land Surface Temperature
LU	Land Use
LULC	Land Use and Land Cover
LULCC	Land Use and Land Cover Change
LULCCs	Land Use and Land Cover Changes
MLC	Maximum Likelihood Classification
MODIS	Moderate Resolution Imaging Spectroradiometer

NDVI	Normalized Difference Vegetation Index
NH-66	National Highway 66
NRI	Non-Resident Indian
OA	Overall Accuracy
OE	Omission Error
OLI	Operational Land Imager
OLI-2	Operational Land Imager-2
PA	Producer's Accuracy
PCC	Post Classification Comparison
RF	Random Forest
RGB	Red, Green, Blue
RS	Remote Sensing
SDG	Sustainable Development Goal
SVM	Support Vector Machine
TM	Thematic Mapper
TIRS	Thermal Infrared Sensor
UA	User's Accuracy
UHI	Urban Heat Island
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WGS	World Geodetic System

Introduction

Land Use and Land Cover (LULC) transitions have become one of the most critical environmental concerns of the twenty-first century, driven by rapid urbanization, changing agricultural practices, infrastructure expansion, and climate variability. Land Cover (LC) refers to the biophysical features, such as soil, water, flora and anthropogenic activities of the Earth's surfaces, and Land Use (LU) refers to how humans manage or modify land [1]. Together, LULC patterns fundamentally shape ecological processes, resource distribution, and human environment interactions across spatial and temporal scales. Consequently, monitoring LULC dynamics is vital for understanding landscape transformations, informing land governance, and advancing global sustainability agendas, particularly the targets of SDG 15 (Life on Land).

These Land Use and Land Cover Changes (LULCCs), are driven by the complex interplay of socioeconomic, political, and natural factors, which play a crucial role in shaping landscape dynamics and determining environmental health and sustainability [2]. These drivers often lead to rapid urbanization and infrastructure development, resulting in a shift from pervious to impervious surfaces, which significantly alters hydrological cycles, enhances surface runoff, degrades water quality and reduces groundwater recharge [3,4]. These transformations alter the surface energy balance and increase Land Surface Temperature (LST), thereby contributing to the Urban Heat Island (UHI) effect in rapidly urbanising regions [5-7]. In addition to thermal and hydrological impacts, LULC transitions influence biodiversity, soil health, ecological productivity, food security, increase CO2 and the stability of ecosystem services. These changes have direct implications for Sustainable Development Goals (SDG) 2 (Zero Hunger), 6 (Clean Water and Sanitation), 11 (Sustainable Cities and Communities), and 13 (Climate Action). In contrast, sustainable land-use strategies such as conservation zoning, wetland protection, and green infrastructure enhance ecological resilience, mitigate climate extremes, and protect livelihoods that depend on natural resources. Remote sensing (RS) combined with Geographic Information System (GIS) techniques has substantially improved the ability to detect, classify, and analyse LULC changes across various spatial and temporal scales. Satellite-based observations offer temporally consistent and spatially explicit data essential for long-term environmental monitoring. These technologies enable the identification of subtle or gradual landscape changes that are often undetectable by traditional ground-based methods. Landsat imagery, in particular, is frequently utilised due to its extensive multi-decadal archive, appropriate spatial resolution, and broad coverage, establishing it as a dependable resource for spatiotemporal LULC analysis [8].

Numerous studies have investigated LULC changes using RS and GIS techniques, consistently demonstrating strong linkages between anthropogenic activities, ecological transformations, and thermal responses. At the global scale, urbanization driven LULCCs have been linked to rising LST ecosystem degradation, carbon emissions, landscape fragmentation, biodiversity loss, and altered flood regimes [9-16]. Similar patterns have been observed across Asia and Africa, where agricultural expansion, aquaculture intensification, and urban sprawl have transformed landscapes and affected soil properties, hydrology, and UHI formation [17-20]. In India, extensive LULCC has been documented in regions such as Madhya Pradesh, Tirupati, Patna, Mumbai, Durgapur Municipal Corporation the Himalayan Region, and

Dhanbad, revealing consistent declines in vegetation, agricultural land, and ecosystem stability due to urban growth [21-27]. Studies in Kerala, further show land-cover transformations linked to urbanization, resulting in declining greenness, flooding, and UHI intensification [28-31]. While research in districts such as Wayanad and Kottayam demonstrates the value of RS–GIS in monitoring vegetation and surface temperatures, investigations remain fragmented and district-specific [32,33]. Notably, despite rapid land transformation in Alappuzha, systematic multi-temporal assessments of LULCC and associated environmental impacts are scarce, indicating a clear need for comprehensive geospatial analyses in the region.

A regional-scale assessment of land cover dynamics in Kerala using MODIS datasets also reported significant increases in urban and built-up lands and cropland/natural vegetation mosaics, along with declining savannas and grasslands between 2001 and 2019 [34]. The study further highlighted the growing influence of urbanisation and land transformation across Kerala, emphasising the need for regional and local-scale investigations to support sustainable land management.

Despite the environmental significance of the Alappuzha district, detailed geospatial investigations on LULC dynamics in the region remain very limited. Only a small number of studies have examined LULC changes in Alappuzha, with the most notable previous work assessing long-term changes for the period 1973–2017 [2]. Although regional-scale investigations have examined land-cover dynamics across Kerala using MODIS datasets, district-level assessments focusing on rapidly transforming coastal landscapes such as Alappuzha remain limited [34]. Consequently, updated evidence reflecting recent and accelerated landscape transformations has been lacking. The present study addresses this research gap by providing a contemporary multi-temporal assessment of Alappuzha district using Landsat imagery for the years 2000, 2015, and 2025, including recent Landsat 9 data. A key contribution of the present study is the incorporation of recent satellite observations together with LULC change matrix analysis to identify the specific transitions among land classes and to provide deeper insights into the processes of landscape transformation. In addition, classification accuracy assessment and annual rate-of-change estimation were employed to evaluate the magnitude, direction, and pathways of land-cover transformation. While previous studies primarily focused on documenting overall LULC change during earlier periods, they did not explicitly quantify land cover transition pathways using change matrix analysis. The present study extends previous research by providing an updated district scale assessment of LULC dynamics up to 2025 and by explicitly quantifying land cover transition pathways through change matrix analysis. By combining these approaches, the study offers a comprehensive and policy-relevant understanding of urban expansion, agricultural decline, vegetation loss, and water-body reduction in Alappuzha district.

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Despite global progress, Alappuzha District in Kerala remains understudied, even though it represents one of India's most environmentally sensitive and socioeconomically important coastal landscapes. Characterised by an intricate network of canals, the Vembanad backwaters, wetlands, paddy fields, and coastal belts, Alappuzha is exceptionally vulnerable to landscape changes. The district's economy, which relies on agriculture, fishing, coir production, and tourism, depends directly on stable land and water systems. LULCCs can disrupt the balance of water systems, increase flood risks, harm wetlands, raise LST, and affect ecosystem services that are vital for local livelihoods. Rapid population growth, increasing human activity in fragile ecosystems, and the demands of urban development further increase the district's vulnerability to environmental stress.

In this situation, evaluating LULCCs in Alappuzha is essential for understanding how human activities are altering productive landscapes and ecological systems. Therefore, this study aims to map, quantify, and analyse LULC changes in Alappuzha District over a period of 25 years (2000, 2015, and 2025) using multi-temporal Landsat datasets and geospatial techniques. Through the documentation of long-term patterns and the identification of key drivers of landscape transformation, this research offers critical insights for sustainable land management, climate adaptation, and ecosystem protection in accordance with SDG 15 (Life on Land). These findings are intended to assist policymakers, planners, and local stakeholders in advancing development strategies that reconcile economic objectives with environmental integrity and enduring ecological sustainability.

Limitations of the Study

This study has certain limitations that should be considered when interpreting the findings. First, the analysis relied on Landsat imagery with a spatial resolution of 30 m, which may not adequately capture small or fragmented land-cover features, particularly in heterogeneous urban and coastal environments. Second, the accuracy assessment for the historical years (2000 and 2015) was based primarily on historical Google Earth Pro imagery and other reference datasets rather than contemporaneous field observations, introducing a degree of uncertainty into the validation process.

Furthermore, the interpretation of the drivers of LULCC was based mainly on published literature, census information, and other secondary data rather than quantitative socio-economic modelling. Despite these limitations, the use of consistent satellite datasets, rigorous image processing and classification procedures, and comprehensive accuracy assessment provides reliable estimates of long-term LULC dynamics in Alappuzha District. Future research should integrate higher-resolution satellite imagery, field-based validation, advanced machine learning and deep learning classification techniques, and quantitative modelling of socio-economic drivers to improve the understanding of landscape transformation. In addition, future studies may evaluate and compare the performance of the Maximum Likelihood Classification (MLC) algorithm with advanced classification approaches, such as Random Forest (RF), Support Vector Machine (SVM), and U-Net, to further enhance LULC classification accuracy in complex coastal landscapes.

Materials and Methods

Study Area

Alappuzha is a small district in western Kerala, located between 9° 06′ 36″ and 9° 53′ 30″ N latitudes and 76° 19′ 03″ and 76° 41′ 33″ E longitudes. The district is bordered by Ernakulam District in the north, Kottayam and Pathanamthitta Districts in the east, the Lakshadweep Sea in the west, and Kollam District in the south. It has a total land area of 1414 square kilometres. According to the 2011 census, it has a total population of 2,127,789 people, with a population density of 1504 people per square kilometre. Alappuzha features a diverse landscape, comprising a sandy stretch of land interrupted by lagoons, rivers, and canals. The district lacks significant elevations, such as hills or mountains, except for scattered hillocks in the eastern part between Bharanikkavu and Chengannur blocks. Ambalappuzha, Cherthala, Karthikappally, and Kuttanad Taluks are entirely situated within the lowland regions. About 80% of the district lies within the coastal area, while the remaining 20% is in the midland province. It has an 82-kilometre-long contiguous coastline. Alappuzha is Kerala’s only district without highlands or forested areas. Water bodies constitute 13% of the district, and the terrain is below sea level in parts. The climate along the coast is moist and hot, while it is slightly cooler and drier inland. The average monthly temperature is 25 °C, and the average annual rainfall is 2763 mm.

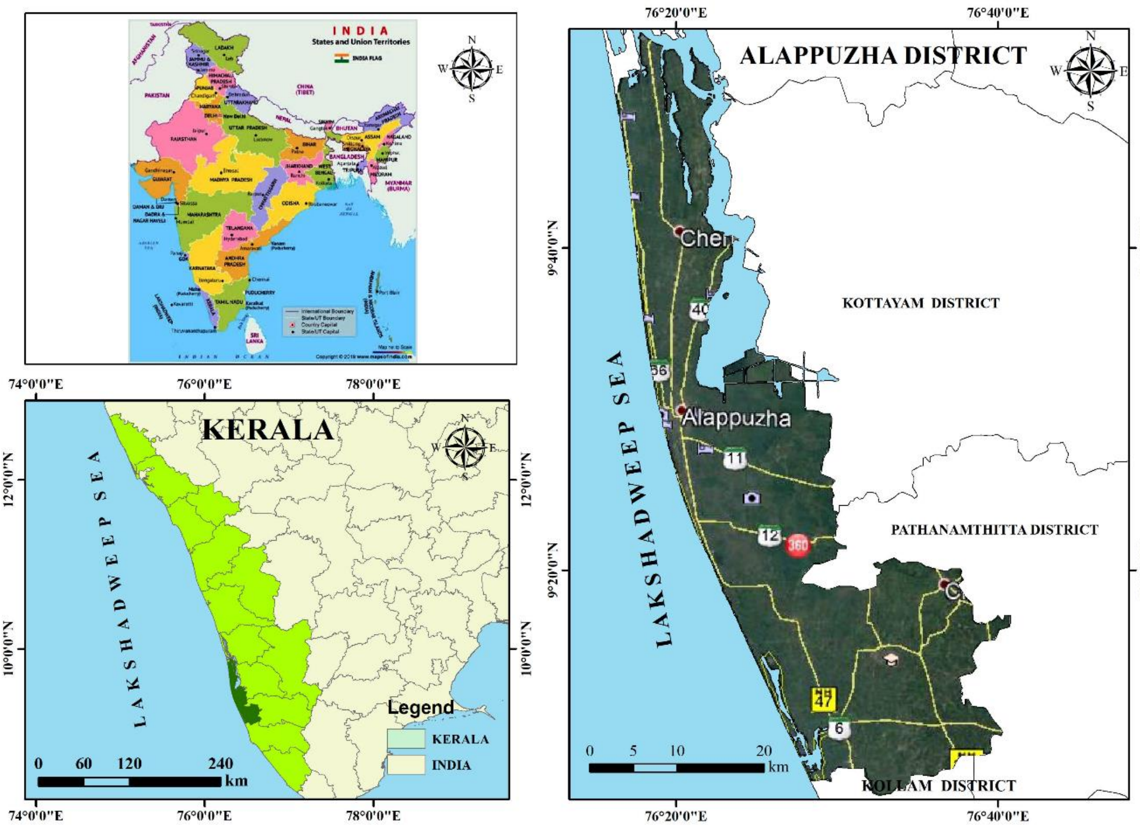

Figure 1: Study Area

Data Acquisition and Pre-processing.

In this study, three Landsat images (path/row: 144/53 and 144/54) were obtained from the United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov/) for three different years. Landsat 7 ETM+ (2000), Landsat 8 OLI/TIRS (2015) and Landsat 9 OLI-2/TIRS (2025) images were selected based on minimum cloud cover and acquisition during the same month (January) to minimize atmospheric and seasonal Variations (Emran et al. 2018), with 30m resolution, and were utilized in the preparation of thematic maps i.e., LULC. Table 1 presents a description of the three Landsat datasets utilized in the study. Data from the Google Earth platform were utilized for the validation of the Landsat data. The three images were registered to a common Universal Transverse Mercator (UTM) coordinate system, Zone 43N, with World geocoded system (UTM WGS) 1984 Projection parameters. Image preprocessing was performed in ERDAS IMAGINE and included geometric correction, atmospheric correction, topographic correction, layer stacking, mosaicking, image enhancement, and subsetting.

Satellite	Sensor	Path/ Row	Date of Image Acquisition	Spatial Resolution	Cloud Cover %
Landsat-7	Enhanced Thematic Mapper Plus (ETM+)	144/53	28/01/2000	30	8
		144/54			1
Landsat-8	Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)	144/53	13/01/2015	30	3.34
		144/54			1.23
Landsat 9	Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS)	144/53	00/01/2025	30	23.62
		144/54			32.51

Table 1: Characteristics of Landsat Images Used for the Study

Image Mosaicking
Following image pre-processing, the Landsat scenes were mosaicked to generate a single continuous raster covering the entire study area. Since the study area extends across two adjacent Landsat rows (53 and 54), mosaicking was necessary to produce a seamless image for subsequent analysis. Overlapping regions between the scenes may contain differences in Digital Number (DN) values due to variations in acquisition conditions and sensor characteristics, resulting in radiometric inconsistencies [36]. The Maximum option was selected as the mosaic method to assign the highest DN value to overlapping pixels and eliminate NoData (0) values in the output image. Furthermore, the Match colour mode was applied to harmonize the radiometric appearance of adjacent scenes by matching colour values across the mosaicked images.

Land Use and Land Cover Classification and Change Detection
Supervised image classification was performed using the Maximum Likelihood Classification (MLC) algorithm in ERDAS IMAGINE software. MLC was selected because it provides reliable performance for medium-resolution Landsat imagery, requires relatively limited training data, and facilitates comparison with numerous previous LULC studies conducted in Kerala. The classifier assigns each pixel to the class with the highest probability of membership based on its spectral characteristics. Training samples for classification were selected through image interpretation and available reference data for five major LULC classes identified within the study area: (i) Agriculture zone, (ii) Built-up land, (iii) Mixed vegetation, (iv) Uncultivable land, and (v) Water body (Table 2).

LU/LC Classes	Description
Agriculture	The components of cropland include mechanized farms and smallholder-operated farms, as well as paddy fields.
Built-up area	All kinds of infrastructure, such as housing, commercial, service, industrial, socioeconomic infrastructure regions, villages, cities, and transportation infrastructure.
Mixed vegetation	Trees and small grasses, including both natural and planted varieties.
Uncultivable land	Land without vegetation cover or very little greenness, primarily encompassing areas with exposed soil and bare rock surfaces, and excavation sites.
Water body	All types of water bodies within the study area were considered, excluding the Vembanad Lake

Table 2: Description of LULC Classes in the Study Area.

For image visualization and interpretation, RGB false colour composite band combinations of 4–3–2 for Landsat 7 and corresponding standard multispectral composites for Landsat 8/9 were used. Following classification, change matrix analysis was carried out using ERDAS Imagine 14 software to quantify class-to-class transitions, overall LULC changes, and gains and losses in each category for the years 2000, 2015, and 2025.

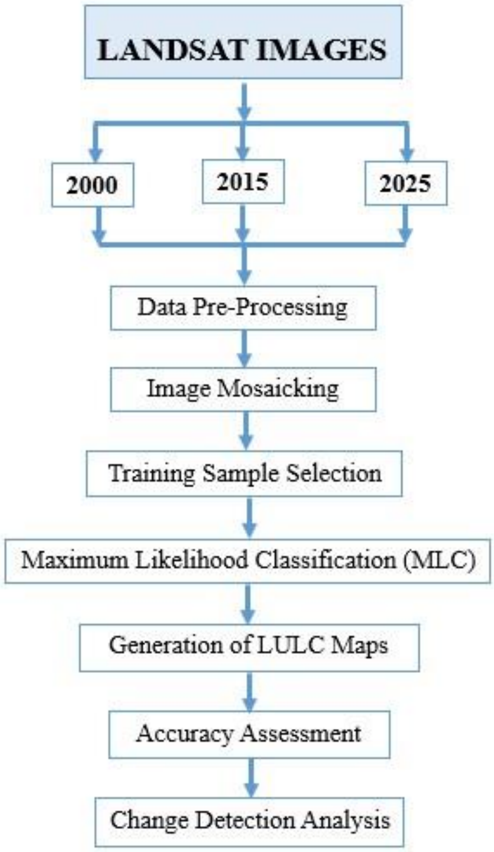

Figure 2: Flowchart of Methodology for LULC and LULCC Detection

Assessment of Classification Accuracy

The classified Land Use/Land Cover (LULC) maps for the years 2000, 2015, and 2025 were evaluated using a confusion (error) matrix, which is the standard method for assessing the accuracy of supervised image classification in remote sensing studies [37,38]. The confusion matrix compares the classified image with independently derived reference data, in which the true land-cover class of each validation sample is known [39,40].

Since contemporaneous field-based observations were unavailable for the historical study years, reference validation data were derived from high-resolution imagery available in Google Earth Pro, including the historical imagery archive where available. Additional validation was supported through visual interpretation of stable landscape features and ancillary spatial information. Therefore, the term "reference data" is considered more appropriate than "conventional field-based ground truth data" for this study.

A stratified random sampling approach was employed to ensure adequate representation of all five LULC classes, namely agriculture, built-up land, mixed vegetation, uncultivable land, and water bodies. For each study year, 300 reference samples were randomly selected for each LULC class. Each reference sample was compared with the corresponding classified pixel in the Landsat-derived LULC map to construct the confusion matrix.

Based on the confusion matrix, Overall Accuracy (OA), Producer's Accuracy (PA), User's Accuracy (UA), Omission Error (OE), Commission Error (CE), and the Kappa Coefficient (κ) were calculated to evaluate the reliability of the classified maps [41-43]. Overall Accuracy represents the proportion of correctly classified samples, Producer's Accuracy indicates the probability that a reference pixel is correctly classified (related to omission error), whereas User's Accuracy represents the probability that a pixel classified into a given category actually belongs to that category (related to commission error). The Kappa Coefficient measures the level of agreement between the classified image and the reference data beyond that expected by chance.

The accuracy assessment indices were calculated using the following equations:

$$Overall\ Accuracy\ (OA) = \frac{Total\ number\ of\ correctly\ classified\ pixels}{Total\ number\ of\ reference\ pixels}\ X\ 100\% \quad (1)$$

$$Comission\ error\ (CE) = \frac{\sum Off\ diagonal\ row\ elements}{Total\ of\ row} \mathrm{X}100\% \quad (2)$$

$$Omission\ error\ (OE)\ = \frac{\sum Off\ diagonal\ column\ elements}{Total\ of\ column} \text{X}100\% \quad \textbf{(3)}$$

Producer's accuracy (%) = 100% - Error of omission (%) **(4)**

User's accuracy = 100% - Error of commission (%) **(5)**

$$\%\ \text{of}\ k\ = \frac{The\ Total\ sum\ of\ correct - Sum\ of\ all\ the\ (row\ total\ x\ column\ total)}{Total\ squared - Sum\ of\ all\ the\ (row\ total\ x\ column\ total)}\ x\ 100 \quad \textbf{(6)}$$

where Overall Accuracy represents the percentage of correctly classified reference samples, Commission Error indicates the proportion of pixels incorrectly assigned to a given class, Omission Error represents the proportion of reference pixels omitted from their correct class, Producer's Accuracy is the probability that a reference pixel is correctly classified, User's Accuracy is the probability that a pixel classified into a given category actually belongs to that category, and the Kappa Coefficient measures the level of agreement between the classified map and the reference data beyond that expected by chance.

This approach is widely adopted in multi-temporal LULC studies where contemporaneous field observations are unavailable for historical periods. However, a small degree of uncertainty may remain due to the temporal availability and spatial resolution of historical reference imagery. The final classification accuracy results for the years 2000, 2015, and 2025 are presented in **Table 3.**

Change Detection through Post-Classification Comparison and LULC Dynamics.
Spatial change was identified through the application of the Post Classification Comparison (PCC) method, which generated a cross-tabulation (transition) matrix [44]. This matrix depicted the transitions in LULC over time by overlaying and comparing two successive classified land cover layers. Detection of LULC changes in reclaimed areas was achieved using Symmetrical Difference Overlay Analysis [45]. Subsequently, maps were compiled, and the conversion of areas from one LULC Class to another during the study period was quantified. Additionally, the annual rate of change was calculated according to [46,47]. Equation (7) provided a standardized measure for LULCCs across different time periods within the study.

$$r = \left(\frac{1}{t_1 - t_2}\right) xIn \left(\frac{S_1}{S_2}\right) \quad \textbf{(7)}$$

Here, 'r' represents the annual rate of change for each class, and S1 and S2 are the LULC class areas at t1 and t2, respectively.

Results and Discussion

Results

Accuracy Assessment

The accuracy assessment results for the classified LULC maps are presented in Table 3. The overall classification accuracy exceeded 90% for all three years, with Kappa coefficients greater than 90% (0.90), indicating a high level of agreement between classified outputs and reference data. These results confirm the reliability of the LULC classifications used for change detection and transition analysis in this study.

LULC Class	**2000**		**2015**		**2025**	
	Producer's Accuracy (%)	**User's Accuracy (%)**	**Producer's Accuracy (%)**	**User's Accuracy (%)**	**Producer's Accuracy (%)**	**User's Accuracy (%)**
Agriculture	87	94	88	91	84	88
Built-up	91	100	87	100	83	100
Mixed vegetation	98	95	93	92	92	92
Uncultivable land	95	82	93	81	93	81
Water body	100	100	100	100	100	100
Overall Accuracy	93		90		91	
Kappa Coefficient	93		91		90	

Table 3: Accuracy Assessment of LULC of 2000, 2015 and 2025.

Land Use and Land Cover Change Dynamics

Five major land cover categories representing the foremost land cover in Alappuzha District have been analyzed based on the proportion of the area. The spatial distribution of LULC classes in Alappuzha District for the years 2000, 2015, and 2025 is presented in Table 4 and Figures 3 and 4. Five major LULC categories were identified: built-up land, agricultural land, mixed vegetation, water bodies, and uncultivable land. Significant changes were observed across all classes over the 25-year study period. Additionally, the annual rates of change for all LULC classes are summarised in Table 5.

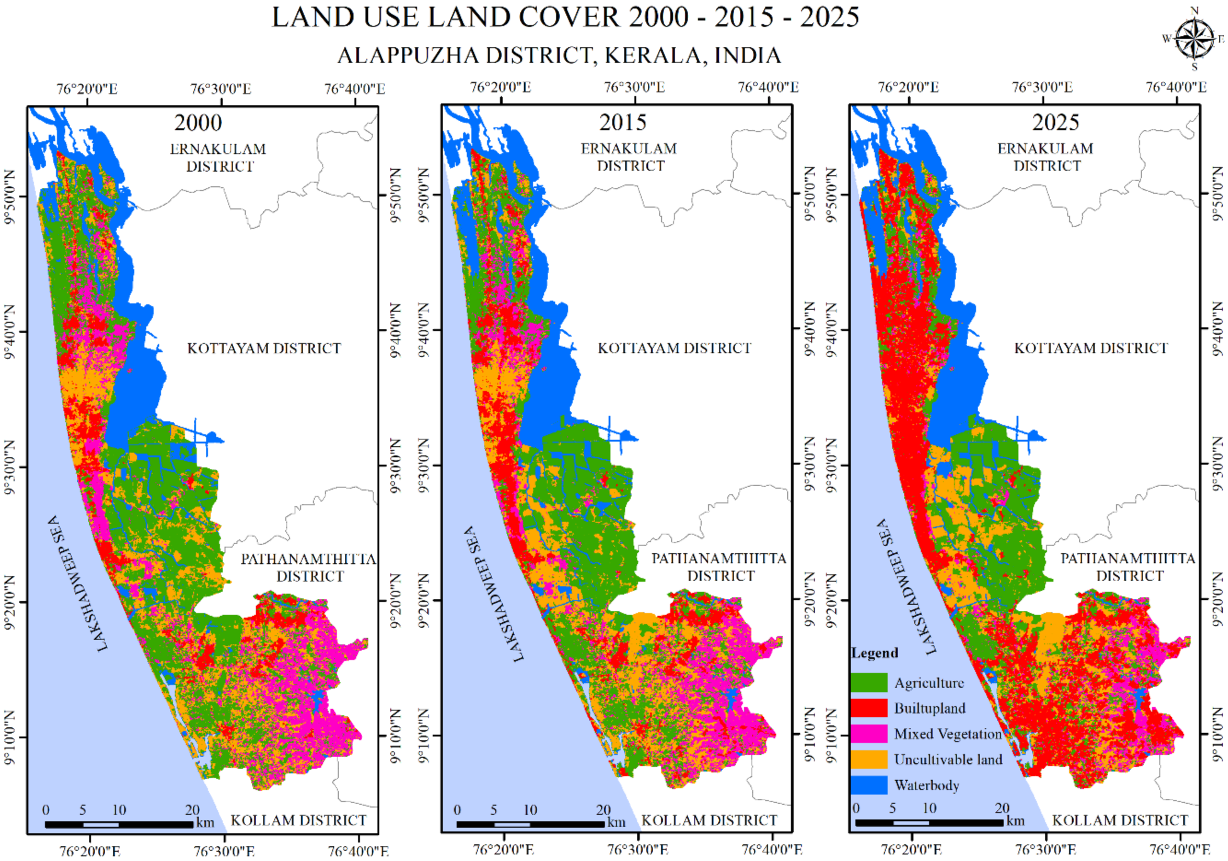

Figure 3: Land Cover Classes in the Study Area for the Years 2000, 2015 and 2025.

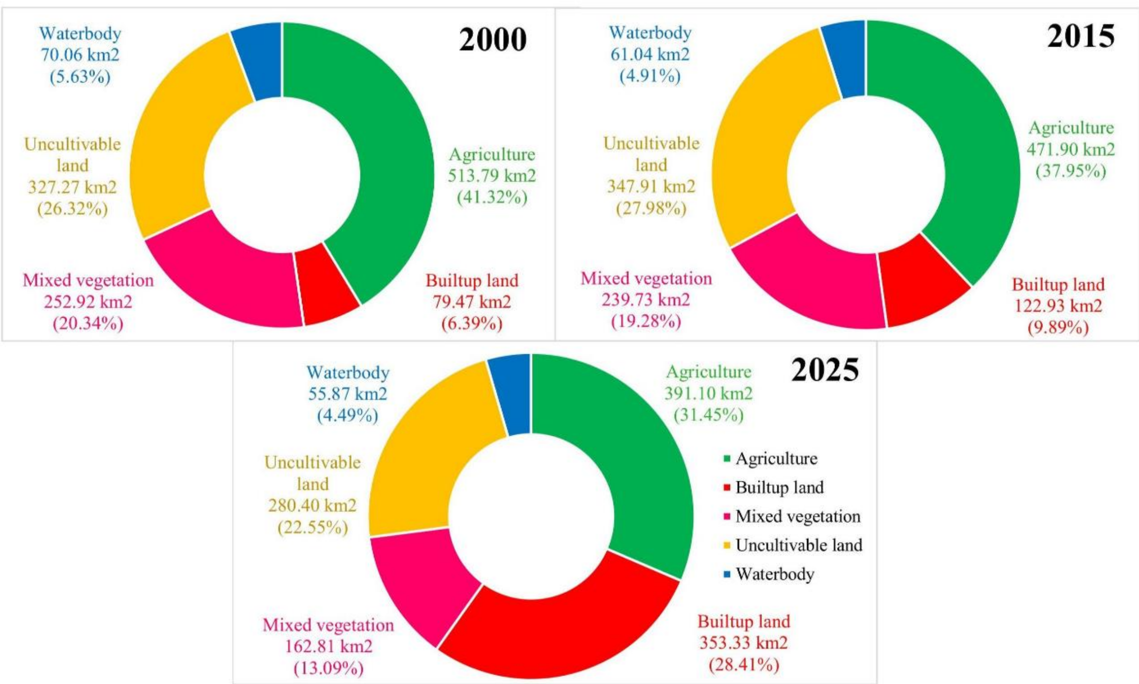

Figure 4: Doughnut Chart Showing the Land Utilization for Each Land Use Classes in Alappuzha District for the Years 2000, 2015 and 2025

Agricultural land showed a consistent decline throughout the study period. The area under agriculture decreased from 513.79 km² (41.32%) in 2000 to 471.90 km² (37.95%) in 2015 and further to 391.10 km² (31.45%) in 2025. This corresponds to a net loss of 122.69 km² (23.88%) over the entire period, with a higher rate of decline (80.80 km² with 17.12%) observed during 2015–2025. Agricultural land exhibited a negative annual growth rate, which intensified from −0.57% per year (2000–2015) to −1.88% per year (2015–2025).

In contrast, **Built-up land** exhibited the most pronounced expansion, increasing steadily across all periods. The built-up area increased from 79.45 km² (6.39%) in 2000 to 122.93 km² (9.89%) in 2015, and further to 353.33 km² (28.41%) in 2025. Overall, the built-up land increased by 344.61% (273.86 km²) between 2000 and 2025. The most rapid expansion occurred during 2015-2025, accounting for 187.42% (230.40 km2). Built-up land recorded the highest annual growth rate, increasing from 2.91% per year during 2000–2015 to 10.56% per year during 2015–2025.

Mixed vegetation also declined substantially over time. The area decreased from 252.92 km² (20.34%) in 2000 to 239.73 km² (19.28%) in 2015, followed by a sharper reduction to 162.81 km² (13.09%) in 2025. The overall reduction in mixed vegetation amounted to 90.11 km² (35.63%) between 2000 and 2025. Mixed vegetation also showed an accelerated rate of decline during the later period, with the annual rate of loss increasing from −0.36% to −3.87%.

Uncultivable land showed comparatively minor changes during the study period. The area increased from 327.27 km² (26.32%) in 2000 to 347.91 km² (27.98%) in 2015, representing a gain of 20.65 km² (6.31%). This was followed by a decline to 280.40 km² (22.55%) in 2025, corresponding to a loss of 67.51 km² (19.40%) during 2015-2025. Overall, uncultivable land declined by 46.87 km2 (14.32%) over the entire study period.

Water bodies steadily declined over the study period, from 70.06 km² (5.63%) in 2000 to 61.04 km² (4.91%) in 2015, representing a loss of 9.02 km² (12.87%) and further to 55.87 km² (4.49%) in 2025, resulting in a total loss of 14.19 km² (20.25%). This corresponds to an average annual decline of approximately 0.9%.
('-' sign indicates decrease)

LULC Class name	**Year**						**Area in change in km² (% Change)**		
	2000		**2015**		**2025**				
	Area (km2)	**% of the total area**	**Area (km2)**	**% of the total area**	**Area (km2)**	**% of the total area**	**2000 and 2015**	**2015 and 2025**	**2000 and 2025**
Agriculture	513.79	41.32	471.90	37.95	391.10	31.45	-41.89 (-8.15)	-80.80 (-17.12)	-122.69 (-23.88)
Built-up land	79.47	6.39	122.93	9.89	353.33	28.41	43.46 (54.69)	230.40 (187.42)	273.86 (344.61)
Mixed vegetation	252.92	20.34	239.73	19.28	162.81	13.09	-13.19 (-5.22)	-76.92 (-32.09)	-90.11 (-35.63)
Uncultivable land	327.27	26.32	347.91	27.98	280.40	22.55	20.65 (6.31)	-67.51 (-19.40)	-46.87 (-14.32)
Water body	70.06	5.63	61.04	4.91	55.87	4.49	-9.02 (-12.87)	-5.17 (-8.47)	-14.19 (-20.25)
Total area	**1243.51**	**100**	**1243.51**	**100**	**1243.51**	**100**			

Table 4: LULC distribution of Alappuzha District for the years 2000, 2015 and 2025.

Note: ('-' Sign Indicates Decrease).

LULC Class	**Annual Rate Change (2000-2015) %**	**Annual Rate Change (2015–2025) %**	**Annual Rate Change (2000-2025) %**
Agriculture	-0.57	-1.88	-1.09
Built-up land	2.91	10.56	5.97
Mixed vegetation	-0.36	-3.87	-1.76
Uncultivable land	0.41	-2.16	-0.62
Water body	-0.92	-0.89	-0.91

Table 5: Percentage of Annual Rate Change

Land Use and Land Cover Change Transition Matrix
Figure 5 and Tables 6, 7, and 8 show the cross-tabulation change matrix for the transformed regions, indicating the proportional shifts between different LULC classes relative to the total area of each class from 2000 to 2015, 2015 to 2025, and 2015 to 2025. Even though all LULC classes transformed in the study region, the extent of these changes

varied significantly, with conversions observed throughout the entire study area. The diagonal values indicate the quantity of unchanged land use types. Between 2000 and 2015, agricultural land moderately declined, with 439.55 km^2 remaining stable, while 51.22 km^2 shifted to uncultivable land, 14.03 km2 into waterbodies and 8.84 km^2 to built-up areas. Built-up land expanded from 79.47 km^2 to 122.93 km^2, mainly at the expense of water bodies (19.45 km^2), mixed vegetation (12.17 km^2), agriculture (8.84 km^2), and uncultivable land (3 km^2). Mixed vegetation remained largely stable (239.37 km^2), with minor conversions into uncultivable land (0.21 km^2) and agricultural land (0.15km2). Uncultivable land remained mostly unchanged (295.14 km^2), while water bodies were relatively stable (46.29 km^2 retained), despite small conversions (Table 6). From 2015 to 2025, rapid urban growth was observed, with built-up land increasing from 122.93 km^2 to 353.33 km^2, primarily converted from agriculture (83.63 km^2), mixed vegetation (75.68 km^2), and uncultivable land (70.82 km^2). Agricultural and mixed vegetation areas declined considerably, while water bodies showed only a slight reduction, with 53.09 km^2 remaining stable (Table 7). Over the long term (2000 to 2025), a major landscape transformation occurred. Agricultural land decreased, with 358.01 km^2 remaining, while significant portions were converted to built-up (80.42 km^2), uncultivable land (60.20 km^2) and water bodies (14.60 km2). Built-up areas increased most sharply, gaining land mainly from uncultivable land (105.57 km^2), mixed vegetation (87.66 km^2), and agriculture (80.42 km2). Mixed vegetation and water bodies showed consistent declines, with only 161.67 km^2 and 40.45 km^2 remaining, respectively (Table 8).

2000 (Area in km^2)	**LULC Class**	2015 (Area in km^2)					
		Agriculture	**Built-up land**	**Mixed vegetation**	**Uncultivable land**	**Water body**	**Total 2000**
	Agriculture	**439.55**	8.84	0.15	51.22	14.03	**513.79**
	Built-up land	0.00	**79.47**	0.00	0.00	0.00	**79.47**
	Mixed vegetation	0.36	12.17	**239.37**	0.90	0.12	**252.92**
	Uncultivable land	28.32	3.00	0.21	**295.14**	0.60	**327.27**
	Water body	3.67	19.45	0.00	0.65	**46.29**	**70.06**
	Total 2015	**471.90**	**122.93**	**239.73**	**347.91**	**61.04**	**1243.51**

Table 6: LULC change matrix from 2000 to 2015

2015 (Area in km^2)	**LULC Class**	2025 (Area in km^2)					
		Agriculture	**Built-up land**	**Mixed vegetation**	**Uncultivable land**	**Water body**	**Total 2015**
	Agriculture	**355.35**	83.63	0.50	30.46	1.96	**471.90**
	Built-up land	0.00	**122.93**	0.00	0.00	0.00	**122.93**
	Mixed vegetation	0.42	75.68	**161.74**	1.89	0.00	**239.73**
	Uncultivable land	30.56	70.82	0.57	**245.14**	0.82	**347.91**
	Water body	4.77	0.27	0.00	2.91	**53.09**	**61.04**
	Total 2015	**391.10**	**353.33**	**162.81**	**280.40**	**55.87**	**1243.51**

Table 7: LULC change matrix from 2015 to 2025

2000 (Area in km2)	**LULC Class**	2025 (Area in km^2)					
		Agriculture	**Built-up land**	**Mixed vegetation**	**Uncultivable land**	**Water body**	**Total 200**
	Agriculture	**358.01**	80.42	0.56	60.20	14.60	**513.79**
	Built-up land	0.00	**79.47**	0.00	0.00	0.00	**79.47**
	Mixed vegetation	1.07	87.66	**161.67**	2.37	0.15	**252.92**
	Uncultivable land	25.78	105.57	0.58	**194.67**	0.67	**327.27**
	Water body	6.24	0.21	0.00	23.16	**40.45**	**70.06**
	Total 2025	**391.10**	**353.33**	**162.81**	**280.40**	**55.87**	**1243.51**

Table 8: LULC change matrix from 2000 to 2025

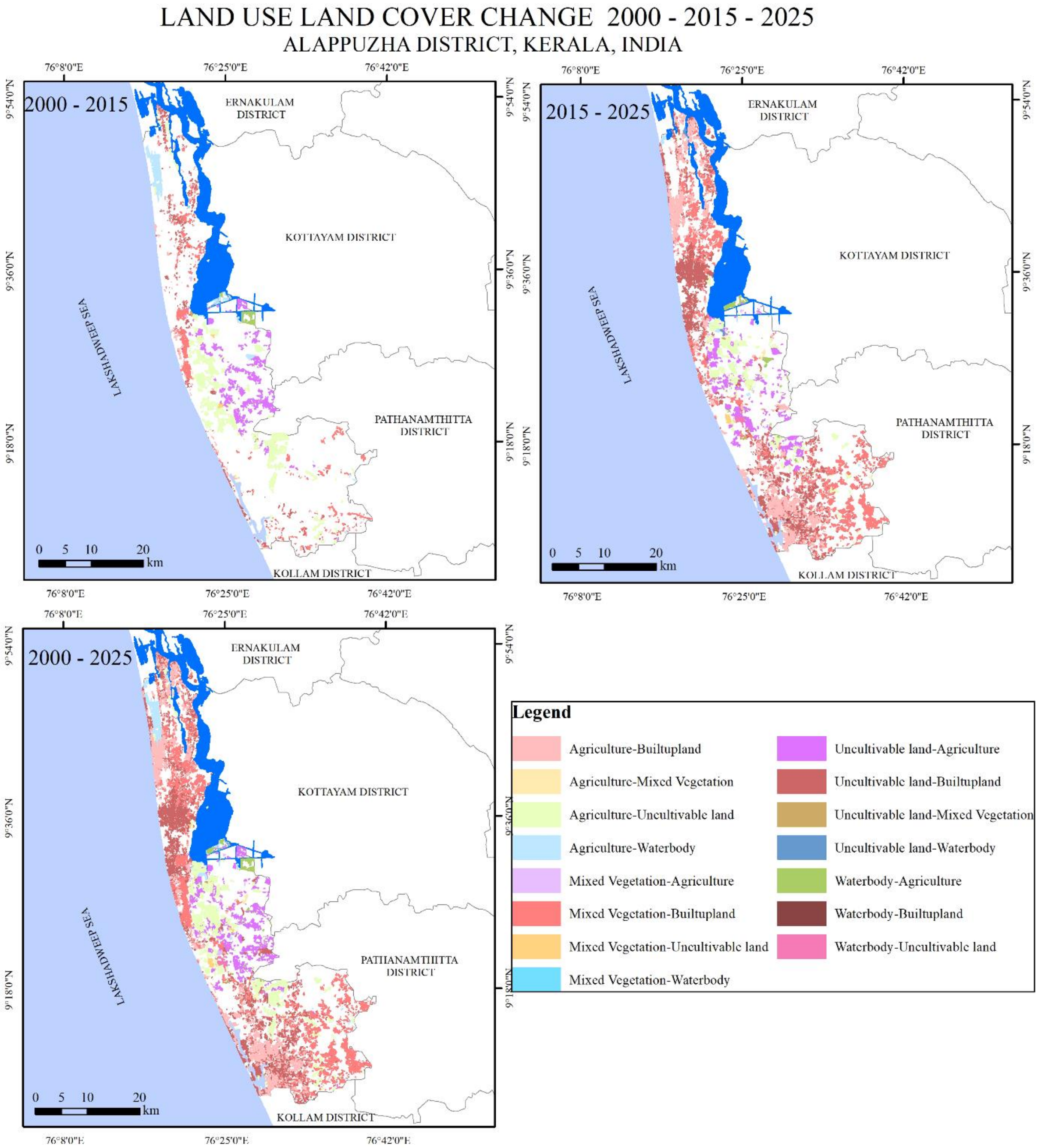

Figure 5: Spatial Distribution of LULCC During 2000 – 2015 – 2025

Discussion

The land use and land cover (LULC) dynamics of Alappuzha district over the 25 years from 2000 to 2025 reveal substantial landscape transformations that are likely associated with socio-economic development and increasing anthropogenic pressure on natural landscapes. The overall pattern is characterised by pronounced urban expansion accompanied by a decline in natural and semi-natural land cover types, indicating growing ecological stress in the district.

The most prominent transformation was the increase in built-up land during the study period, evolving from a relatively minor component of the landscape in 2000 to the second most dominant land cover class by 2025. The overall increase of 344.61% (273.86 km2) highlights the rapid pace of urbanization in Alappuzha. While built up expansion during 2000-2015 was moderate (54.69%, 43.46 km2), growth accelerated sharply after 2015 (187.42%, 230.40 km2 during 2015-2025), indicating a shift in the district's development trajectory (Table 4). This expansion occurred largely at the expense of uncultivable land (105.57 km2), mixed vegetation (87.66 km2), and agricultural land (80.42 km2), as reflected in the conversion of substantial areas of these classes to built-up land (Table 8). Similar long term (1973 to 2017) urban growth trends in Alappuzha have been reported by [2]. These findings are also consistent with the regional-scale analysis of Kerala by, which reported increasing urban and built-up land alongside declining vegetation-related land-cover categories across the state [34]. The increase in built-up land in Alappuzha is driven by population growth in the district. According to census data, the population in our study area was 2,001,083 in 1991, which increased to 2,127,789 in 2011, reflecting a growth of 7.26%. By 2021, the population further increased to an estimated 2.20 million, projected growth for 2021 in the absence of official census data due to delays associated with the COVID-19 pandemic. This substantial rise in population has led to a higher demand for residential, commercial, and infrastructural development, contributing significantly to the expansion of built-up land. In addition to population pressure, the flourishing tourism industry has substantially influenced land transformation in the Alappuzha District. Tourism demanded the construction of resorts, hotels, restaurants, and associated facilities, particularly in ecologically sensitive coastal and backwater regions, resulting in changes in land use. Although tourism provides economic benefits, it has also accelerated habitat fragmentation and environmental degradation, placing considerable pressure on natural resources and ecosystems. Road infrastructure development has further amplified urban expansion. Major road projects such as the National Highway 66 (NH-66) Alappuzha Bypass, six-laning works, and the Aroor–Thuravoor elevated highway have improved accessibility and connectivity, making the surrounding areas more attractive for urban and commercial development. These transport corridors have served as focal points, especially after 2015, for land-use conversion, reinforcing the dominance of built-up land across the Alappuzha district.

Agricultural land experienced a sustained decline of 23.88 km2 (122.69%) between 2000-2025, with an average annual decline of 1.09% per year (Tables 4 and 5), reflecting increasing pressure from urban and semi-urban activities and structural changes in the local economy. The reduction in agricultural area is closely linked to shifts in livelihood preferences, with a growing proportion of the population moving toward education-based and non-agricultural employment. This transition has reduced the availability of agricultural labour, leading to land abandonment and its subsequent conversion for residential, commercial, and infrastructural purposes. Such a shift has also altered paddy cultivation in Alappuzha, which become increasingly concentrated in the Kuttanad region, while paddy fields in the northern and southern parts of the district have largely diminished. This spatial contraction of rice cultivation challenges Alappuzha's long-standing identity as the 'rice bowl of Kerala'. Similar trends have been reported elsewhere in the state, where higher literacy rates and the appeal of secondary and tertiary sector employment have reduced the attractiveness of farming [48].

Another factor is urban migration and improved infrastructure, which have shifted focus away from agriculture, further increasing the decline. In the Kuttanad region, agricultural decline has been further exacerbated by frequent and prolonged inundation of low-lying paddy fields. Anthropogenic alterations to hydrological systems have intensified flooding, rendering traditional cultivation increasingly unviable [49]. The results indicate that a notable proportion of agricultural land (14.60 km2) was converted into water bodies between 2000 and 2025, largely associated with the expansion of aquaculture, particularly prawn and shrimp farming ponds in areas such as Chemmen Padam. Previous studies have reported that aquaculture offers higher economic returns than conventional paddy cultivation, encouraging farmers to shift land use in response to market demand and export opportunities [50,51].

Although agricultural land has declined substantially, approximately 358.01 km² remained under cultivation during 2000–2025 (Table 8), supported by legal safeguards, cultural practices, and physical constraints. The Kerala Paddy Land and Wetland Conservation Act (2008) has played a critical role in restricting the conversion of paddy fields and wetlands, particularly in ecologically sensitive low-lying areas. Community-based initiatives such as padasekharams and Kudumbashree joint farming schemes have fostered strong cultural and social commitment to paddy cultivation, Kuttanad, preserving its identity as the 'rice bowl of Kerala'. The unique below-sea-level farming system of Kuttanad further limits alternative land uses, as frequent flooding and waterlogged conditions make urban development technically challenging and economically unviable. Together, these legal, cultural, and environmental factors have contributed to the continued persistence of paddy fields in the region, even as agricultural land elsewhere in the district has declined.

Uncultivable land exhibited a fluctuating trend during the study period, reflecting the dynamic interaction between socio-economic change, policy interventions, and regulatory limitations. The area under uncultivable land increased from 327.27 km² in 2000 to 347.91 km² in 2015 (6.31%), indicating temporary land degradation and the abandonment of productive agricultural land (Table 4). This initial increase suggests a transitional phase, during which agricultural land was rendered non-viable due to labour shortages, financial constraints, recurrent flooding, and declining profitability, leading to its reclassification as fallow or uncultivable land. Between 2015 and 2025, uncultivable land declined sharply to 280.40 km² (19.40%), resulting in a net decrease of 46.87 km² (14.32%) over the entire study period (Table 4). A significant portion of this land was converted into built-up areas (105.57 km²) and agricultural land (25.78 km²) (Table 8). While some degraded lands were reclaimed for cultivation through collective farming initiatives, a larger share was absorbed by expanding urban and infrastructural development, highlighting increasing anthropogenic pressure on land resources.

At the same time, approximately 60.20 km² of agricultural land was converted into uncultivable land, largely due to the shift of agricultural labourers toward non-farm employment, financial limitations, and land abandonment [52]. The transition from joint family systems to nuclear households further weakened traditional farming structures, reducing the capacity for labour-intensive agricultural practices. Policy interventions also played a mixed role in shaping these changes. While the Kudumbashree Collective Farming initiative facilitated the reclamation of fallow and waste lands for cultivation, contributing to the conversion of 25.78 km² of uncultivable land back into agricultural land, the Kerala Land Reforms Act (1963) and its 1969 amendment fragmented large landholdings into smaller, economically less viable plots, indirectly encouraging land conversion for residential and commercial purposes.

Despite the presence of legal frameworks aimed at protecting agricultural land, land-use conversion continues through a combination of regulatory loopholes and socio-economic pressures. In many cases, agricultural land is first abandoned and reclassified as uncultivable or fallow land, after which it becomes eligible for conversion into built-up land. In other instances, agricultural land is directly converted into built-up land, particularly for housing, through approvals granted under the Kerala Land Utilisation (KLU) Order, 1967, or through corrections in local paddy land data banks under the Kerala Paddy Land and Wetland Conservation Act, 2008. Administrative challenges, delays in updating land records, fragmented landholdings, and local-level decision-making further weaken effective enforcement of land-protection regulations.

The pronounced decline in uncultivable land after 2015 is also closely associated with large-scale infrastructure projects such as the NH-66 Alappuzha Bypass and six-laning works, which accelerated land acquisition and land-use conversion along major transport corridors. Decline in uncultivated land as a result of rapid urbanization has also been reported by [2]. Collectively, these processes explain the observed land-use transitions and highlight the limitations of existing regulatory mechanisms in preventing agricultural land loss despite statutory protection.

Mixed vegetation experienced a net decrease of 35.63% (90.11 km2) over the span of 25 years, with an annual decline of 1.76%. During 2000 to 2015, 13.19 km2 was lost, recording a 5.22% decrease with an annual decline of 0.36%. During 2015 to 2025, mixed vegetation further lost 76.92 km2 (32.09%), representing an annual decline of 3.87% (Tables 4 and 5). Changes in the socioeconomic status of the people led to accelerated development of infrastructure and real estate in Kerala (Dixit et al. 2018), which eventually required the removal of vegetative cover, resulting in LULCC. Perusal of literature has shown decreased vegetative cover in various parts of Kerala resulting from escalated urbanization which is evident from our result, where 87.66 km2 of mixed vegetation was converted into Built-up land (Table 8) [53]. The reduction of mixed vegetation in the study area has been most pronounced after 2015, largely due to rapid infrastructure expansion and intensified human-driven land-use changes. The widening of NH 66 in Alappuzha district led to the removal of a large number of trees, with estimates ranging from approximately 12,000 to 70,000 trees along the Thuravoor–Oachira stretch, including ecologically important species such as banyan and jackfruit (The Hindu, 2022). This also resulted in habitat loss, fragmentation of vegetation patches, and disruption of local microclimatic conditions and increased the Land surface temperature of the area. Although compensatory plantation programmes were initiated under the Green Highway Policy, the slow pace of implementation and low short-term survival of transplanted trees meant that lost ecological functions were not adequately replaced. Additionally, before land sale and acquisition, some landowners felled mature trees and sold the timber for higher financial returns, while others cut old trees to meet emergency economic needs. All these factors significantly contributed to the decline of mixed vegetation in the region and weakened its ecological stability.

The water bodies experienced a net decrease of 20.25% (14.19 km2) over the span of 25 years, with an annual decline of 0.91%. During the period from 2000 to 2015, 9.02 km2 was lost, recording a 12.87% decrease with an annual decline of 0.92%. Water Body further declined during 2015-2025, 5.17 km2 (8.47%), with an annual decline of 0.89% (Tables 4 and 5). Over the entire study period, 23.16 km2 of water bodies were converted into uncultivable land (Table 8). From 2000 to 2015, 19.45 km2 of water bodies were converted into built-up land (Table 6). This transition can be attributed to both natural factors, such as groundwater depletion, and anthropogenic activities, including sand filling for construction and agricultural expansion. The encroachment of infrastructure, such as concreting natural channels, has further disrupted hydrological systems, leading to desiccation of water bodies [54]. A similar trend of water body decline in the district has been noted by [55]. While the present study observed a decline in water bodies between 2000 and 2025, a previous study by in the same region reported an increase of 5.56 km2 in water bodies between 1973 and 2017 [2]. This discrepancy may be linked to temporal differences and the expansion of aquaculture ponds, which are often spectrally similar to natural water bodies and may influence classification outcomes.

The study investigated the LULCCs in Alappuzha for the years 2000, 2015, and 2025. The findings indicate severe ecological stress on the district’s land use and land cover. A positive change was observed for built-up areas, whereas negative change was noted for all other classes, with the highest decline recorded in mixed vegetation. The steady rise in built-up areas and reduction in natural land reflect a complex interaction of socio-economic growth, NRI remittances, population growth, and urban expansion. Rise in population density can be justified by the concentration of the municipalities of Alappuzha (Alappuzha, Cherthala, Kayamkulam, Mavelikkara, Chengannur, and Haripad), as reported by for the period 1973-2017, which highlights the district’s long-term demographic intensification [2]. In addition, infrastructure development and the district’s shift toward a more diversified economy have further contributed to land conversion. While traditional sectors like coir and fisheries continue to shape local livelihoods, new investments in IT, tourism, and small-scale industries have intensified land demand and accelerated the transformation of rural landscapes. Major projects such as the NH-66 expansion, improved connectivity, and the growth of tourism infrastructure have pushed development into ecologically sensitive zones, especially low-lying paddy fields. As land availability shrinks and environmental pressures increase, the findings underscore the need for balanced planning and sustainable management of LULCC to preserve ecological stability and support Alappuzha’s evolving economic trajectory.

Conclusion

This study assessed the land use and land cover changes (LULCCs) in Alappuzha District, Kerala, over 25 years (2000–2025) using multi-temporal Landsat imagery and geospatial techniques. The findings reveal significant landscape transformation characterised by rapid urban expansion and substantial declines in agricultural land, mixed vegetation, water bodies, and uncultivable land, indicating increasing ecological stress across the district. Built-up land exhibited the most pronounced increase, reflecting the combined influence of population growth, urbanisation, infrastructure development, tourism expansion, and broader socio-economic transitions.

The observed changes highlight the urgent need for integrated land-use planning, stricter protection of agricultural lands and wetlands, and sustainable development strategies that balance economic growth with ecological conservation. The findings provide an important scientific basis for evidence-based policy formulation, wetland conservation, climate-resilient development, and long-term environmental management in Alappuzha District. Future studies integrating higher-resolution satellite imagery, advanced machine learning classification techniques, socio-economic modelling, and land surface temperature analysis will further improve the understanding of landscape dynamics and support more effective environmental planning.

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Dr. Anitha V carried out the data analysis, interpretation, and manuscript writing, while Dr. D. Prabha contributed through critical review, proofreading, and editorial corrections.

Competing Interest
The authors declare that they have no competing interests.

Data Availability
All data generated or analysed during this study are included in this published article.

Ethics
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