ORIGINAL RESEARCH

Long-term mangrove extent dynamics in Tarout Bay, Arabian Gulf, Saudi Arabia (1990-2026)

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ABSTRACT. Mangrove ecosystems in arid coastal environments experience substantial spatial and temporal changes, requiring consistent long-term monitoring. We examined mangrove extent in Tarout Bay, Arabian Gulf, Saudi Arabia, for 1990, 2000, 2010, 2020 and 2026 using Landsat surface-reflectance composites and NDVI thresholding, with Sentinel-2 imagery providing contemporary landscape context. Mapped extent increased from 15.90 to 142.44 ha (795.8%), representing a net increase of 126.54 ha. The greatest net expansion occurred during 2010-2020 (62.50 ha; 6.25 ha yr^{-1}), followed by a slower increase during 2020-2026 (18.71 ha; 3.12 ha yr^{-1}). These findings demonstrate substantial long-term mangrove expansion, with considerable variation in the rate of change across observation periods. However, the absence of an independent classification accuracy assessment and uncertainties associated with the spatial resolution of Landsat imagery limit quantitative interpretation. The results provide an extent-based baseline for evaluating mangrove dynamics and supporting coastal conservation, field verification and restoration monitoring in arid environments.

Key words: *Avicennia marina*, mangrove extent, temporal dynamics, remote sensing, Arabian Gulf.

Dinámica a largo plazo de la expansión de los manglares en la bahía de Tarout, Golfo Arábigo, Arabia Saudita (1990-2026)

RESUMEN. Los ecosistemas de manglar en entornos costeros áridos experimentan cambios espaciales y temporales sustanciales, lo que requiere un seguimiento constante a largo plazo. Analizamos la extensión de los manglares en la bahía de Tarout, en el Golfo Arábigo (Arabia Saudita), para los años 1990, 2000, 2010, 2020 y 2026, utilizando compuestos de reflectancia superficial de Landsat y umbrales del índice de vegetación de diferencia normalizada (NDVI), complementados con imágenes del satélite Sentinel-2 para proporcionar un contexto paisajístico actual. La extensión mapeada aumentó de 15,90 a 142,44 ha (795,8%), lo que representa un incremento neto de 126,54 ha. La mayor expansión neta se produjo entre 2010 y 2020 (62,50 ha; 6,25 ha $año^{-1}$), seguida de un aumento más moderado entre 2020 y 2026 (18,71 ha; 3,12 ha $año^{-1}$). Estos hallazgos demuestran una expansión sustancial de los manglares a largo plazo, con una variación considerable en la tasa de cambio a lo largo de los periodos observados. No obstante, la ausencia de una evaluación independiente de la precisión de la clasificación, junto con las incertidumbres asociadas a la resolución espacial de las imágenes Landsat, limitan la interpretación cuantitativa. Los resultados proporcionan una línea base, fundamentada en la extensión, para evaluar la dinámica de los manglares y apoyar la conservación costera, la verificación en campo y el seguimiento de los procesos de restauración en entornos áridos.

Palabras clave: *Avicennia marina*, extensión de manglares, dinámica temporal, teledetección, Golfo Arábigo.

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INTRODUCTION

Mangrove forests are dynamic intertidal ecosystems that provide critical functions, including shoreline stabilization, habitat provision, fisheries support, sediment retention, and climate regulation. Their spatial distribution reflects interactions among tidal inundation, sediment dynamics, sea-level variability, climatic conditions, and anthropogenic disturbance (Contessa et al. 2023; Zhang et al. 2024; Ju et al. 2025). Recent global assessments demonstrate that mangrove trajectories are spatially heterogeneous, with expansion occurring alongside persistent losses in many regions (Contessa et al. 2023; Ju et al. 2025).

Long-term Earth observation provides an effective framework for resolving these dynamics. The Landsat archive enables consistent reconstruction of multi-decadal mangrove distributions, while Sentinel-2 imagery offers finer spatial resolution for contemporary mapping and detection of fragmented coastal vegetation (Vasquez et al. 2024). Li et al. (2019) previously investigated mangrove distribution in northern Tarout Bay and Tarout Island using Landsat imagery, Google Earth Engine, multiple spectral indices, and classification algorithms, reporting classification accuracies exceeding 90%. Recent advances in remote sensing increasingly emphasize the importance of distinguishing persistence, gain, and loss, rather than relying solely on net changes in mangrove extent (Vasquez et al. 2024; Tian et al. 2026). This transition-based approach can reveal substantial spatial turnover that remains concealed when changes are expressed only as total area.

Such spatially explicit assessment is particularly important in arid coastal environments, where mangroves persist under high temperatures, hypersalinity, limited precipitation, and strong evaporative stress. These environmental constraints can interact with sea-level variability, hydrological alteration, urbanization, and coastal development to influence mangrove persistence and establishment (Zhang et al. 2024; Mohammed et al. 2026). Previous studies in Tarout Bay have documented mangrove distribution and environmental changes (Almahasheer et al. 2013; Al-Ali et al. 2015; Zayid 2022), while the national time-series assessment by Aljaddani (2025) provides a broader perspective on mangrove dynamics across Saudi Arabia. Recent research from the Arabian Gulf confirms the value of multi-temporal satellite observations for detecting long-term mangrove responses under extreme arid conditions and identifying areas of expansion, stress, and degradation (Mohammed et al. 2026). However, detailed assessments of long-term spatial transitions in Tarout Bay remain limited.

Tarout Bay, along the Arabian Gulf coast of Saudi Arabia, represents a particularly relevant setting for examining these processes. Mangroves occur within a heterogeneous coastal landscape comprising intertidal mudflats, sabkha, shallow waters, bare land, and densely urbanized areas. In such landscapes, increasing mangrove extent does not necessarily indicate spatial stability, because persistent stands may coexist with newly established vegetation and localized losses. Recent global analyses similarly demonstrate that mangrove gain and loss arise from spatially variable natural and anthropogenic processes, highlighting the importance of examining gross transitions alongside net change (Ju et al. 2025).

The objective of this study was to quantify changes in mapped mangrove extent in Tarout Bay across five observation years (1990, 2000, 2010, 2020 and 2026) and evaluate temporal variation in net expansion using Landsat imagery. Sentinel-2 imagery was used to characterize the contemporary coastal landscape. The analysis provides a historical baseline for mangrove monitoring while acknowledging uncertainties associated with satellite classification and the absence of independently validated spatial transition estimates.

MATERIALS AND METHODS

Study area

Tarout Bay is located along the Arabian Gulf coast of the Eastern Province, Saudi Arabia (Figure 1). The bay is a shallow, arid coastal system characterized by intertidal mudflats, sabkha, shallow waters, mangrove stands, and extensive urban development. Mangrove vegetation is dominated by *Avicennia marina* (Figure 2), which occurs under high salinity, elevated temperatures, and limited freshwater input typical of the Arabian Gulf.

Satellite image selection and preprocessing

Landsat Collection 2, Tier 1, Level-2 surface-reflectance data were analyzed in Google Earth Engine (GEE) for 1990, 2000, 2010, 2020 and 2026. Landsat 5 TM (1990), Landsat 7 ETM+ (2000 and 2010), Landsat 8 OLI (2020) and Landsat 9 OLI-2 (2026) were used according to sensor availability. Images were filtered to the study boundary and the respective calendar year; the 2026 acquisition window ended on 1 September. Cloud and cloud-shadow observations were masked with QA_PIXEL, and reflectance was calculated using the Collection 2 scale factor (0.0000275) and offset (-0.2). Per-band annual median composites were clipped to the

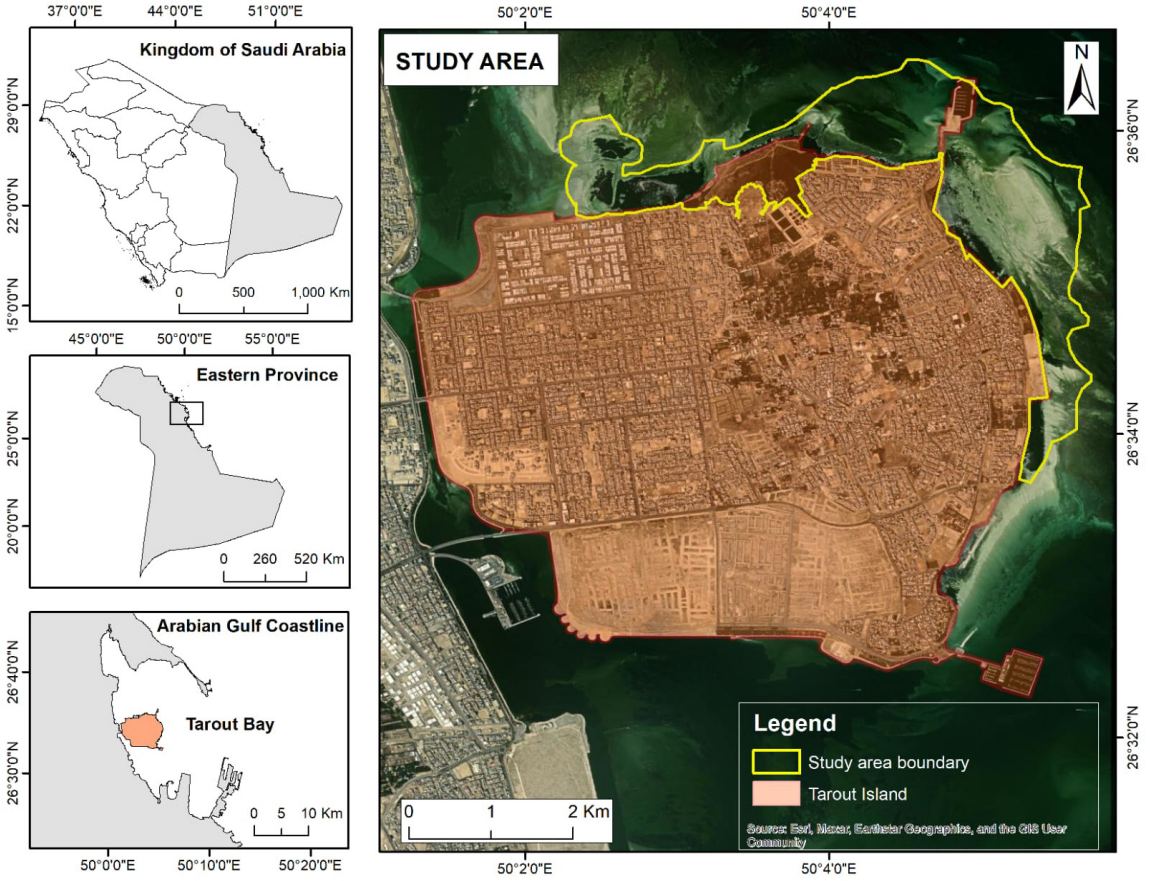


Figure 1. Location of the study area in Tarout Bay, Eastern Province, Saudi Arabia, showing its geographic position along the Arabian Gulf coast and the delineated study-area boundary.



Figure 2. Field view of *Avicennia marina* mangrove habitat and the surrounding intertidal environment in Tarout Bay, Arabian Gulf, Saudi Arabia (source: author's field photograph, January 2024).

study area and analyzed at nominal 30 m resolution. Annual compositing reduces short-term variability but does not ensure identical tidal conditions or eliminate Landsat 7 scan-line gaps. Scene identifiers, precise acquisition dates, processing-grid parameters and co-registration errors were not documented in the available analytical record.

Mangrove classification

Annual mangrove maps were produced independently by thresholding the Normalized Difference Vegetation Index, NDVI = (NIR - Red)/(NIR + Red). Pixels with NDVI ≥ 0.20 in 1990 and 2000, or NDVI ≥ 0.30 in 2010, 2020 and 2026, were labelled mangrove candidates; other valid pixels were labelled non-mangrove. These thresholds reproduce the original scripts but were not independently calibrated. The different thresholds used for ETM+ in 2000 and 2010 cannot be explained by sensor generation alone. The Normalized Difference Moisture Index, NDMI = (NIR - SWIR1)/(NIR + SWIR1), and Modified Normalized Difference Water Index, MNDWI = (Green - SWIR1)/(Green + SWIR1), supported visual interpretation but were not classification rules. Classification was limited to the study boundary; a separately validated intertidal mask, minimum mapping unit and independent training dataset were not documented. Thus, spectrally similar coastal vegetation and mixed shoreline pixels remain possible sources of error.

Spatial change and area estimation

Mangrove extent was calculated for each observation year by summing the areas of pixels classified as mangrove using ee.Image.pixelArea() and converting the results to hectares (1 ha = 10,000 m^2). Net extent change was calculated as the difference between successive mapped mangrove areas, while annualised net change was obtained

by dividing this difference by the corresponding observation interval (Δt, years). Although pairwise spatial transitions were initially examined, inconsistencies between transition-derived changes and independently mapped endpoint extents prevented reliable quantification of mangrove persistence, gross gain, loss and spatial turnover. Consequently, these metrics were excluded from the quantitative analysis. Reported changes therefore represent differences in mapped mangrove extent rather than independently validated spatial transitions. Figure 3 illustrates the conceptual workflow.

Classification uncertainty

No independent, acquisition-matched validation samples or probability-based reference design were available for the Landsat maps or the contextual Sentinel-2 image. Accordingly, confusion matrices, overall and class-specific accuracies, area-adjusted estimates and 95% confidence intervals cannot be reported. Visual inspection was used only to aid interpretation and does not constitute independent validation. Reported mangrove extents are therefore unvalidated mapped estimates potentially affected by threshold selection, tidal conditions, mixed pixels, spatial alignment and Landsat 7 ETM+ data gaps.

RESULTS

Long-term mangrove expansion

Mangrove extent increased markedly across Tarout Bay during 1990-2026 (Figures 4 and 5), rising from 15.90 ha in 1990 to 142.44 ha in 2026, corresponding to an endpoint-based net increase of 126.54 ha (795.8%). Area estimates are reported to two decimal places for consistency with GIS-derived calculations; however, this numerical precision does not represent measurement accuracy, given the 30 m spatial resolution of Landsat imagery and potential classification and boundary uncertainties. Mangrove cover increased from 2.15%

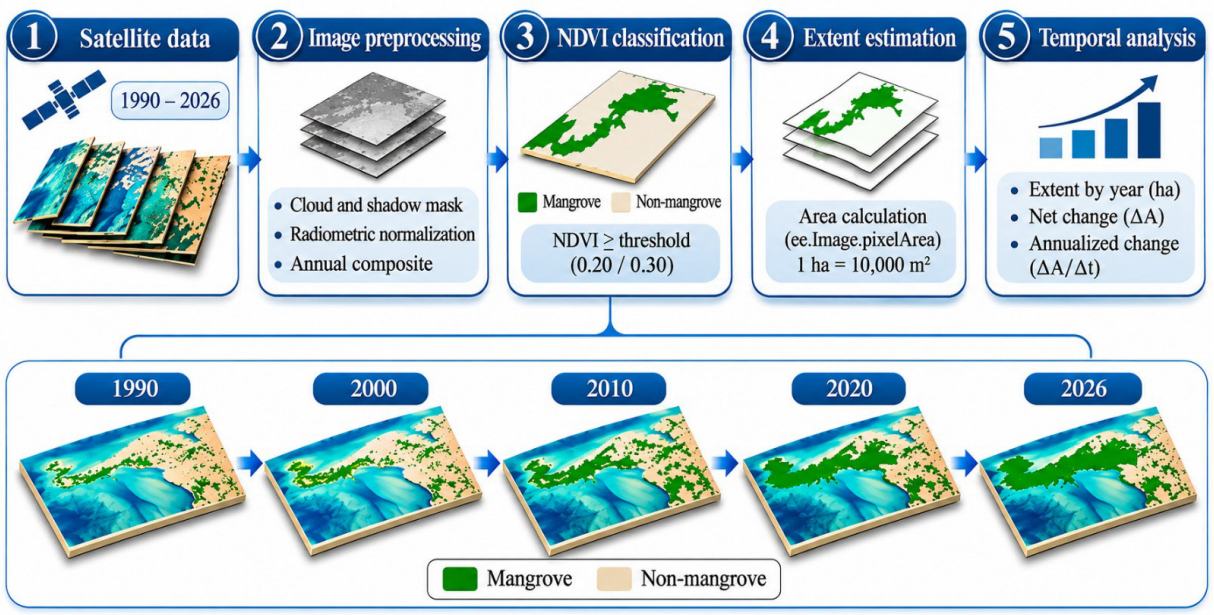


Figure 3. Schematic workflow for Landsat-based mangrove classification and assessment of net and annualized extent changes in Tarout Bay (1990-2026). Illustrated spatial patterns are conceptual rather than observed distributions.

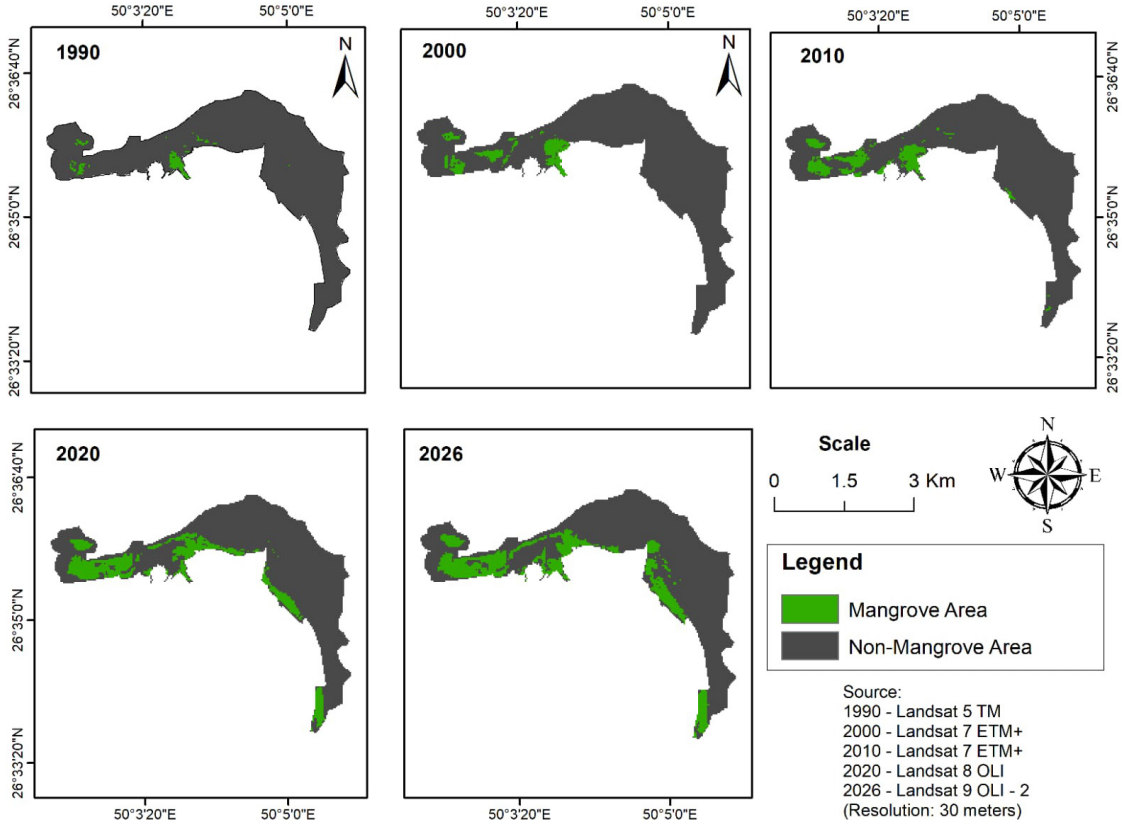


Figure 4. Mapped mangrove extent in Tarout Bay for 1990 (Landsat 5 TM), 2000 and 2010 (Landsat 7 ETM+), 2020 (Landsat 8 OLI), and 2026 (Landsat 9 OLI-2), at a nominal spatial resolution of 30 m. Image acquisition periods are described in the Methods; exact scene dates and independently validated mapping uncertainties are unavailable.

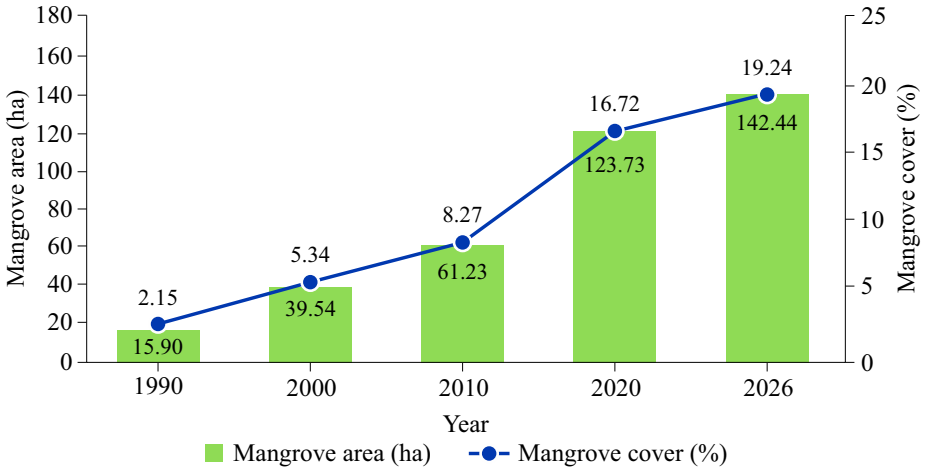


Figure 5. Temporal changes in mangrove area (ha) and percentage cover (%) in Tarout Bay, Arabian Gulf, Saudi Arabia, from 1990 to 2026.

to 19.24% of the mapped landscape. Expansion was relatively gradual during the first two decades, reaching 39.54 ha in 2000 and 61.23 ha in 2010, followed by a pronounced increase to 123.73 ha in 2020. By 2026, mangrove extent reached 142.44 ha, indicating continued but slower net expansion during the most recent period.

Temporal changes in mangrove extent

The mapped mangrove extent increased from 15.90 ha in 1990 to 142.44 ha in 2026, representing a net increase of 126.54 ha (Table 1). The corresponding period-specific net changes were 23.64 ha (1990-2000), 21.69 ha (2000-2010), 62.50 ha (2010-2020), and 18.71 ha (2020-2026). Examination of the original area summaries revealed differences between the independently calculated mangrove extents and spatial transition estimates. Consequently, the unreconciled persistence, gross gain, and gross loss values were excluded from the analysis to ensure numerical consistency. The greatest net increase occurred during 2010-2020, accounting for 49.4% of the total mapped expansion.

During 2020-2026, mangrove extent increased from 123.73 to 142.44 ha, corresponding to a net increase of 18.71 ha (3.12 ha yr^{-1}), compared with 6.25 ha yr^{-1} during 2010-2020. This indicates a reduction in the rate of net mangrove expansion during the most recent observation period. However, net extent changes do not distinguish spatial gains from losses and should not be interpreted as direct measures of mangrove establishment or mortality.

Spatial turnover requires consistent estimates of mangrove persistence, gain, and loss derived from spatially aligned classifications. Accordingly, gross and normalized turnover metrics were excluded pending verification of the original transition datasets. The extent-based results demonstrate substantial long-term mangrove expansion in Tarout Bay, although the magnitude and spatial distribution of simultaneous gains and losses remain to be quantified reliably.

Contemporary coastal landscape

Figure 6 provides a descriptive, higher-resolution Sentinel-2 view of contemporary mangroves, water, bare land/sabkha and built-up surfaces in Tarout Bay. The available record does not document a reproducible multiclass Sentinel-2 classifier or independent validation. Consequently, the figure is treated as contextual land-cover interpretation rather than an independently validated quantitative classification or direct evidence for 30-m Landsat transitions. The contemporary Sentinel-2 depiction illustrates a heterogeneous coastal setting but can-

Table 1. Changes in mapped mangrove extent, net change, and annualized net change across successive observation periods in Tarout Bay, Arabian Gulf, Saudi Arabia.

Period	Initial extent (ha)	Final extent (ha)	Net change (ha)	Annualized net change (ha yr^{-1})
1990-2000	15.90	39.54	23.64	2.36
2000-2010	39.54	61.23	21.69	2.17
2010-2020	61.23	123.73	62.50	6.25
2020-2026	123.73	142.44	18.71	3.12
1990-2026	15.90	142.44	126.54	3.52

Note: net change was calculated as the difference between final and initial mapped mangrove extent. Annualized net change was calculated by dividing net change by the duration of each observation period. Values represent extent-based changes rather than independently verified spatial gains and losses.

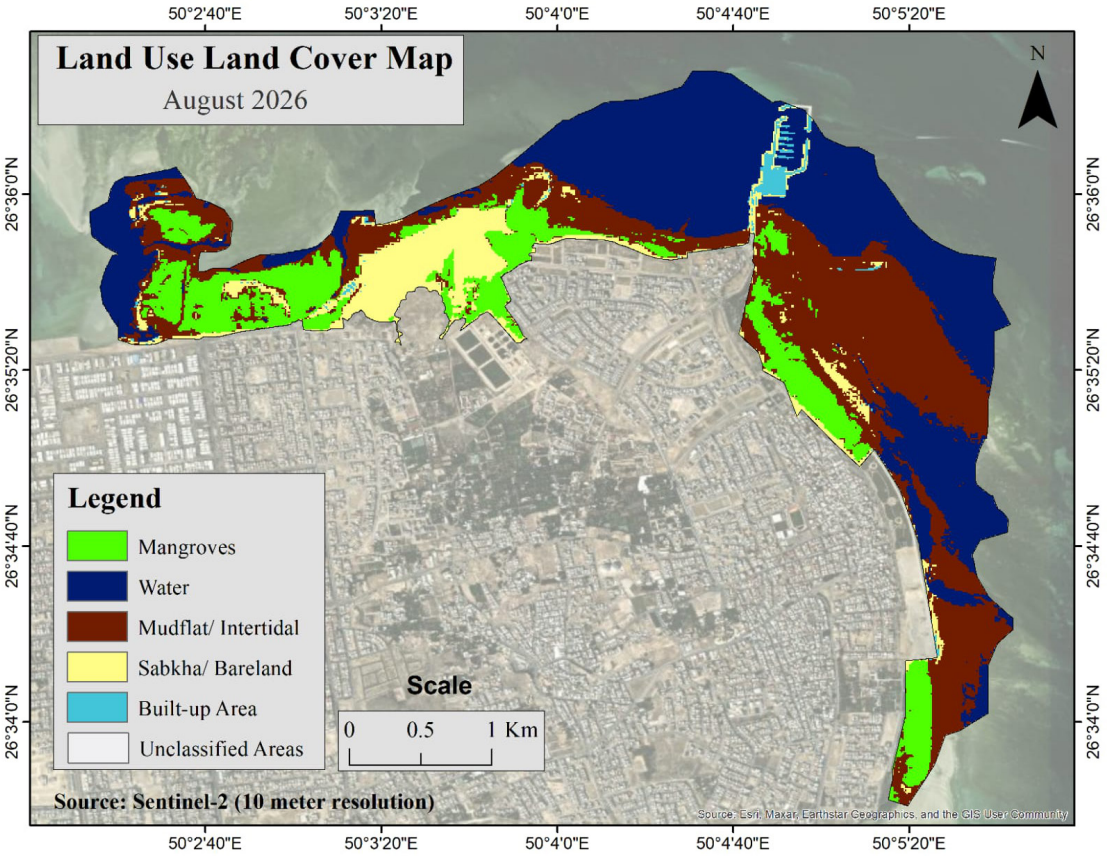


Figure 6. Sentinel-2 depiction of the contemporary coastal landscape in Tarout Bay (August 2026; nominal 10 m). Land-cover interpretation is contextual and was not independently validated or used to confirm Landsat change estimates.

not independently confirm the location or magnitude of historical Landsat gains and losses. Direct cross-resolution inference would require an explicit spatial-scale and co-registration assessment that is not available in the present analysis.

DISCUSSION

Mapped mangrove extent increased from 15.90 ha in 1990 to 142.44 ha in 2026, suggesting substantial long-term expansion in Tarout Bay under arid coastal conditions. Nevertheless, these estimates are derived from threshold-based classifications without independent accuracy assessment and should not be interpreted as error-free measurements. Natural colonization, planting and restoration may all have contributed to expansion, but the available imagery and site records do not permit their relative contributions to be quantified (Friis and Burt 2020; Mohan et al. 2024).

Despite this long-term increase, mangrove expansion in Tarout Bay was temporally heterogeneous, with the greatest extent-based net increase of 62.50 ha (6.25 ha yr^{-1}) occurring during 2010-2020, followed by slower expansion of 18.71 ha (3.12 ha yr^{-1}) during 2020-2026. Such variability may reflect interactions among tidal connectivity, sediment dynamics, shoreline stability, prop-

agule availability, and anthropogenic interventions, which can influence mangrove establishment and persistence (Hagger et al. 2022; Contessa et al. 2023). However, the extent-based results do not establish the spatial distribution of mangrove gains and losses or the processes responsible for the observed changes. Furthermore, potential classification errors, mixed pixels, and image registration uncertainties along intertidal boundaries limit the reliability of interpreting apparent spatial transitions without independent validation.

The temporal variation in mapped mangrove extent indicates substantial differences in net expansion across successive observation periods. The greatest net increase occurred during 2010-2020 (62.50 ha), accounting for approximately 49.4% of the total expansion recorded between 1990 and 2026. In contrast, net expansion declined to 18.71 ha during 2020-2026. Previous studies have demonstrated that mangrove gains and losses may occur simultaneously, potentially obscuring spatial dynamics when assessed solely through net area changes (Hagger et al. 2022; Contessa et al. 2023). However, the unreconciled transition estimates and absence of independent classification validation prevent reliable quantification of gross spatial turnover or conclusions regarding ecological stabilization.

The slower net expansion during 2020-2026 does not necessarily indicate increased mangrove loss or reduced ecosystem stability, as net extent changes cannot distinguish newly established mangroves from areas experiencing retreat. The annualized net increase declined from 6.25 ha yr^{-1} during 2010-2020 to 3.12 ha yr^{-1} during 2020-2026, indicating a reduction in the rate of mapped expansion. However, the absence of reconciled spatial transition estimates prevents quantitative assessment of gross loss rates or proportional vulnerability across observation periods. Earlier investigations in Tarout Bay also documented heterogeneous mangrove conditions and localized degradation (Al-Ali et al. 2015).

Environmental and anthropogenic factors may contribute to the observed temporal variation in mangrove extent. Mangrove establishment and persistence are sensitive to tidal inundation, sediment elevation, shoreline configuration, and hydrological connectivity, while coastal development can modify these conditions through reclamation, dredging, and changes in sediment transport (Friis and Burt 2020; Goldberg et al. 2020; Hagger et al. 2022). Such interactions may contribute to spatial differences in habitat suitability and disturbance exposure within Tarout Bay, consistent with evidence that mangrove dynamics are governed by interacting natural and anthropogenic processes (Mohan et al. 2024; Tian et al. 2026). Nevertheless, the observed temporal changes do not independently establish the underlying drivers or their relative contributions. Quantitative integration of historical coastal modifications, hydrodynamic conditions, sediment characteristics, and restoration records would therefore be necessary to distinguish natural ecosystem dynamics from anthropogenic influences.

At a broader spatial scale, the expansion observed in Tarout Bay is consistent with the national trend reported by Global Mangrove Watch (GMW v4.1.12). National mangrove extent in Saudi Arabia increased from approximately 3,658 ha in 2000 to 6,505 ha in 2025, representing an increase of 77.8%, compared with a 260.3% increase in Tarout Bay between 2000 and 2026. During 2010-2020, national mangrove extent increased by approximately 33.1%, whereas Tarout Bay experienced an increase of 102.1% (Bunting et al. 2026). Although differences in spatial coverage, observation periods and mapping methodologies limit direct quantitative comparability, these national estimates provide broader context for the observed expansion in Tarout Bay rather than independent validation of the local classification results.

The 36-year mapped series demonstrate substantial long-term mangrove expansion in Tarout Bay, although the magnitude and spatial distribution of simultaneous gains and losses remain uncertain. The absence of independent classification accuracy assessment and inconsistencies between

the original extent and transition datasets prevent reliable estimation of mangrove persistence and gross spatial turnover. Consequently, the present findings should be interpreted as extent-based changes rather than independently verified ecological transitions. Future investigations should integrate spatially aligned satellite classifications, higher-resolution imagery, field validation, and historical restoration records to improve change detection and identify the environmental and anthropogenic drivers of mangrove dynamics.

CONCLUSIONS

Landsat-derived maps indicate substantial mangrove expansion in Tarout Bay between 1990 and 2026, with mapped extent increasing from 15.90 to 142.44 ha (795.8%). The greatest net increase occurred during 2010-2020 (62.50 ha), followed by slower expansion during 2020-2026 (18.71 ha). These findings provide a preliminary baseline for long-term mangrove monitoring in arid coastal environments. However, the absence of independent classification accuracy assessment and unresolved differences between the original extent and transition datasets limit quantitative interpretation of spatial change. Future investigations should integrate harmonized satellite classifications, higher-resolution imagery and field validation to quantify mangrove gains, losses and persistence and identify the drivers of observed changes.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the research reported in this manuscript.

Author contributions

Naif Alqahtani: conceptualization; supervision; validation; visualization; writing-review and editing. Saleh Alzamanan: conceptualization, resources, and visualization. Abdullah Alotaibi: data curation; investigation; software; visualization. Rand AlHamzah: data curation; investigation; methodology; resources. Sharon Mathew: formal analysis; investigation; methodology; software. Shubham Prajapati: formal analysis; investigation; software. Amal Aldaej: methodology; validation; writing-review and editing. Mohammed Awad: formal analysis; investigation; methodology; supervision; validation; writing-original draft preparation.

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