

Life Cycle Assessment of Mangrove Restoration in the Saudi Arabian Context

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Abstract—Mangrove restoration can provide important climate benefits through long-term carbon sequestration, while restoration activities generate greenhouse gas (GHG) emissions. This study applies a simplified life cycle assessment (LCA) framework to evaluate project-related GHG emissions and carbon sequestration from mangrove restoration in the Saudi Arabian context. The functional unit is one hectare of restored mangrove habitat evaluated over 25 years. Project-related emissions were modelled in SimaPro using ecoinvent 3.9.1 and the IPCC 2021 GWP100 method, while carbon sequestration was estimated using a literature-based approach. The results indicate gross carbon sequestration of 768.75 t CO₂/ha, compared with project-related life-cycle emissions of 2.09 t CO₂-eq/ha. Project emissions represent less than 0.3% of the estimated sequestration potential. The nursery was the main emissions hotspot, followed by mangrove management and transportation. Overall, mangrove restoration can represent a promising nature-based option for long-term carbon sequestration, with project-related emissions remaining small relative to the estimated sequestration benefit.

Keywords—Mangrove restoration, Life cycle assessment, Carbon sequestration, Blue carbon, Greenhouse gas emissions, Saudi Arabia.

I. INTRODUCTION

Mangrove ecosystems are an important component of coastal environments and are increasingly recognized as blue carbon ecosystems because of their ability to capture and store carbon in biomass and sediments. In addition to carbon sequestration, mangroves provide ecosystem services such as shoreline protection, habitat provision, biodiversity support, and improvement of coastal water quality. These functions have increased interest in mangrove conservation and restoration as nature-based approaches for climate-change mitigation [1], [2].

Climate-change mitigation requires a combination of technological, material-based, and nature-based solutions. Previous studies have investigated sustainability pathways including lower-impact construction materials [3], waste-derived materials for circular-economy applications [4], and CO₂ utilization through catalytic processes [5]. Mangrove restoration represents a complementary nature-based pathway because it can remove atmospheric carbon while providing additional ecological benefits.

Mangroves occur along the Saudi Arabian coasts, including the Red Sea, where their carbon-storage performance is influenced by the region's arid and nutrient-limited environmental conditions [6]. Regional studies have also identified opportunities for mangrove expansion and restoration in the Red Sea [7]. These findings highlight the importance of evaluating restoration projects within the Saudi context rather than relying only on global estimates.

Although mangrove restoration can provide long-term carbon sequestration, restoration activities themselves can generate greenhouse gas (GHG) emissions through nursery operation, transportation, planting, and management. Life cycle assessment (LCA) provides a structured approach for quantifying these project-related emissions and comparing them with the expected sequestration benefit. Therefore, this study applies a simplified LCA framework to quantify the life-cycle GHG emissions of mangrove restoration in Saudi Arabia, identify the main emission-contributing stages, and estimate net carbon removal over the assessment period.

II. MATERIALS AND METHODS

A. Goal and Scope

The goal of this study is to evaluate the life-cycle greenhouse gas (GHG) emissions associated with mangrove restoration in the Saudi Arabian context and to assess the net carbon removal potential of the restoration project. The assessment follows the general principles of ISO 14040 and ISO 14044 [8], [9]. The LCA framework applied in this study, as defined by ISO 14040 and ISO 14044, is presented in Fig. 1.

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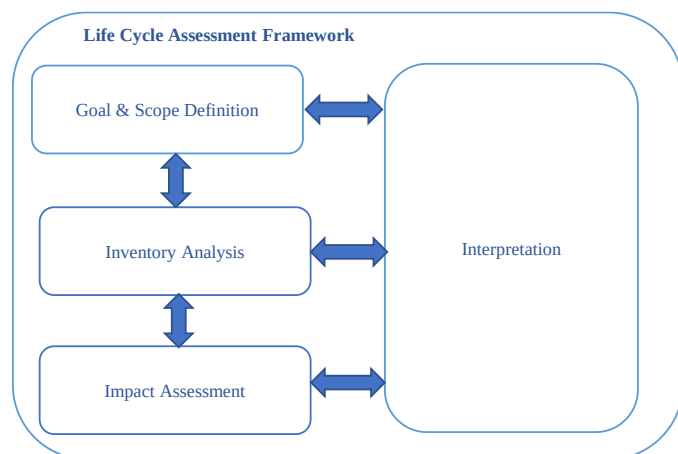


Fig. 1 Life cycle assessment framework based on ISO 14040 and ISO 14044.

According to ISO 14040 and ISO 14044, life cycle assessment is structured into four interrelated phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [8], [9]. The goal and scope phase establishes the purpose of the study, functional unit, system boundary, and methodological assumptions. The inventory analysis quantifies relevant material and energy inputs and environmental outputs, while the impact assessment translates these inventory flows into potential environmental impacts. Interpretation is conducted throughout the assessment to evaluate significant findings, assess consistency with the defined goal and scope, and support conclusions and recommendations. These phases are iterative rather than strictly sequential, allowing earlier methodological choices or data requirements to be refined as the assessment progresses [8], [9], [10].

The functional unit (FU) is defined as one hectare of restored mangrove habitat, with a density of 2500 trees/ha, evaluated over a 25-year period. All project-related GHG emissions and carbon sequestration results are expressed relative to this functional unit.

B. System Boundary

The system boundary includes the main activities associated with mangrove restoration: propagule collection, propagule transportation to the nursery, nursery operation, transportation of saplings to the restoration site, planting, and mangrove management. Mangrove management includes chainsaw operation and the associated use of petrol and lubricating oil. Propagule collection and planting are assumed to be performed manually. Propagules are transported approximately 30 km to the nursery, while saplings are transported approximately 36 km from the nursery to the restoration site.

The sequence of the main life-cycle stages included within the system boundary is illustrated in Fig. 2.

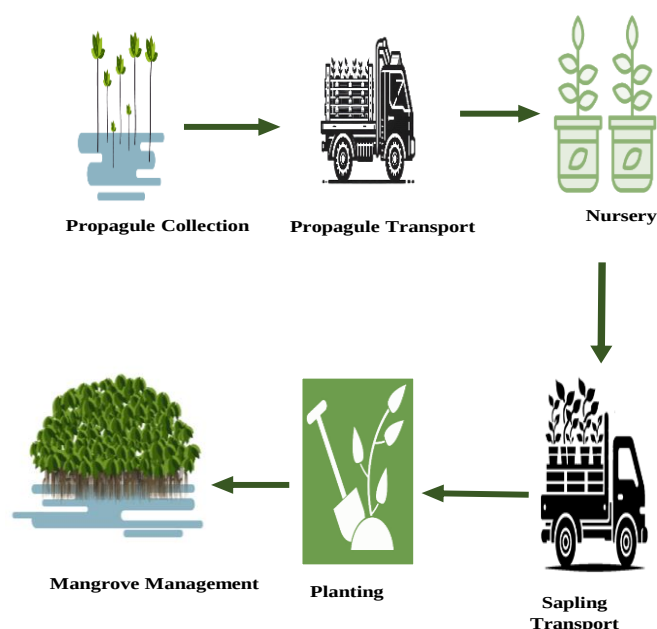


Fig. 2 Main life-cycle stages included within the system boundary of the mangrove restoration project.

Fertilizer use, park infrastructure, worker transportation, and other maintenance activities were excluded because sufficient inventory data were not available. The conceptual framework of the assessment, including project-related life-cycle GHG emissions and carbon sequestration, is illustrated in Fig. 3.

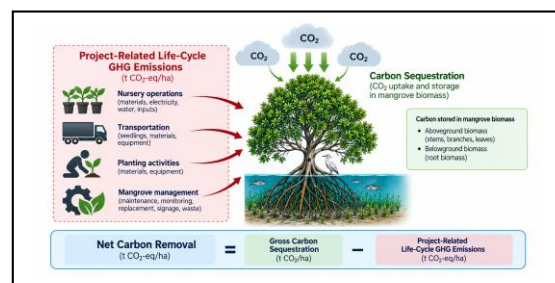


Fig. 3 Conceptual framework for estimating net carbon removal from mangrove restoration.

C. Life Cycle Inventory

Life-cycle inventory data were modelled using SimaPro 9.5.0.2 [11] and the ecoinvent 3.9.1 database [12]. A tree density of 2500 trees/ha and a sapling survival rate of 90% were assumed. Consequently, 2778 saplings were considered necessary to obtain 2500 surviving trees. The main inventory parameters and assumptions used in the assessment are summarized in Table I.

TABLE I
SELECTED LIFE CYCLE INVENTORY PARAMETERS AND
ASSUMPTIONS FOR MANGROVE RESTORATION

Inventory item	Value	Unit / assumption
Target tree density	2500	trees/ha
Sapling survival rate	90	%
Saplings required	2778	saplings/ha
Propagule mass	43.3	g/propagule
Propagule transport distance	30	km
Sapling mass	1.8	kg/sapling
Sapling transport distance	36	km
Nursery electricity	—	Saudi Arabian electricity mix, ecoinvent 3.9.1
Propagule collection	Manual	no direct emissions assumed
Planting	Manual	no direct emissions assumed

The assumed mass of each propagule transported to the nursery was 43.3 g, while each sapling transported to the planting site was assumed to weigh 1.8 kg. Electricity used during nursery operation was represented using the Saudi Arabian electricity mix available in ecoinvent. Nursery operation included electricity for seawater pumping and drainage, together with the main materials required for sapling production.

D. Life Cycle Impact Assessment

Climate change was selected as the primary impact category. GHG emissions were calculated using the IPCC 2021 GWP100 V1.02 method [13], applying a 100-year time horizon. The method accounts for fossil, biogenic, and land-transformation-related GHG emissions and expresses the results as CO₂ -equivalent.

E. Carbon Sequestration and Net Carbon Removal

Carbon sequestration was estimated using a literature-based approach. A sequestration rate of 12.3 kg CO₂ per tree per year was adopted based on Cooper et al. [14]. For 2500 surviving trees over 25 years, the gross carbon sequestration was calculated as 768.75 t CO₂ /ha. For the net balance, carbon sequestration was expressed as CO₂ -equivalent (CO₂ -eq).

Net carbon removal was calculated as:

$$\text{Net carbon removal} = \text{Gross carbon sequestration} - \text{Project-related GHG emissions}$$

III. RESULTS AND DISCUSSION

The total life-cycle greenhouse gas emissions associated with mangrove restoration were estimated at 2.09 t CO₂ -eq/ha over

the 25-year assessment period. In comparison, gross carbon sequestration was estimated at 768.75 t CO₂ /ha, resulting in a net carbon removal of 766.66 t CO₂ -eq/ha. Therefore, project-related emissions represent less than 0.3% of the estimated carbon sequestration potential. This indicates that the emissions generated during restoration activities are small compared with the expected long-term climate benefit of the restored mangrove system. The main results are summarized in Table II.

TABLE II
LIFE-CYCLE GHG EMISSIONS AND CARBON SEQUESTRATION
RESULTS

Indicator	Value	Unit
Gross carbon sequestration	768.75	t CO ₂ /ha
Propagule collection	0	t CO ₂ -eq/ha
Propagule transport	0.003	t CO ₂ -eq/ha
Nursery	1.096	t CO ₂ -eq/ha
Sapling transport	0.374	t CO ₂ -eq/ha
Planting	0	t CO ₂ -eq/ha
Mangrove management	0.616	t CO ₂ -eq/ha
Total project emissions	2.09	t CO₂ -eq/ha
Net carbon removal	766.66	t CO₂ -eq/ha

The contribution analysis shows that the nursery stage is the largest source of GHG emissions, contributing 1.096 t CO₂ -eq/ha, or about 52.5% of the total project emissions. Mangrove management is the second-largest contributor, accounting for 0.616 t CO₂ -eq/ha, or approximately 29.5%. Transportation activities contribute about 18%, with transport of saplings to the planting site being the main transport-related source. Propagule collection and planting were assumed to be manual and therefore did not contribute direct emissions in the model. The contribution of each life-cycle stage to total project emissions is shown in Fig. 4.

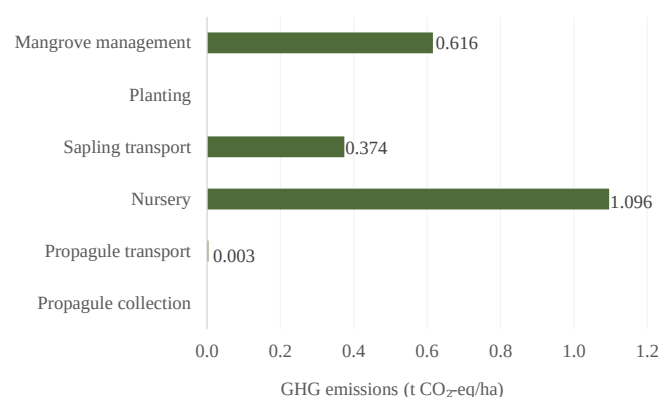


Fig. 4 Contribution of individual life-cycle stages to project-related GHG emissions from mangrove restoration.

The estimated carbon sequestration used in this study is based on the literature and should therefore be interpreted with caution. The sequestration rate of 12.3 kg CO₂ per tree per year was based on Cooper et al. [14]. However, mangrove carbon accumulation can vary considerably among locations due to differences in environmental conditions. Studies of Red Sea mangroves have shown that arid conditions and limited nutrient

availability can influence carbon storage capacity [6]. Therefore, the results presented here should be considered indicative of the potential climate benefit of mangrove restoration in Saudi Arabia rather than a site-specific prediction.

Despite these uncertainties, the results show that project-related emissions are small relative to the estimated carbon sequestration benefit. The nursery and mangrove management stages represent the main opportunities for reducing emissions, while optimization of transportation could provide an additional reduction. These findings demonstrate how LCA can be used to identify emission hotspots and support the design of lower-emission mangrove restoration projects.

IV. CONCLUSION

This study demonstrates the usefulness of life cycle assessment for evaluating the climate performance of mangrove restoration projects by considering both carbon sequestration benefits and emissions generated during project implementation. The findings show that project-related emissions are small compared with the estimated long-term carbon removal benefit, while the nursery and management stages represent the main opportunities for improving project performance.

The proposed framework can support the planning and design of future mangrove restoration projects in Saudi Arabia by identifying emission hotspots and highlighting areas where operational improvements can be made. Future studies could strengthen the assessment by incorporating site-specific measurements of carbon sequestration and more detailed inventory data for restoration activities.

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