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**Cover: Stripe-necked Mongoose *Urva vitticolla* in poster colours, adapted from photograph by Ashni Dhawale, by Pooja Ramdas Patil.**

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COMMUNICATION

# Utilization of a new restoration technique for the rehabilitation of a degraded mangrove ecosystem: a case study from Koggala Lagoon, Sri Lanka

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**Abstract:** Mangrove ecosystems, amongst the most productive and biologically complex on Earth, are being degraded worldwide, and their widespread decline during the past decades has affected vital ecosystem services. Mangroves at Koggala lagoon on the southern coast of Sri Lanka have been degraded at an alarming rate due to agricultural practices, coastal zone development, and tourism activities. Most of the banks are heavily eroded due to boat and sea plane activities, and the mangrove ecosystem has been significantly damaged. Implementation of a scientific rehabilitation project was needed to restore this degraded mangrove ecosystem, and research was carried out to enrich the mangrove community by re-establishing mangroves on the eroded banks using corrosion-resistant plastic barrels. The sustainability of replanted mangroves was monitored under phase one and the re-establishment of ecological functions in the mangrove community was monitored under phase two. The accumulated biomass carbon during the period of two and half years was calculated by an allometric equation suggested for calculating biomass carbon of mangroves using the girth and height of individuals. The highest rate of girth increment was observed by the 24$^{th}$ month from establishment, whilst the growth rate declined between the 18$^{th}$ and the 30$^{th}$ months. During the study period, the average above-ground and below-ground biomass per barrel showed a linear increment. Our case study showed that the new method used for restoration is successful in establishing mangroves in sites with high erosion. This restoration technique was successful in coping with the situation in Koggala lagoon where previous restoration attempts were failures. Thus, we recommend this restoration method for sites facing the threat of severe erosion.

**Keywords:** Allometric equations, carbon stocks, ecological function, eroded banks, growth rate, mangrove establishment, restoration technique.

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**Author contributions:** M.G.G Dhanushka contributed to the study conception and design. Experimental arrangements and data collection were conducted by M.G.G Dhanushka. Data analysis was performed by K.M.G.G. Jayasuriya. The first draft of the manuscript was written by M.G.M. Prasanna, I.H. Vitanage and K.M.G.G. Jayasuriya and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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## INTRODUCTION

Mangroves are among the world's most productive and biologically complex ecosystems, acting as bridges between land and sea. Thriving in intertidal areas along tropical and subtropical coastlines, mangroves consist of salt-tolerant woody plant species and are commonly found in lagoons, bays, and estuaries (Prasanna & Ranawana 2014), including several locations in Sri Lanka (Ministry of Environment 2012). Mangroves provide a multitude of essential goods and services crucial for human well-being and survival. They play a crucial role in maintaining the ecological integrity of coastal zones and provide many ecosystem services categorized as provisioning, regulatory, supportive as well as cultural services (Donato et al. 2011; Feller et al. 2017). Carbon sequestration is one of the most significant services provided by mangroves, as they possess a remarkable capacity to capture and retain high amounts of carbon in the soil owing to high productivity compared to other terrestrial ecosystems (Alongi 2014). Consequently, mangroves contribute significantly to the reduction of greenhouse gases and aid climate change mitigation efforts. Despite their importance, mangrove ecosystems have suffered global degradation (Duke et al. 2017; Feller et al. 2017), resulting in the decline of their ecosystem services over the past decades. According to Mukherjee et al. (2014), approximately 60% of major global ecosystem services have been degraded either totally or partially.

### Mangrove Ecosystems of Sri Lanka

Sri Lanka, a tropical island with numerous estuaries and lagoons, possesses a diverse range of mangrove ecosystems along its coastline (Edirisinghe et al. 2012). These mangrove ecosystems consist of two types of plant communities: true mangroves and mangrove associates. True mangroves are woody plants that exclusively occur in mangrove forests, displaying specific adaptations to the environment and physiological mechanisms to tolerate high salinity levels (Tomlinson 2016). In contrast, mangrove associates are primarily herbaceous plants found in terrestrial or aquatic habitats, but they can also be present within the mangrove ecosystem (Tomlinson 1986). Most Sri Lankan mangrove areas (92.6%) are confined to the dry and intermediate zones. Similar to the global situation, Sri Lankan mangroves were also degraded especially during the last four decades due to various anthropogenic activities (Wickramasinghe et al. 2022).

Nevertheless, mangrove research and rehabilitation efforts have progressed steadily over the last several decades as the importance of mangrove ecosystems has been better understood and documented. Furthermore, the mangrove ecosystems are considered a predominantly important ecosystem for coastal communities due to their provision of ecosystem services, such as supplying timber and fuel wood, supporting fisheries, sediment trapping, coastal defence and carbon storage (Donato et al. 2011; Feller et al. 2017). Amongst all the ecosystems across the tropics, mangrove ecosystems are considered one of the most threatened (Duke et al. 2017) mainly due to impacts from anthropogenic activities including conversion to agriculture and aquaculture as well as urbanisation and pollution (Feller et al. 2017). Under these circumstances, huge efforts are being put into mangrove rehabilitation and restoration in degraded areas. Though, such large-scale efforts are generally unsuccessful due to various reasons such as poor species selection, inappropriate location selection and poor knowledge of mangrove ecology as well as physiology (Kodikara et al. 2017). However, when elements of species biology and hydrological requirements are incorporated into the design and implementation of rehabilitation projects with an appropriate knowledge base, some efforts are becoming more successful (Feller et al. 2017).

### Status of Koggala Lagoon mangrove ecosystem

The Koggala lagoon is situated in the Southern province of Sri Lanka, specifically between 5°58'–6°20' N & 80°17'–80°22' E. It encompasses an area of 727 ha and consists of 14 islets (IUCN and Central Environmental Authority, 2006; Gunaratne et al. 2010). Several tributaries, including the Koggala Oya, provide freshwater input to the lagoon. The hydrology and water quality of the lagoon, including salinity and pH, are influenced by heavy rainfall and the characteristics of the lagoon mouth due to its location in the wet zone of the country. Previous studies have reported the presence of 10 true mangrove species in the lagoon. However, the classification of *Acrosticum aurium* and *Dolchandrone spathacia* as true mangroves by IUCN and Central Environmental Authority (2006) is disputed by the experts' team of the National Red List (2012), who considers them as mangrove associates. Therefore, the number of true mangrove species identified in the lagoon is recognized as eight. Mangroves are found in a narrow strip surrounding the lagoon's islands and along the stream banks. Unfortunately, due to activities such as boating and sea plane landing, and take-off, many of the banks have undergone degradation and significant erosion, leading to substantial damage to the mangrove ecosystems in the area.

The structure of the lagoon mouth has changed since 1990 due to the removal of the natural sand barrier (Gunarathne 2011). Consequently, sand started to deposit on the river mouth and the bridge over Pol Oya in Galle-Matara main road, blocking the water flow. A rubble mound groyne system (old groyne) was built in 1997 to prevent the issue. Due to this artificial construction, erosion of the lagoon bank became threatened as the Galle-Matara main road and bridge became vulnerable to sea erosion. Another groyne (new groyne) (Image 1) was established in 2005 to control the said situation (Gunarathne 2011). The outlet (Image 2) has been diverted westward creating an approximately 30–40 m wide open passage to the sea consequently (Gunawickrama & Chandana 2006).

The construction of an artificially built groyne in the Koggala lagoon initially resulted in a reduction of sand deposition. However, it also led to seawater intrusion into the lagoon (Gunawickrama & Chandana 2006). Over time, sand deposition resumed at the river mouth, causing water blockage and a subsequent decrease in water salinity and a rise in water level. The increased water level further contributed to bank erosion within the lagoon. These degraded banks, characterized by high erosion and stream flow, present challenges for natural regeneration and make it impossible to rehabilitate the mangrove community. Additionally, the degradation and heavy erosion of the banks caused by boating and seaplane activities further exacerbate the problem.

Despite previous attempts at planting mangrove seedlings in the Koggala lagoon, the general approach has failed multiple times in recent years. Natural regeneration has not been observed in the degraded banks of the lagoon, necessitating a new restoration approach and the implementation of a continuous monitoring mechanism to ensure the success of mangrove restoration. Therefore, the primary objective of the study was to enhance the mangrove community in the Koggala lagoon using a technique suitable for the prevailing conditions in the lagoon.

## METHODS

### Establishment of the restoration trail

A controlled plot using general restoration processes could not be established due to the unsuitable ground conditions and heavy erosion of the lagoon banks. A new restoration approach was designed to support restored plants to withstand the bank erosion. In this approach mangrove saplings were planted in plastic barrels.

Empty and well-cleaned chemical plastic barrels (~38 cm diameter and ~79 cm height) were gathered from factories located in the area. The top and bottom of all the barrels were removed. Thirty seven of these barrels were placed in holes excavated in eroded banks of three islands: Thalathuduwa, Kuruluduwa (Image 3) and Ganduwa. Barrels were placed with 60–90 cm spacing between each other, covering ~600 m stretch of the banks. The barrels were filled with soil excavated from the same restoration site. Two true mangrove species occurring in the area, *Rhizophora mucronata* and *R. apiculta* were selected as restoring species for this pilot study. These two species were selected as they contain large numbers of prop and stilt roots which assist in the proper establishment of the plant in the planted site. The availability of diaspores at the time of nursery establishment was also considered. Four *R. mucronata* saplings (~20–35 cm height) and one *R. apiculta* sapling (~20–35 cm height) were planted in each barrel. Saplings were raised in a nearby nursery using the diaspores collected from trees in the existing vegetation of the Koggala lagoon.

### Maintenance and monitoring

Planted seedlings were observed weekly during the first six months, and later monthly. Dead saplings were not replaced as it would affect the final analysis. There was no need to replenish the soil, as the soil in the barrels was not eroded during the period (Image 4). The diameter at breast height (dbh) and height of each sapling in each barrel were recorded on the first day of planting and then after every six months for two and half years. Monthly measurements were not taken as the changes in girth and height were not significant within a month.

### Data analysis

Height and dbh increments were separately plotted against time. A logistic four-parameter sigmoidal curve was fitted to determine the pattern of growth (Tsoularis 2001). The growth rate based on height and dbh was calculated separately for six months period from the initial planting date to August 2020. Accumulated biomass carbon during the period of two and half years was calculated using the dbh and height of the individuals with an allometric equation suggested for calculating biomass carbon of mangroves.

Above ground biomass (AGB) for *Rhizophora mucronata*,

Image 1. Satellite image of lagoon outlet with the existing groyne structures in 2010 (Source: Google Earth Pro 2022).


Image 2. The present situation of Koggala Lagoon mouth (Source: Google Earth Pro 2022).


**Image 3. First mangrove planting in Kurulu Duwa island in July 2018.**


**Image 4. The soil in the barrels was not eroded even after a year from planting, another mangrove hedge was planted in barrels parallel to the previous mangrove hedge.**

$\log_e(AGB) = 6.247+2.64 \log_e(dbh)$ (Amarasinghe & Balasubramaniam 1992b)

and for *Rhizophora apiculata*,

$AGB = 0.251\ \rho\ dbh^{2.46}$ (Komiyama et al. 2005)

Bellow ground biomass (BGB) for both species,

$BGB = 0.199\ \rho^{0.899}\ dbh^{2.46}$ (Komiyama et al. 2005)

## RESULTS

### Survival of plants during the two-and-half years of the monitoring period

After the first six months of establishment, all the *R. mucronata* and *R. apiculata* saplings survived in the study site. Within the next six months period, more *R. apiculata* saplings died compared to *R. mucronata* saplings. After 18 months of establishment, 85 % of the R. *mucronata* and 67 % of R. *apiculata* saplings survived (Figure 1). Thereafter, none of the remaining saplings died during the observation period of 30 months.

### Growth of established saplings

The height of both *R. mucronata* and *R. apiculta* increased gradually with time, following a sigmoidal curve as expected (Figure 2). However, the height increment of *R. apiculata* was slightly higher than that of *R. mucronata.* The dbh of the saplings of both species increased with time in a similar pattern (Figure 3). dbh increment of *R. apiculata* was also higher than that of *R. mucronata*.

The height increment rate of *R. apiculata* was higher than that of *R. mucronata* throughout the observational period (Figure 4A). However, during the first 12 months period, the dbh increment rate of *R. mucronata* was higher than that of *R. apiculta*, whereas, during the rest of the period, the dbh increment rate of *R. apiculata* was slightly higher than *R. mucronata* (Figure 4B). The rate of height increment of the two species increased with time until the $18^{th}$ month from the establishment and started to decline thereafter. Thus, the highest rate of height increment was observed by the $18^{th}$ month of the establishment. The highest rate of dbh increment was observed by the $24^{th}$ month from establishment whilst the increment rate declined between the $18^{th}$–$30^{th}$ month from establishment.

### Biomass Carbon accumulation by the established stand

The average above-ground and below-ground biomass per barrel showed a linear increment during the study period (Figure 5). At the end of the study period, the average above-ground biomass per barrel was 70.7 ± 11.7 kg. This biomass included 29.7 ± 4.9 kg of carbon and it is equivalent to 108.2 ± 17.9 kg of $CO_2$. Bellow ground biomass content at the time of final observation was 35.0 ± 5.8 kg per barrel. This included 14.7 ± 2.4 kg of carbon and equivalent to 53.5 ± 8.3 kg of $CO_2$. By the end of the study period, plants have accumulated 105.8 ± 17.5 kg of biomass per barrel which contained 44.4 ± 7.3 kg of carbon per barrel and which is equivalent to 161.7 ± 26.8 kg of $CO_2$. Thus, these plants have sequestrated 217.15 tonnes of carbon per hectare, which is equivalent to 788.1 tonnes of $CO_2$ per hectare.

According to the calculations up to the final sampling date, the study site has accumulated 2,619.5 kg, 1294.5 kg and 3,914.9 kg of above-ground, below-ground and total biomass respectively. Furthermore, the total biomass accumulated up to the final monitoring date included 1,643.9 kg of carbon which is equivalent to 5,983.9 kg of $CO_2$.

However, up to the end of the monitoring period, no natural recolonization was observed in the restored area.

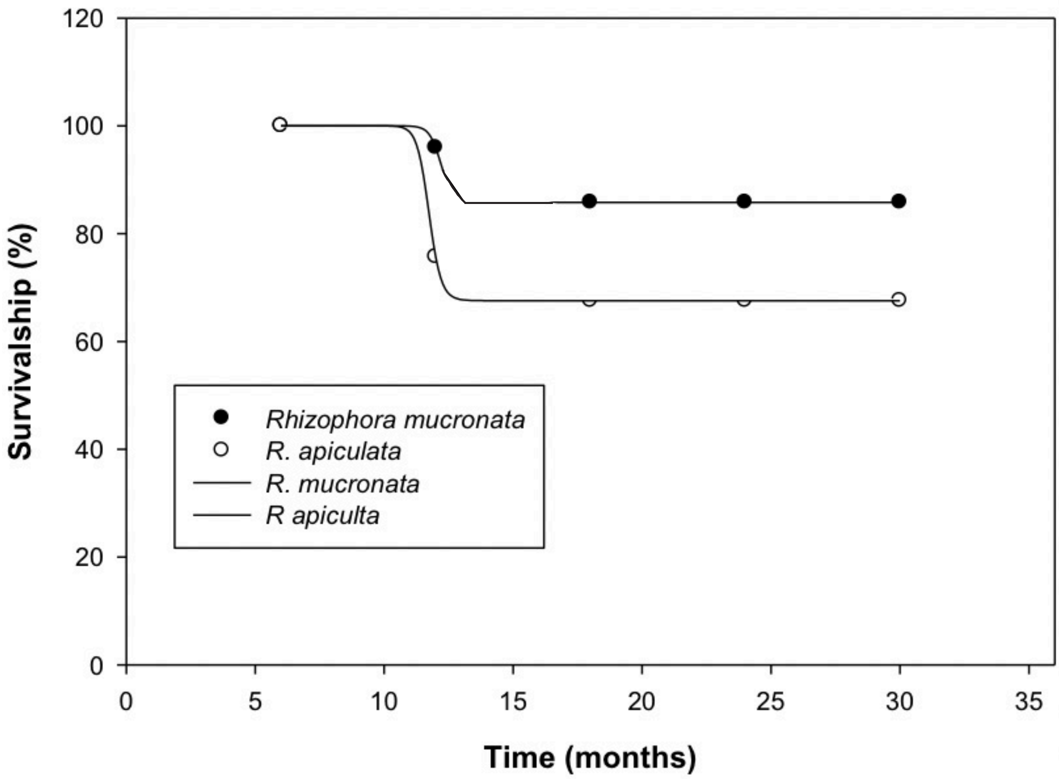


**Figure 1. Survival percentage of *Rhizophora mucronata* and *R. apiculata* saplings during the 30th months of the observation period. Four-parameter logistic curves were fitted to observe the pattern of survival.**

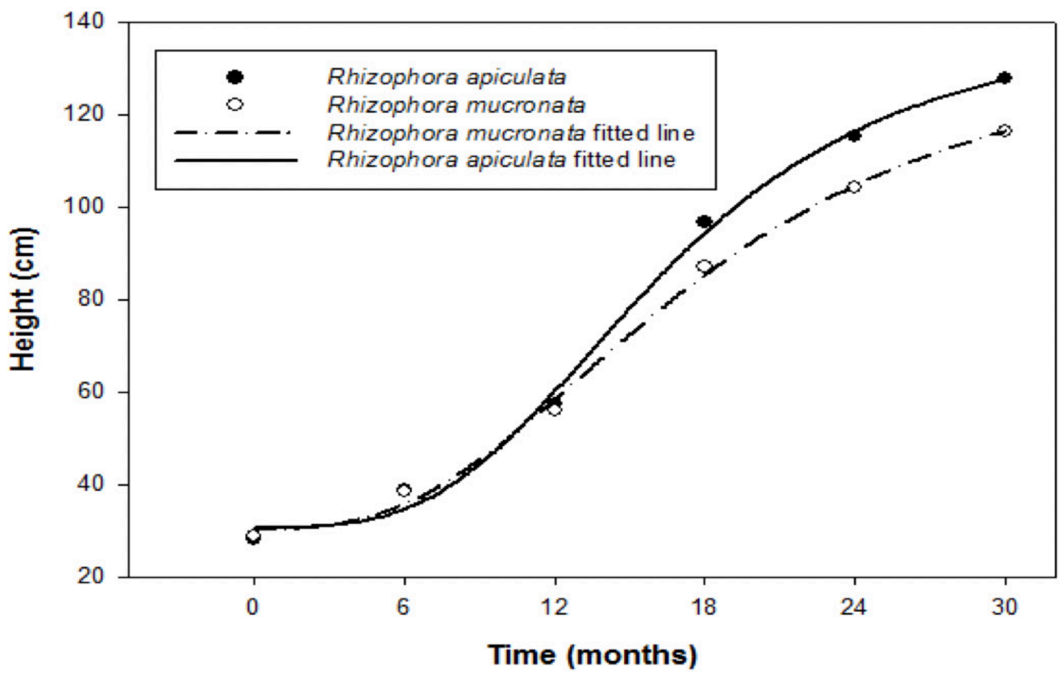


**Figure 2. Height increment of *Rhizophora mucronata* and *R. apiculata* saplings against time, during the monitoring period. Four-parameter logistic sigmoidal curves were fitted to determine the pattern of height increment.**

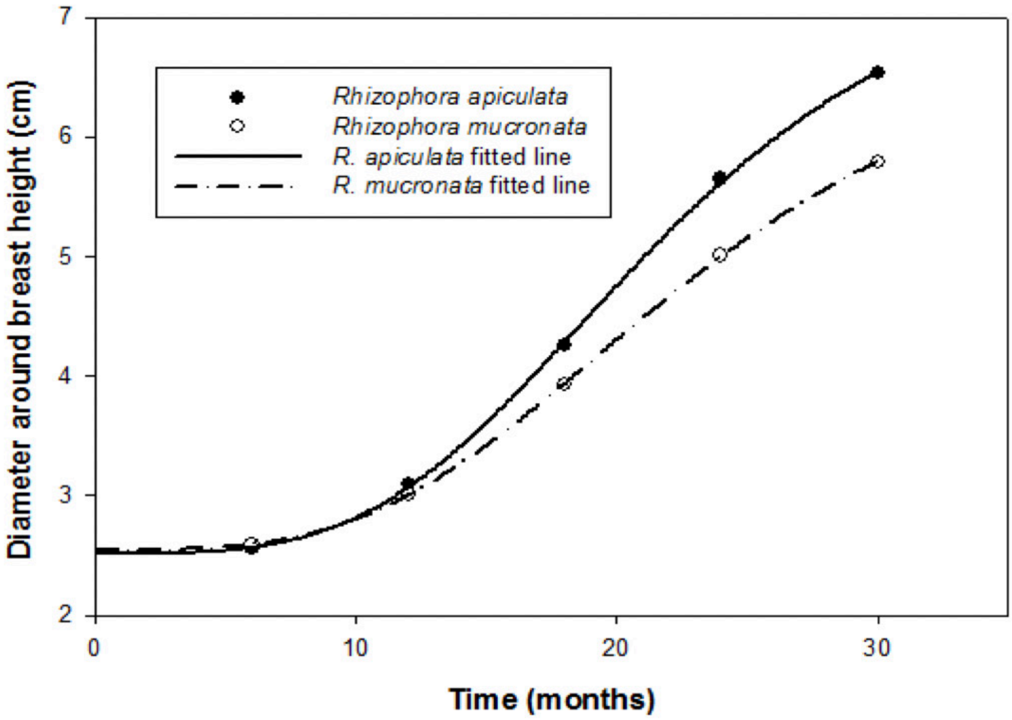


**Figure 3. Diameter at breast height increment of *Rhizophora mucronata* and *R. apiculata* saplings during the monitoring period. Four parameter logistic sigmoidal curves were fitted to determine the pattern of height increment.**

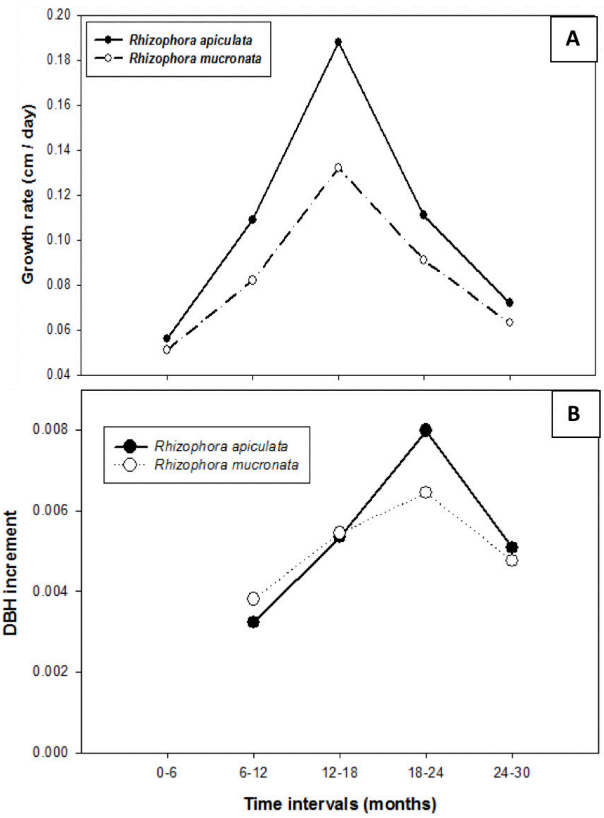


**Figure 4. A—Height increment rate | B—girth increment rate of *Rhizophora mucronata* and *R. apiculata* were established in barrels in the Koggala lagoon.**

## DISCUSSION

The results of this study indicate the success of the restoration technique employed, as evidenced by the high survival rates of the restored species after a substantial period since the establishment (2½ years). The observed survival rates of 85% for *R. mucronata* saplings and 65% for *R. apiculta* suggest the effectiveness of the restoration approach.

Comparison with previous trials conducted without a controlled plot revealed a significant improvement in sapling survival. In contrast to previous attempts, where none of the saplings survived for more than a year, the current restoration technique demonstrated higher success rates. These findings align with research conducted by Kodikara et al. (2017) on mangrove restoration projects in Sri Lanka, where most restored sites exhibited less than 50% survival, and only a small number surpassed this threshold. Thus, the higher sapling survival rates observed at the Koggala mangrove restoration site indicate a comparative success compared to other restoration efforts.

Sapling growth analysis showed that saplings of both species used have normal sigmoidal growth patterns and they were reaching the maturity level. Especially, the reduction in growth rate during the 24$^{th}$–30$^{th}$ month of

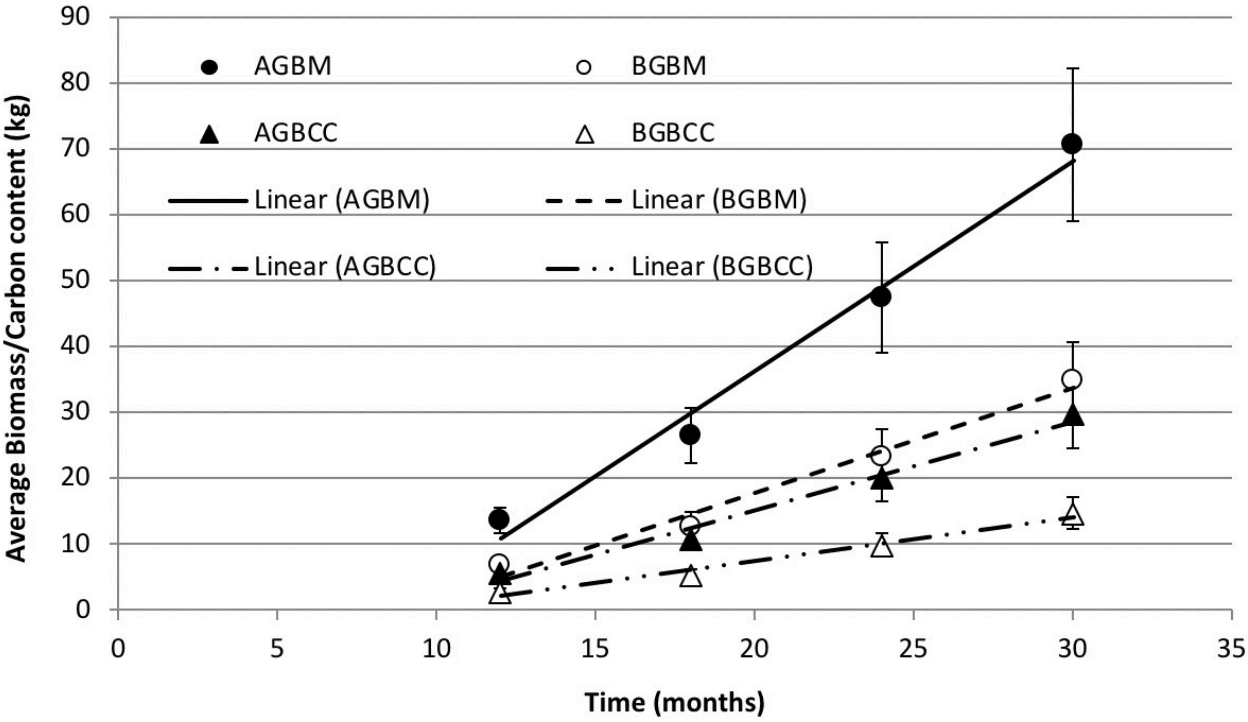


**Figure 5. Average biomass and carbon accumulation of the established plant with time. Error bars are ± SE.**


**Image 5. Mangrove plants after forty-five months from planting.**

establishment shows that these saplings were gradually reaching the matured stage. Thus, it seems that the plants have well established within the restored sites.

The restoration of the mangrove site demonstrated a significant potential for carbon sequestration, with an observed carbon sequestration rate of 217.15 tonnes per ha (equivalent to 788.1 tonnes of $CO_2$ per ha), highlighting its contribution to reducing atmospheric $CO_2$ levels. However, it cannot be compared with the total carbon content reported in other mangroves. However, the above-ground biomass carbon content of the restored site (128.8 t per ha) was higher than the average above-ground carbon content for global mangroves (78 t of carbon per ha; Estrada & Soares 2017), Mahanadi Mangrove, India (Sahu et al. 2016), and Negambo estuary (80.5 t of carbon per ha; Perera et al. 2018). This value is slightly lower than that was reported for Batticaloa lagoon (131 t of carbon per ha; Perera et al. 2018) in Sri Lanka. These unusually high values may have been caused due to lower planting spacing of the restoration site than the usual spacing of a natural mangrove community. Further, the used spacing in the current study is less than the recommended spacing between mangrove seedlings planting for restoration (80–120 cm recommended [Intenational Coral Reef Initiative and Pole-Relais, Zones Humides Tropicales, 2020] vs. 60–90 in the current study). Thus, thinning of the mangrove vegetation of the restored site may be required to allow the saplings to grow in their usual manner.

Our analysis showed a higher growth rate in *R. apiculata* compared to *R. mucronata* when considering the dbh and height. This could be due to the genetic potential of the two species as the same type of observation has been reported by Nit et al. (2011). However, further studies are needed to conclude the growth rates of the two species.

Our case study showed that the new method of mangrove restoration is successful in establishing mangroves in sites facing high erosion (Image 5). Especially, it seems that the new method is successful in coping with the situation in the Koggala lagoon as previous normal restoration trials conducted on this site failed. Thus, we recommend this restoration method for sites facing the threat of severe erosion.

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**Sinhala abstract:**

ලෝකයේ පරිසර පද්ධතීන් අතර ජීවවිද්‍යාත්මකව සංකීර්ණතම සහ ජෛව නිෂ්පාදිතාවය අධිකතම පරිසර පද්ධතියක් වන කඩොලාන පරිසර පද්ධතිය, ලොවපුරා දිනෙන් දින විනශය කරා ඇදීයයි. පසුගිය දශක ගණනාවක් පුරා සිදුවූ කඩොලාන විනශය නිසා, කඩොලාන මගින් ලබාදුන් බොහොමයක් පාරිසරික සේවාවන් මිනිසට අහිමිවෙමින් පවතී. ශ්‍රී ලංකාවේ දකුණු මුහුදු තීරයේ කොග්ගල කළපුව ආශ්‍රිත කඩොලාන පරිසරයද, සංචාරක ව්‍යාපාරයට සම්බන්ධ කටයුතු, කෘෂිකාර්මික කටයුතු සහ නාගරික සංවර්ධන කටයුතු නිසා එසේ සීග්‍රලෙස විනාශවන කඩොලාන පරිසර පද්ධතියකි. මෙම කළපුවේ ඉවුර, කළපු ජලතලය මත මුහුදු ගුවන්යානා ගොඩබෑම නිසා අධික ලෙස ඛාදනයට ලක්වී ඇති අතර, කඩොලාන පරිසරයද අධිකව විනාශයට ලක්වී ඇත. මෙම කඩොලාන පරිසර පද්ධතිය නැවත පුනරුත්තාපනය කිරීම සඳහා, විද්‍යානුකූල ව්‍යාපෘතියක අවශ්‍යතාවය පැනනැගී ඇතිහෙයින්, ඒ සඳහා පෙරහුරුවක් ලෙසද, මෙම පද්ධතියෙහි කඩොලාන ප්‍රතිස්තාපනය කිරීම අරමුණු කොටගෙනද, පර්යේෂණයක් ආරම්භ කරනලදි. ඛාදනය වූ ඉවුරෙහි සමන්‍ය ආකරයට කඩොලාන ප්‍රතිස්තාපනය කල නොහැකි හෙයින්, කඩොලාන පැල ඉවුරෙහි ස්ථාපිත කිරීම සඳහා විඛාදනයට ලක් නොවන ප්ලස්ටික් බැරල් යොදා ගන්නාලදි. ප්‍රතිස්තාපනයෙන් අනතුරුව, පළමු පියවර යටතේ, පරිසර පද්ධතියේ කඩොලාන ශාක ස්ථිරව ස්ථාපනයවීම අධීක්ෂණය කරනුලැබූ අතර, දෙවන පියවර යටතේ ස්තාපිත පරිසර පද්ධතිය මගින් ලබාදෙන පාරිසරික සේවාවන්ගේ ප්‍රතිස්තාපනයවීම අධීක්ෂණය කරනු ඇත. කඩොලාන ප්‍රතිස්තාපනය වීමෙන් අවුරුදු 2.5 කට පසුව කඩොලාන ජෛව ස්කන්ධයතුල තිරකර ඇති කාබන් ප්‍රමණය, කඩොලාන ශාක විශේෂවල ජෛව ස්කන්ධ කාබන් ප්‍රමාණය ගණනය කිරීම සඳහා ඉදිරිපත් කර ඇති සමීකරණ යොදාගෙන ගණනය කරන ලදි. කඩොලාන ශාක ප්‍රතිස්තාපනයෙන් මාස 24කට පසුව කඩොලාන ශාක කඳේ වට ප්‍රමාණය වැඩිවීමේ වැඩිම වේගය වාර්තාවිය. එමෙන්ම, ශාකවල වර්ධන වේගය, මාස 18 සිට 30 දක්වා ක්‍රමිකව අඩුවිය. පර්යේෂණ කාලය තුළදී, මධ්‍යන අපි-භෞමික සහ අධෝ-භෞමික ජෛව ස්කන්ධ කාබන් ප්‍රමාණය රේඛීයව වැඩිවිය. සිදුකරන ලද මෙම පර්යේෂණයේ ප්‍රථිඵල වලට අනුව ඛාදනය වූ කළපු ඉවුරුවල කඩොලාන ප්‍රතිස්තාපනය කිරීම සඳහා භාවිතා කරන ලද ක්‍රමය ඉතා සුදුසු බවට නිගමනය කලහැක. විශේෂයෙන්, ඛදනය වූ කොග්ගල කළපුවෙ ඉවුරුවල කඩොලාන ප්‍රතිස්තාපනය කිරීම සඳහා, විඛාදනය නොවන ප්ලස්ටික් බැරල්වල කඩොලාන සිටුවීම ඉතාම යෝග්‍ය වූ හෙයින්, මෙවැනි ඛාදනය වූ ඉවුරු සහිත වෙනත් කළපුවල කඩොලාන ප්‍රතිස්තාපනය කිරීම සඳහා මෙම ක්‍රමය නිර්දේෂ කල හැකිය.

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## Notes



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