International Journal of Environment and Climate Change

Volume 14, Issue 11, Page 746-754, 2024; Article no.IJECC.126528
ISSN: 2581-8627
(Past name: British Journal of Environment & Climate Change, Past ISSN: 2231–4784)

Carbon Sequestration Potential of *Rhizophora mucronata* in Tongke-Tongke Mangrove Forest, Sinjai Regency, Indonesia

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijecc/2024/v14i114584

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/126528

Original Research Article

Received: 20/10/2024
Accepted: 08/11/2024
Published: 15/11/2024

ABSTRACT

Mangroves play a crucial role in coastal ecosystems, offering significant ecological benefits and acting as important carbon sinks. This study focuses on the carbon sequestration potential of *Rhizophora mucronata* in the Tongke-Tongke mangrove forest, Sinjai Regency, Indonesia. By measuring the carbon content in leaves, roots, and sediments, the study found carbon content ranges from 0.09 to 0.11 tons/ha in leaves with a carbon absorption capacity ranging from 0.33–0.42 tonnes/ha and 0.44 to 0.72 tons/ha in roots with absorption capacity reaching 1.60–2.64 tonnes/ha, with sediment carbon content varying significantly ranges from 8.66–156.83 tons/ha with an absorption capacity of 31.79–575.55 tons/ha. The carbon content in mangrove stands reaches 109.23–180.87 tonnes/ha, with carbon uptake reaching 400.89–663.80 tonnes/ha. Results indicate

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***Cite as:** Pare, Mariani, Wayan Kantun, and dan Nuraeni L. Rapi. 2024. "Carbon Sequestration Potential of Rhizophora Mucronata in Tongke-Tongke Mangrove Forest, Sinjai Regency, Indonesia". International Journal of Environment and Climate Change 14 (11):746-54. https://doi.org/10.9734/ijecc/2024/v14i114584.*

that R. mucronata has a substantial carbon absorption capacity, underscoring the importance of these ecosystems in climate change mitigation. The findings aim to inform conservation strategies and potential carbon trading initiatives, contributing to global climate resilience.

Keywords: Mangrove; carbon; carbon absorption; Rhizopora mucronate; Tongke-Tongke.

1. INTRODUCTION

The mangrove ecosystem has a very important role in maintaining environmental balance and supporting the life of aquatic biota. Mangroves function as a natural barrier that protects coastal areas from the threat of erosion and storms. This is important in maintaining the stability of coastal areas which are vulnerable to damage due to sea wave activity and strong winds. Mangroves are able to filter pollutants and sedimentation from land and maintain good water quality for the survival of aquatic organisms (Manikasari & Mahayani 2018 and Sulochanan et al. 2022). The existence of mangroves not only provides ecological benefits, but also provides protection for coastal areas and the people living around them.

The role of the mangrove ecosystem is not only in physical protection, but also as an important habitat for various marine species and migratory birds (Husain et al. 2020 and Oracion et al. 2022). Mangroves are able to provide shelter, foraging areas and breeding grounds for very diverse species (Putra et al. 2021). The high biodiversity in mangrove areas contributes to ecological balance, both on land and at sea. The existence of mangroves helps maintain populations of marine species such as fish, crustaceans and bird species that use this area during migration (Latuconsina 2021).

The issue of climate change is currently one of the biggest global challenges, and mangroves play a crucial role in mitigating the impacts of climate change. Mangroves have the unique ability to absorb and store carbon through a process known as carbon sequestration (Sulistyorini et al. 2020). In this process, mangroves absorb carbon dioxide from the atmosphere through photosynthesis, storing it in biomass such as stems, leaves and roots, as well as in organic-rich soil (Melati 2021). Previous research results show that mangrove forests can store up to four times more carbon per hectare than tropical forests on land. This makes mangroves a natural solution in efforts to mitigate climate change.

Various studies have revealed the great potential of mangrove forests in storing carbon, such as research by Murdiyarso et al. (2015) shows that mangrove ecosystems in Indonesia store more than 3.14 billion tons of carbon, which contributes 10-15 percent of global coastal carbon stocks. Additionally, another study by Matatula et al. (2023) shows that above-ground carbon stocks in mangrove forests in Kupang Regency reached 454,712 tons per hectare (Tidore et al. 2018) the estimated carbon content stored in mangrove leaf litter in Lansa Village, North Minahasa is 2.16 tons/ha/year. The above-ground carbon stock in the mangrove forests of Kupang Regency, East Nusa Tenggara is on average 454,712 tonnes/ha (Matatula et al. 2023). The carbon content in the pneumatophore biomass of Avicennia maria in North Minahasa Regency, North Sulawesi is on average 0.28 kgC/m2 (Kindangen et al. 2021). Demta Bay, Papua Province, holds a carbon potential of 124.72 tons/ha (Indrayani et al. 2021). Meanwhile, the potential carbon stock of the mangrove ecosystem in the Riau Islands reaches 2052.78 tons/ha (Hidayati et al. 2023). Diana et al. (2023) obtained measurement results of the carbon content stored in the soil in the Mahakan Delta mangrove ecosystem, East Kalimantan, amounting to 1,120 tons/ha.

Seeing the important role of mangroves in storing carbon and reducing the impact of climate change, research on the carbon potential of mangrove ecosystems in Sinjai Regency, South Sulawesi, becomes very relevant. One of the dominant mangrove types in Sinjai Regency is *Rhizophora mucronata. Rhizophora mucronata* has a high ability to absorb carbon. This research aims to measure the carbon content stored in *Rhizophora mucronata* mangroves and sediments. The research results are expected to provide scientific data regarding the carbon potential of the research area, but also support efforts to conserve and restore the mangrove ecosystem. In addition, this research opens up opportunities to develop carbon-based economic schemes, such as carbon trading, which can provide economic benefits to local communities through incentives to conserve mangrove forests. In the long term, this research is expected to contribute to global efforts in mitigating climate change and preserving sustainable coastal ecosystems.

2. MATERIALS AND METHODS

This research was carried out from July to September 2024 in the Tongke-Tongke Mangrove Forest area, Tongke-Tongke Village, East Sinjai District, Sinjai Regency. The research used three stations based on the representation of the mangrove ecosystem at that location, each at the coordinates: Station 1: 5° 08' 48" South Latitude, 120° 16' 19" East Longitude; Station 2: 5° 08' 55" S, 120° 16' 21" E; Station 3: 5° 09' 01" South Latitude, 120° 16' 28" East Longitude. Carbon content testing for leaves, roots and soil was carried out at the Chemical Oceanography Laboratory, Hasanuddin University, Makassar. Carbon measurements in mangrove stands use the vegetation analysis method by measuring stem diameter in plots measuring 10 x 10 m^2. Analysis was carried out using allometric equations to calculate biomass, carbon content and carbon uptake. Measurements on leaves and roots used the ashing method. The leaves are dried at 80°C, then weighed to calculate the carbon stored.

Meanwhile, the roots were weighed and dried in the oven for 48 hours. Carbon in the soil was measured using a 20 cm deep coring pipe, then analyzed using the Walkley and Black method to calculate the organic carbon content. Leaf and root samples were dried at 60°C, then ashed at 500-600°C for 5 hours to measure the carbon content. The carbon content is calculated as 47% of the biomass, and CO_2 storage is calculated using the carbon to CO_2 conversion formula. Biomass estimation was carried out using the allometric equation, and the conversion of carbon to CO_2 was carried out using an equivalence factor of 3.67.

3. RESULTS AND DISCUSSION

3.1 Carbon Uptake in Leaves

The carbon content and uptake in mangrove leaves at three different observation stations in the Tongke-Tongke mangrove forest area showed that at station 1, the carbon content reached 0.10 tons/ha with a higher absorption capacity, namely 0.35 tons/ha. Station 2 has a slightly higher carbon content, namely 0.11 tons/ha, with an absorption capacity of 0.42 tons/ha and is the highest value among the three stations. For station 3 the carbon content reached 0.09 tonnes/ha, with carbon uptake of 0.33 tonnes/ha (Fig. 1). Although carbon content varied between stations, carbon uptake remained significant at all locations.

The differences in carbon content and carbon uptake in mangrove leaves for each station can be explained through the concept of mangrove ecophysiology. Mangroves are known as effective carbon sinks because of their high photosynthetic ability by converting carbon dioxide from the atmosphere into biomass. Even though the carbon content of leaves is relatively low, carbon uptake is quite high. This shows high photosynthetic efficiency at the research location. Alongi et al. (2014) stated that a good mangrove environment can increase the rate of photosynthesis even though the carbon accumulation in leaf tissue is not always large.

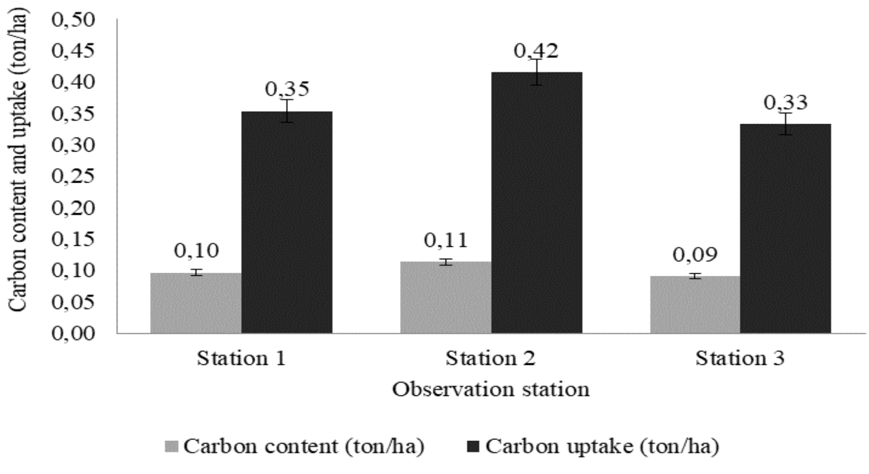

Fig. 1. Carbon content and uptake in mangrove leaves in Tongke-Tongke Village

More optimal environmental conditions such as the availability of light and nutrients can support the rate of photosynthesis and productivity of mangroves (Mustofa 2015). The decrease in carbon content is related to leaf age or seasonal changes that influence carbon accumulation in leaves (Santrum et al. 2021).

Mangrove leaves play a major ecological role in absorbing carbon dioxide (CO_2) from the atmosphere through photosynthesis thereby supporting the primary productivity of the mangrove ecosystem, providing nutrition for various organisms and this productivity plays an important role in maintaining the stability of the food chain in coastal areas. Mangrove leaves that fall and fall to the ground contribute to the carbon cycle in the ecosystem. When mangrove leaves are decomposed in mangrove sediment, the carbon contained therein is stored in the soil layer which tends to be anaerobic and slows down the decomposition process. This helps keep carbon stored in the long term thereby reducing its release into the atmosphere. Mangrove leaves help reduce dissolved carbon levels in coastal water to maintain carbon balance in the aquatic environment which has an impact on water quality. The ability of leaves to absorb carbon contributes to the resilience of the mangrove ecosystem to climate change by reducing CO_2 in the atmosphere, thus helping to stabilize the temperature around the mangrove ecosystem.

3.2 Carbon Uptake in Roots

The comparison of carbon content and uptake in mangrove roots has the same pattern as the content and uptake in leaves. At Station 1 the carbon content is 0.44 tons/ha with an absorption capacity of 1.60 tons/ha. Station 2 has a higher carbon content, namely 0.72 tonnes/ha, with more significant carbon uptake of 2.64 tonnes/ha. Meanwhile, Station 3's carbon content is 0.55 tonnes/ha with carbon uptake of 2.01 tonnes/ha (Fig. 2).

Apart from leaves, mangrove roots also play a role in the carbon cycle of the mangrove ecosystem. The roots not only act as a structure that supports the tree in muddy habitats, but also as a carbon storage site. The carbon absorption capacity of mangrove roots is much higher than that of mangrove leaves. This difference in storage and absorption abilities is thought to be related to the biogeochemical dynamics of mangrove roots which can absorb large amounts of carbon even though the content does not accumulate to a large extent in the root tissue (Putri et al. 2023). Mangrove roots also play an important role in storing carbon in organic form in sediment, which can persist for long periods of time and is a major component in mitigating climate change (Kauffman et al. 2011).

Mangrove roots play a role in absorbing and storing carbon so that they have ecological implications, especially maintaining the stability of coastal ecosystems, mitigating climate change and supporting biodiversity. Mangrove roots are able to store carbon in the long term, making it one of the most efficient carbon absorbing ecosystems, increasing sediment stability, strengthening coastlines, supporting food networks, as a natural biofilter, as a balancer for carbon levels on the coast to reduce ocean acidification and help in adaptation. climate change.

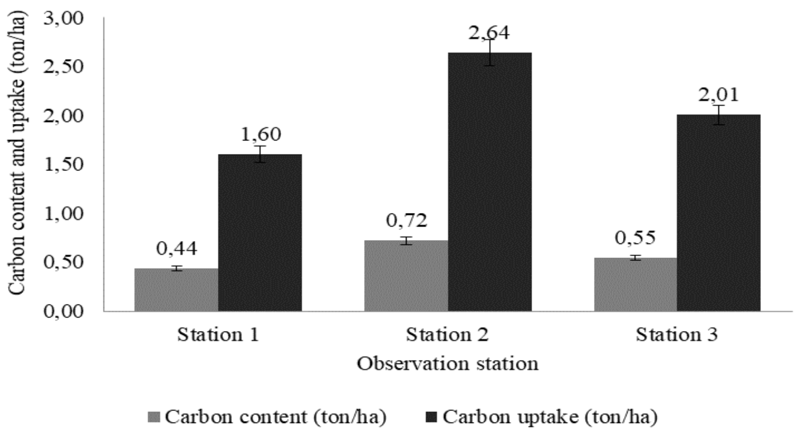

Fig. 2. Carbon content and uptake in mangrove roots in Tongke-Tongke Village

3.3 Carbon Uptake in Sediments

The carbon content and uptake in mangrove sediments at Station 1 reached 156.83 tonnes/ha with carbon uptake of 575.55 tonnes/ha. Station 2 has a much lower carbon content, namely 8.66 tonnes/ha, with carbon uptake of 31.79 tonnes/ha. Station 3 has a carbon content of 84.16 tonnes/ha, with carbon uptake of 308.88 tonnes/ha. Station 1 recorded the highest value for all parameters measured (Fig. 3).

Mangrove sediment is one of the main components in the carbon storage cycle known as blue carbon, namely carbon stored in coastal ecosystems such as mangroves, seagrasses and sea grass meadows. Mangroves store carbon both in above-ground biomass (stems, leaves and branches) and in subsurface sediments. The carbon content in this sediment is very important because mangrove sediments are able to store carbon in the long term, due to anaerobic conditions which slow down the rate of decomposition of organic material (Kauffman et al. 2011). The carbon stored in mangrove sediments comes from various sources, such as organic material from fallen leaves, dead roots, decomposed wood, as well as the results of microbial activity that degrades organic material in the sediment (Tahir et al. 2021).

Sediments function as very efficient carbon sinks. Kauffman & Donato (2012) stated that mangrove ecosystems can store large amounts of carbon because their sediment structure allows the accumulation of organic material under anaerobic conditions. This anaerobic environment slows down the decomposition of organic material so that carbon can be stored for a longer time. This condition is very important for the mangrove ecosystem, because it allows the accumulation of carbon not only from the mangrove vegetation itself, but also from the contribution of external organic material carried by sea or river currents.

Mangrove sediments are efficient carbon stores because their conditions are anaerobic so they are able to slow down the decomposition of organic matter, protect the rapid release of carbon because sediments are able to store carbon stably, reduce the rate of ocean acidification, as a source of nutrition for coastal ecosystems, have the ability to absorb and neutralize pollutants, helps in maintaining stability and reducing soil erosion

3.4 Carbon Uptake in Mangrove Stands

The highest total biomass in mangrove stands was at Station 1 at 384.83 tonnes/ha and the lowest was 232.41 at Station 2. Almost half of the biomass produced by mangroves consisted of carbon. The highest carbon content was also obtained at Station 1 at 180.87 tonnes/ha, and the highest carbon uptake reached 663.80 tonnes/ha. This figure reflects the capacity of the mangrove ecosystem at each station to absorb and store carbon more efficiently and in large enough quantities (Fig. 4).

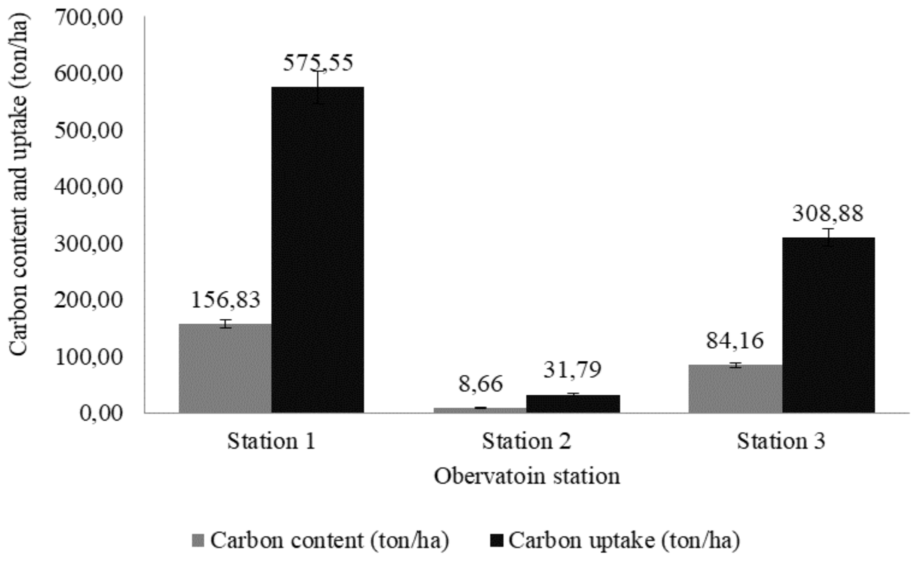

Fig. 3. Carbon content and uptake in sediments in the Mangrove Area of Tongke-tongke Village

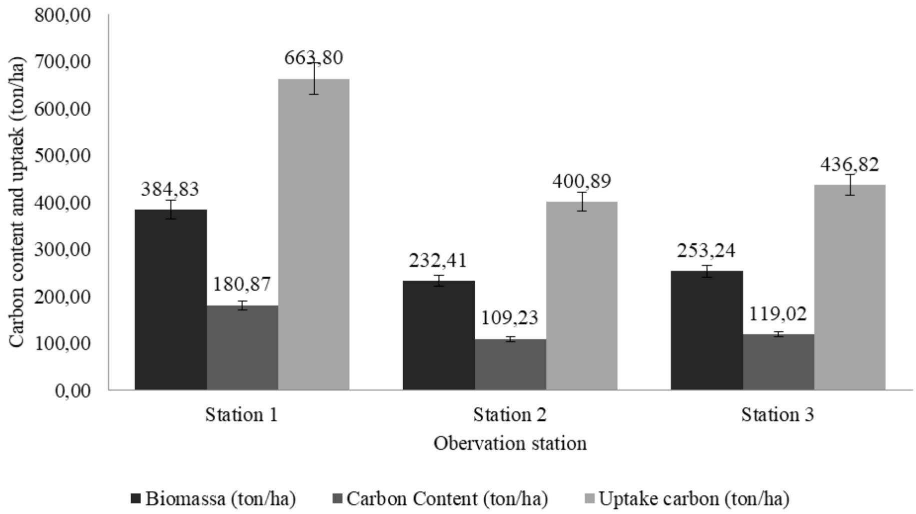

Fig. 4. Carbon content and uptake in Mangrove Stands in Tongke-tongke Village

The carbon content of mangrove stands is an important factor in understanding the role of mangrove ecosystems in mitigating climate change. The biomass produced by mangroves is closely correlated with their carbon storage capacity. Mangrove trees store carbon in two main forms, namely above ground biomass which includes stems, leaves and branches, and below ground biomass which includes roots. Research results show that 45-50% of mangrove tree biomass consists of carbon, which confirms the important role of this ecosystem in absorbing carbon from the atmosphere (Kauffman et al. 2020). Therefore, the greater the biomass produced by mangrove trees, the higher their carbon storage capacity.

Mangrove stems are a key component in storing carbon in this coastal ecosystem. Stems, which are the main part of above ground biomass, can store carbon for long periods of time because of the dense wood structure. This makes mangrove trees able to function as more efficient carbon stores than terrestrial ecosystems. Apart from that, mangrove stems are also able to adapt to dynamic environmental conditions, such as tidal fluctuations and salt water intrusion, which helps maintain ecosystem stability and long-term carbon storage functions (Wahyuda et al. 2022).

The carbon content in mangrove stems can vary based on environmental factors, such as tree species, soil conditions and local climate. Several studies have shown that variations in the composition of tree species in an area can influence the concentration of carbon stored in biomass. In areas with certain mangrove species, the carbon content in their stems may be lower than in other species. This variation is also influenced by environmental factors, such as salinity and nutrient availability (Wahyuda et al. 2022). Variations in carbon content between locations or tree types have an overall role in mitigating climate change. Even in locations where mangrove biomass is relatively small, these trees still store quite high concentrations of carbon. This shows that every mangrove area, regardless of size, makes a positive contribution to reducing carbon emissions and mitigating the impacts of global climate change.

Mangroves have the unique ability to absorb and store carbon which makes a major contribution to climate change mitigation in supporting their own growth, but mangroves also play a role in reducing the amount of carbon dioxide (CO_2) released into the atmosphere. The photosynthesis process in mangroves allows these trees to absorb CO_2 from the atmosphere and convert it into biomass. The absorbed carbon is then stored in the stems, leaves and roots of the mangrove, and most of this carbon is trapped in the sediment around the root system, creating effective long-term carbon storage (Tahir et al. 2023). Mangroves not only mitigate carbon emissions, but also act as carbon reservoirs capable of storing carbon for centuries.

The ability of mangroves to absorb carbon has excellent ecological implications related to climate change mitigation, namely mitigating carbon emissions (Inoue 2019) protecting biodiversity and reducing the impact of natural disasters, as well as controlling soil and water quality. Mangroves absorb and store very large amounts of carbon both in biomass (stems, leaves and roots) and in sediment. This helps in reducing carbon dioxide emissions from the atmosphere which is the main greenhouse gas causing climate change (Alongi 2014). Carbon storage can last hundreds of years, making it important in climate mitigation efforts.

Mangroves support marine and coastal ecosystems which provide habitat for various organisms (Oracion et al. 2022). The ability of mangroves to absorb carbon helps maintain environmental stability needed by coastal organisms, thus encouraging the preservation of biodiversity (Idris et al. 2019). Mangroves also help protect coastlines from erosion, storms and sea waves, play a role in maintaining the health of the ecosystem structure so that its natural protective function continues and the risk of damage from natural disasters is reduced. The ability of mangroves to absorb carbon can affect soil fertility and water quality in coastal ecosystems. This process helps prevent soil oxidation and maintain nutrient levels and water quality, which play an important role in the productivity of local fisheries and the surrounding marine ecosystem.

The potential for applying the findings of mangrove carbon uptake in this research is very large, especially in carbon trading, with potential uses related to carbon market initiatives for mangroves, restoring mangroves to increase carbon credits (Sutaryo 2009) integrating with low carbon emissions initiatives, funding for conservation purposes and local communities. This is confirmed that mangroves can store carbon up to several meters in the soil, thereby increasing the storage capacity to be greater than other tropical rainforest ecosystems (Alongi 2014). This can be seen from the carbon storage capacity which reaches 4 times more per hectare than land forests, has an annual carbon storage rate, has carbon storage efficiency in the soil (Zaman et al. 2023) is resistant to external influences and has economic value in the carbon market.

4. CONCLUSION

The carbon content in mangrove leaves ranges from 0.9–0.11 tonnes/ha, with a carbon absorption capacity ranging from 0.33–0.42 tonnes/ha. The carbon content in the roots ranges from 0.44–0.72 tons/ha with an absorption capacity of 1.60–2.64 tons/ha. The carbon content in the sediment ranges from 8.66–156.83 tonnes/ha with an absorption capacity of 31.79–575.55 tonnes/ha. Mangrove stand biomass ranges from 232.41–238.83 tonnes/ha. The carbon content in mangrove stands reaches 109.23–180.87 tonnes/ha, with carbon uptake reaching 400.89–663.80 tonnes/ha. The results showed differences in carbon content at each observation station, where there were significant differences between Station 1 and Station 2, as well as between Station 2 and Station 3. Between Station 1 and Station 3 there were no significant differences.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

ACKNOWLEDGEMENT

Thank you so much to the community who helped in taking samples and the laboratory assistants who helped in testing samples in the laboratory.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/126528