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Research Article

Carbon stock assessment of Rani community forest in Makawanpur district and its role in climate change mitigation

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ABSTRACT

Accurately measuring forest carbon (C) stocks is crucial for evaluating Community Forests' contribution to mitigating climate change and for bolstering Nepal's carbon-based payment systems. In order to determine the importance of Rani Community Forest in Makawanpur District for mitigating climate change, this August 2024 study evaluated the forest's capacity to store carbon. In accordance with the MoFSC Guideline for Forest Carbon Measurement (2010), 31 concentric circular plots were sampled. Aboveground and belowground biomass carbon stocks were estimated following national guideline-recommended allometric equations, and Soil organic carbon (0–30 cm) was analyzed using the Walkley–Black method (1934). Results showed that total vegetation biomass was 292.21 t ha^{-1}, corresponding to total vegetation carbon stock 137.33 t ha^{-1} where trees/poles contributed 91.98% of vegetation carbon. As a result, the total SOC stock was 79.73 tha^{-1}, with an average soil bulk density of 1.23 g cm^{-3} and a SOC content of 2.17%. The maximum SOC was found in the 0–10 cm layer, and a one-way ANOVA showed significant variations in SOC throughout depths ($p < 0.004$). A significant positive correlation ($r = 0.62$, $p < 0.001$) between SOC and aboveground vegetation carbon indicated strong vegetation–soil linkages. The total carbon stock of 217.05 t ha^{-1} corresponds to 796.57 t ha^{-1} Carbon-dioxide (CO_2,) demonstrating substantial carbon sequestration potential. These findings emphasize the critical role of Community Forests in Nepal's climate mitigation strategies and their potential contribution in $REDD^+$ and carbon financing mechanisms.

Keywords: Biomass, Community Forest, Soil organic carbon, $REDD^+$

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INTRODUCTION

Forests are one of the most crucial land-based ecosystems for regulating the climate due to their capacity to absorb and sequester large quantities of atmospheric carbon dioxide (CO_2) (Lal, 2005; Acharya *et al.*, 2011; Ghimire, 2022). Worldwide, forests hold more than 600 Gt of carbon within living plants, deadwood, litter, and soils, positioning them as vital natural solutions for climate-related issues (Berber & Butt, 2017; Singh *et al.*, 2025). Given the rapid impacts of climate change, safeguarding and improving forest carbon reserves has emerged as a key global concern. Nations with extensive forest areas, like Nepal, have significant potential to aid climate mitigation efforts through sustainable forest management and initiatives focused on community-based conservation (MoFE, 2018; Khatri *et al.*, 2018; Adhikari & Ghimire, 2019; Ghimire, 2021).

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Nepal's community forestry initiative, which commenced in the late 1970s, is globally recognized for its efficacy in empowering local communities to oversee forest resources. Approximately 3 million hectares of forested land, representing around 45% of Nepal's total forest coverage, are under the stewardship of more than 23,000 Community Forest User Groups (CFUGs) (Ghimire & Lamichhane, 2020; Nuberg *et al.*, 2025). These CFUGs play a pivotal role in the restoration of degraded forests, enhancing forest productivity, and improving the delivery of ecosystem services, including carbon sequestration (Khatri *et al.*, 2018; Ghimire & Lamichhane, 2023; Dhungana *et al.*, 2024). Precise and context-specific assessments of forest carbon at the community level are imperative as Nepal progresses towards national carbon accounting and the implementation of REDD (Reducing Emissions from Deforestation and Forest Degradation) (Khatri *et al.,* 2018; MoFE, 2018; Ghimire & Lamichhane, 2025).

Vegetation carbon sequestration and soil carbon stock represent two pivotal components of forest carbon dynamics and are instrumental in the mitigation of global climate change (Lal, 2005; Ghimire *et al.,* 2023; Lamichhane & Ghimire, 2024). Forest vegetation assimilates atmospheric CO_2 through the process of photosynthesis and subsequently sequesters it within both aboveground and belowground biomass, thereby constituting one of the foremost natural mechanisms for the reduction of atmospheric carbon (Lamichhane & Ghimire, 2024). Concurrently, forest soils serve as substantial and stable reservoirs of organic carbon, which is primarily derived from decayed litter, root turnover, and microbial metabolic activities. Soil carbon may represent a considerable proportion of total ecosystem carbon, frequently surpassing vegetation carbon in numerous forest types (Ghimire *et al.,* 2019; Kafle, 2019; Ghimire *et al.*, 2023). The interplay between vegetation and soil carbon reservoirs is intricately connected; productive and well-managed forests are likely to augment soil carbon concentrations through sustained inputs of organic matter (Lal, 2005; Shrestha *et al.*, 2012). Therefore, it is crucial to comprehend both soil carbon stock and vegetation carbon sequestration in order to accurately estimate total forest carbon, assess ecosystem health, and develop effective climate mitigation strategies under frameworks like $REDD^+$ (Shrestha *et al.,* 2012; Khatri *et al.,* 2018; MoFE, 2018).

The Rani Community Forest (CF), located in the Makawanpur District of the Siwalik region in central Nepal, is predominantly characterized by *Shorea robusta* C.F. Gaertn., a species recognized for its elevated wood density, protracted decomposition rates, and significant biomass accumulation (CFOP, 2022). Nevertheless, there exists a conspicuous deficiency of thorough carbon inventories within Rani CF, particularly regarding multi-depth soil carbon assessment and its correlation with the structural composition of the vegetation. This deficiency in knowledge constrains the forest's capacity to engage in carbon financing and $REDD^+$-based incentive frameworks. The relevance of this research is underscored by the fact that previous evaluations of Rani CF have predominantly concentrated on aboveground vegetation carbon, while soil carbon, which frequently constitutes a considerable fraction of the total ecosystem carbon, has been largely neglected. As Nepal progresses towards the implementation of $REDD^+$ and the establishment of result-based carbon remuneration, there exists a pressing requirement for exhaustive, site-specific, and scientifically rigorous carbon baselines that encompass both biomass and soil carbon pools. Consequently, this study seeks to address these deficiencies by delivering a thorough assessment of biomass carbon, soil organic carbon at various depths, and the interrelationship between vegetation and soil carbon within the Rani Community Forest.

This holistic methodology facilitates the first comprehensive baseline carbon evaluation for the Rani Community Forest. The findings of this research possess immediate ramifications for forest policy formulation, carbon trading prospects, enhancement of community livelihoods, and overarching national objectives pertaining to carbon neutrality, sustainable forest management, and climate resilience.

MATERIALS AND METHODS

Study Area

This study was conducted in Rani Community Forest during the month of August in the year 2024, situated within Ward No. 6 of Hetauda Sub-Metropolitan City, Makawanpur District, Nepal (Figure 1). The Community Forest encompasses an area of 152 hectares and is positioned at altitudes ranging from 350 to 750 meters.The area experiences average temperatures of 15–25°C during winter and 30–40°C during summer. The terrain is moderately sloping (10–35°). The forest is dominated by *Shorea robusta* C.F.Gaertn., accompanied by *Terminalia alata* Roth, *Schima wallichii* (DC.) Korth, *Terminalia chebula* Retz., and *Terminalia bellirica* (Gaertn.) Roxb. (CFOP, 2022).

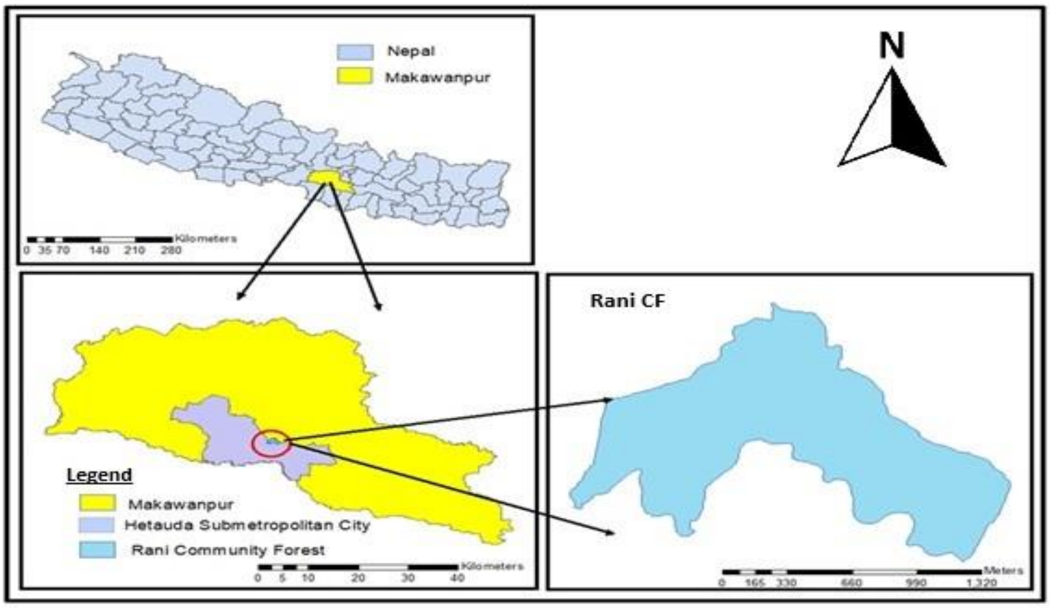

Figure 1: Map showing study area

Forest Sampling:

The forest assessment was performed using a simple random sampling method. A total of thirty-one concentric circular plots were created at a 1% sampling intensity following the guidelines set by MoFSC (2010). The dimensions of the plots were: trees (DBH ≥ 30 cm) – 500 m² (radius 12.62 m); poles (DBH 10–29.9 cm) – 100 m² (radius 5.64 m); saplings – 25 m² (radius 2.82 m); and litter, herbs, and grasses – 1 m² (radius 0.56 m). Tree diameters at breast height (DBH) were assessed with a diameter tape, and tree heights were noted using a laser rangefinder

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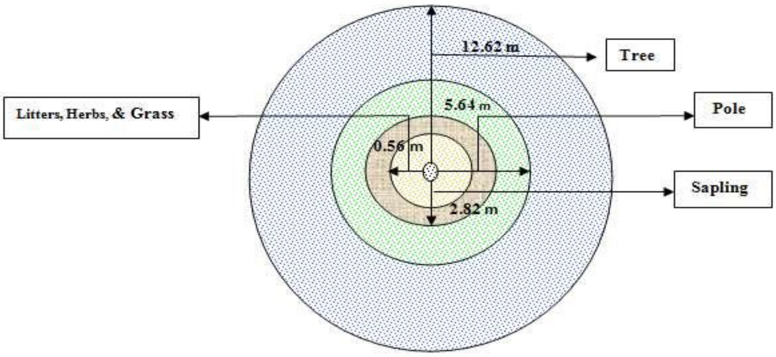

Figure 2: Sample plot design

Soil Sampling and Laboratory Analysis

Soil samples were collected from the center of each plot at three depth intervals (0–10, 10–20, and 20–30 cm) utilizing a core sampler with a diameter of 6.5 cm and a height of 10 cm. The collected samples were put in labeled bags and sent to the laboratory for further analysis. Soil bulk density was measured using the direct core method following the oven-drying of samples at 105 °C, and the bulk density was computed using this formula:

Bulk density (gm cm^{-3}) = Oven dry weight of soil (gm) / Volume of the soil in (cm^3)…….1

Where,

Volume of the soil= Volume of core – Volume of the stone ………………………………...2

Soil organic carbon content (%) was analyzed by titration method as suggested by Walkley and Black method (1934). Total soil organic carbon was calculated using the formula from Chabra *et al.*, (2003):

SOC= pxdx%C……………..3

Where,

SOC= Soil organic carbon stock

p= Soil bulk density ($gmcm^{-3}$)

d= Soil depth (cm)

%C= Organic carbon concentration (%)

Aboveground Tree/Pole Biomass Estimation

Allometric equation was used to estimate above-ground biomass, with tree and pole biomass calculated following the equation proposed by Chave *et al.*, (2005).

AGTB =0.0509 x ρD^2 x H…………….4

Where,

AGTB =above ground tree biomass (kg)

ρ=Wood Specific Gravity ($gmcm^{-3}$)

D= diameter at breast height (cm)

H= tree height (m)

Sapling Biomass Estimation

The above-ground biomass of saplings was estimated using the equation developed by Haase & Haase (1995).

$Y=aD^b$……………...5

Where,

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Y represents the total dry biomass (kg),
D represents the diameter at 15 cm above the ground (cm) and
a and b are the constant whose values were considered as 4.264 and 1.0232, respectively.

Litters, Herbs and Grasses (LHG) Biomass

Samples were destructively gathered from 1 m^2 subplots to assess litter, herb, and grass biomass. The samples were dried in an oven at 60°C for 72 hours, and their weights were measured. Biomass for per unit area was subsequently determined using the equation provided by MoFSC (2010):

LHG Biomass= (Wf/A) x (Wd/Ww) x1/1000………6

Where,
LHG= Biomass of Leaves, herbs and grasses (tha^{-1});
Wf= Weight of the fresh field sample of leaf litters, herbs and field grasses, destructively sampled within an area of size A (g);
Wd= weight of oven dry sub sample of leaf litter, herb and grasses taken to the laboratory to determine moisture content (g);
Ww= weight of fresh sub sample of leaf litters, herbs and grasses taken to the laboratory to determine moisture content (g); and
A= size of the area in which leaf litter, herb and grass were collected (ha)

Belowground Biomass Estimation

Below ground biomass includes biomass roots of trees below the ground. Root-shoot ratio Method of 1:5 as suggested by MacDicken (1997) was used to estimate the belowground biomass. According to this belowground biomass is 20% of aboveground tree-pole biomass.
Below-ground biomass = Above-ground biomass× 0.20……………7
The biomass carbon was then calculated using stock method. The carbon content is assumed to be 47% of dry biomass (IPCC, 2006).

Carbon to Carbon-dioxide (CO_2) Conversion

In carbon trading and valuation, carbon stocks are generally expressed in terms of carbon dioxide (CO_2) equivalents instead of elemental carbon. Consequently, all carbon estimates obtained from different evaluation methods were transformed to CO_2. The transformation was carried out utilizing the molecular weight ratio of CO_2 to carbon, as suggested by Pearson *et al.*, (2005). The following formula was used:
CO_2 = Carbon × 3.67……………….8

Statistical Analysis

One-way ANOVA was utilized to examine SOC variations among different depths. The Pearson correlation evaluated the relation between aboveground tree carbon and SOC. Statistical analyses were conducted using the Statistical Package for Social Sciences (SPSS) version 25

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RESULTS

Vegetation Biomass and Carbons stock

The overall biomass of vegetation in the Rani CF, which includes tree-pole biomass, saplings, and litter-herb-grass (LHG), was calculated to be 292.21 tha^{-1}. Consequently, the overall carbon stock in vegetation was 137.34 tha^{-1}). Within the carbon pools, trees/poles accounted for the largest share (126.30 tha^{-1}; 91.97%), followed by saplings (8.93 tha^{-1}; 6.51%), and LHG (2.09 tha^{-1}; 1.52%) (Table 1). The significant carbon contribution from trees/poles (91.98%) aligns with the structural traits of a Sal-dominated Forest, characterized by the dominance of large-diameter, dense-wood species in biomass accumulation. The sapling and LHG layers combined represented under 9% of the total vegetation carbon, aligning with the low biomass usually observed in closed-canopy forests characterized by limited understory vegetation

Table 1: Vegetation biomass and carbon stock in the CF

Carbon Pool	Mean Biomass±SD (tha^{-1})	Carbon Fraction	Mean Carbon Stock±SD (tha^{-1})	% of Vegetation Carbon
Trees/Poles	268.74±33.62	0.47	126.31±13.46	91.97
Saplings	19.02±4.87	0.47	8.94±2.26	6.51
LHG	4.45±1.12	0.47	2.09±0.62	1.52
Total	292.21		137.34	100.00

Soil Carbon Stock (SOC)

Bulk density rises with soil depth (from 1.18 to 1.29 g cm^{-3}), which may be due to compaction and less organic matter integration in lower layers. Similarly, SOC% fell from 2.74% in the surface layer to 1.67% in the lower layers. This vertical layering is a typical pattern in forest soils, where the input of organic matter is highest at the surface because of the decomposition of leaf litter and turnover of roots. The overall SOC values (79.73 t ha^{-1} at a depth of 0–30 cm) indicate moderately carbon-rich soils characteristic of Siwalik Forest ecosystems. The notable ANOVA result ($p<0.004$) emphasizes different carbon distribution patterns across the three soil layers. The top layer (0–10 cm) contained the largest SOC stock (32.34 t ha^{-1}), suggesting that litter inputs and microbial activity facilitate active carbon cycling at the surface. The mid-layer (10–20 cm) retained considerable SOC, possibly due to root biomass contributions from mature trees. The minimal SOC in the 20–30 cm layer indicates restricted organic matter penetration and gradual carbon stabilization mechanisms at depth.

Table 2: SOC across depths in the CF

Soil Depths (cm)	Mean BD±SD (gcm^{-3})	Mean Carbon Content % ±SD	SOC ±SD (tha^{-1})	% Contribution to total SOC
0-10	1.18±0.05	2.74±0.26	32.34±3.17	40.56
10-20	1.23±0.06	2.10±0.19	25.84±2.52	32.41
20-30	1.29±0.08	1.67±0.23	21.55±2.31	27.03
Total			79.73	100.00

Relationship between Vegetation carbon and Soil Carbon

Pearson's correlation analysis indicated a moderate positive association between soil carbon stock and aboveground tree carbon stock ($r = 0.62$, $p < 0.001$), demonstrating that increased tree biomass in plots correlates with elevated soil carbon levels. This illustrates ecological interconnection: management techniques that promote tree growth will probably boost soil

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carbon storage. As a result, older stands improve soil organic matter build-up through higher litter deposition and ongoing root turnover.

Total Carbon Stock and CO_2 Equivalent

With a total carbon stock of 217.07 tha^{-1}, which corresponds to 796.64 CO_2 tha^{-1}, Rani CF ranks among the efficient mid-hill forests in Nepal concerning its carbon sequestration potential. The estimated revenue (US$7966.40 per hectare) is based on a steady CO_2 price (US$10/ton) but does not consider market volatility, transaction expenses, verification costs, and policy limitations that greatly influence real earnings from carbon trading. This possible revenue illustrates that carbon trading can offer significant economic advantages to community forest user groups while also encouraging local communities to improve forest conservation initiatives

DISCUSSION

The findings from Rani CF indicate significant carbon storage present in both vegetation and soil pools, highlighting the ecological and climate mitigation value of Sal-dominated community forests in Nepal. The prevalence of Shorea robusta, a species recognized for substantial biomass accumulation, probably played a role in the notably high tree carbon stock observed. Similar research conducted in Chitwan (Pandey & Bhusal, 2016), Makawanpur (Ghimire *et al.*, 2018), Tanahu (Gautam *et al.*, 2023), and Dang districts (Regmi *et al.*, 2023) has observed tree carbon stocks ranging from 120–160 t ha^{-1} in established Sal forests, suggesting that Rani CF corresponds with regional vegetation carbon standards. This accord probably arises from comparable forest structure, species composition, and community-driven management approaches that promote natural regeneration and control forest disturbance. Soil samples taken from three depth intervals exhibited a consistent rise in bulk density and a related decrease in organic carbon content as depth increased (Table 2). In contrast, the soil organic carbon (SOC) percentage dropped from 2.87 in the topsoil (0–10 cm) to 1.65% at a depth of 20–30 cm. This vertical gradient illustrates the buildup of organic material close to the soil surface as a result of litter accumulation and root decay, a trend frequently seen in Sal-dominated forests of Nepal (Kafle, 2019; Lamichhane & Ghimire, 2022). The comparatively high SOC stock (79.73 tha^{-1}) indicates advantageous conditions for the stabilization of organic matter, such as dense canopy cover, moderate soil moisture, and minimal disturbance (Shrestha & Singh, 2008; Bhandari & Bam, 2013; Kafle, 2019). These findings align with previous research indicating high SOC in effectively managed community forests, implying that comparable management practices, such as controlled harvesting and soil management measures, enhance soil carbon storage. The Siwalik area, despite its fragile geological nature, frequently sustains abundant surface organic layers because of quick litter decomposition and thick root systems (Kafle, 2019). The reduction in SOC with depth aligns with recognized trends in tropical and subtropical forests, where biological activity and organic contributions decrease in lower horizons (Guo & Gifford, 2002; Kafle, 2019; Ghimire *et al.*, 2023). This correlation with global results suggests that the processes of soil development and the dynamics of organic matter in Rani CF adhere to broadly similar ecological principles, even with local variations in climate or parent material. These findings emphasize the importance of maintaining the litter layer and preventing soil disturbances like digging, unmanaged grazing, or fire, as these could lower carbon storage.

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The positive relationship between vegetation carbon and SOC emphasizes that vegetation structure significantly affects belowground carbon stores. Established, adequately stocked woodlands provide organic material via fallen leaves, small branches, woody debris, and root decay (Lal, 2005; Shrestha & Singh, 2008; Lee *et al.*, 2014). The noted correlation aligns with earlier research in Sal forests and other subtropical woodlands, indicating that management techniques fostering high stand density simultaneously improve soil carbon. This indicates that forest management strategies aimed at boosting stand density, like enrichment planting, assisted natural regeneration, and grazing protection, also indirectly improve soil carbon sequestration. Moreover, the overall carbon stock (217.05 t C ha^{-1}) and related CO_2 equivalent (796.57 t CO_2 ha^{-1}) highlight the significant function of community forests in fulfilling Nepal's nationally determined contributions (NDCs) and carbon-neutral strategies (MoFE, 2018; GoN, 2020). These figures are similar to those found in other mid-hill and inner Terai forests, suggesting that Rani CF is thriving, akin to well-managed community forests in other areas. Higher carbon stocks in certain studies could result from variations in plot size, the allometric models applied, or the consideration of deadwood and root biomass, aspects not measured in this study.

This research emphasizes the forest's potential role in national climate reduction initiatives and carbon credit systems. Significantly, carbon-dense forests such as Rani CF can gain from $REDD^{+}$ incentives, voluntary carbon markets, and ecosystem service payment programs, offering economic prospects for local populations. Accurate measurement, consistent monitoring, and clear governance can assist CFUGs in taking advantage of these new financial mechanisms. The research offers essential baseline data for carbon accounting and illustrates how community-driven forest management plays a crucial role in climate mitigation. Future studies should focus on areas like measuring deadwood carbon and understanding long-term soil carbon dynamics, as this would enhance the comparability of findings with various national and international research. Carbon modeling at the landscape level may further enhance these case study evaluations.

CONCLUSION

Rani CF has a significant ability to sequester carbon, with 137.34 t C ha^{-1} held in vegetation and 79.73 t C ha^{-1} in soil, leading to an overall carbon stock of 217.07 t ha^{-1} (796.64 CO_2 tha^{-1}). Trees and poles are the primary source of biomass carbon, whereas SOC plays a crucial role in total carbon storage. The reduction in SOC with depth and its positive correlation with vegetation carbon highlight the necessity for combined vegetation–soil management strategies that preserve canopy cover, enhance organic matter contributions, and reduce soil disruption. These results highlight Rani CF's ability to significantly aid Nepal's climate mitigation goals, such as $REDD^{+}$ and additional carbon financing strategies. Protection of forests by the community, along with sustainable logging and soil preservation, can improve carbon reserves both above and below ground. Nonetheless, this research has constraints. It excludes carbon found in deadwood, lower soil depths, or seasonal changes in carbon behavior. Consequently, the overall forest carbon values provided here might be particular to each case. Future studies must include extensive soil monitoring, evaluations of deadwood carbon, and the application of modern tools and technologies to enhance carbon measurement across wider spatial ranges.

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Author's contribution
PG: Conceptualization, Writing original draft, Validation, Methodology, Formal analysis, Data curation, Review & editing. UL: Writing original draft, Methodology, Data curation, Review & editing.

Conflicts of Interest
The authors declare that there is no conflict of interest regarding the publication of this manuscript.

Ethics Approval Statement
This study did not involve human or animals. Prior to conduct this study, approval from relevant local authorities was obtained. This study was conducted in accordance with local regulations and ethical guidelines. No protected or endangered plant or animal species were harmed during this study.

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