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Assessing Soil Carbon Sequestration Potential of Pristine Montane Heath Forests in Imbak Canyon Conservation Area (ICCA), Sabah, Malaysia

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ABSTRACT

The carbon sequestration of soils in the Imbak Canyon Conservation Area (ICCA), Sabah, Malaysia, was evaluated in this study. The study aimed to assess the potential for carbon sequestration in the pristine montane heath forest in the designated conservation area. According to our research, the lowland dipterocarp forest along the Nepenthes trail is in transition to heath forest and is characterized by granular soil texture in the 0-20 cm depth range. Three replicates of a soil sample were extracted from each sampling location with 250 m intervals as undisturbed 20 cm-deep vertical cores using a soil auger. Total Carbon (TC), Nitrogen (TN), and Total Organic Carbon (TOC) analyses were performed on the samples. Firstly, TC and N were simultaneously measured using the LECO CN928 Combustion Analyzer. The TOC was determined using a modified Walkley-Black rapid dichromate oxidation method. The Nepenthes trail, representing the montane heath forest, was found to have exceptionally low levels of TN and TC, at 0.006% and 0.876%, respectively. Based on statistical analysis, Bulk Density (BD), Soil Organic Carbon (SOC), and the Carbon to Nitrogen ratio (C/N) exhibited statistically significant differences across all five sampling points ($p < 0.05$) except for the TN and TC ($p > 0.05$). The average BD of the soil was 1.256 g cm^{-3}, indicating inadequate C retention. On the Nepenthes trail, the high C/N ratio of 146 may prolong decomposition and contribute to the low SOC content of the soil. The soil carbon stock in the pristine montane heath forest is estimated at 16.76 tC/ha. These findings are expected to help address potential threats to soil restoration and contribute to ICCA's land management strategies and plans.

INTRODUCTION

Carbon sequestration is an essential process that naturally occurs in pristine forests, playing a vital role in mitigating climate change. As climate change becomes an increasingly urgent global issue, people must understand its far-reaching impacts and the actions needed to address it. In line with

Sustainable Development Goal 13: Climate Action and Goal 15: Life on Land, many nations and organizations are initiating urgent action to combat climate change and its adverse impacts. The forests of Sabah, located in Malaysian Borneo, which cover about 59% of 7.25 million ha of Sabah, have received remarkable attention for their potential to pool carbon [1-3].

Numerous studies have been conducted to comprehend the significance of soil carbon sequestration in virgin forests and its relationship to other ecosystem functions. The intact forest in Long Mio, Sabah, is reported to have the capability to store higher total soil carbon stocks compared to logged-over forest and plantation forests located within the same study area [4]. The forested landscape in Sabah includes Crocker Mountains, Maliau Basin Conservation Area (MBCA), Imbak Canyon Conservation Area (ICCA), Danum Valley Conservation Area (DVCA), Tawau hills and Tabin Wildlife Forest Reserves were identified as having higher aboveground carbon densities that represent a large tract of remaining old growth with high biodiversity [5]. Undisturbed forests have been confirmed to possess the highest capability to store carbon than agroforestry and monoculture cropping systems [6]. This highlights the importance of preserving the natural and pristine forest to maintain carbon sequestration and mitigate greenhouse gas emissions.

Soils hold the largest carbon pools, more than four times that in plants and the atmosphere. Soil carbons are indispensable for estimating the greenhouse gas balances and assessing the ecosystem services in a pristine forest. Hence, determining soil organic carbon is imperative as part of the effort to preserve belowground as one of the largest carbon pools in the forest. Due to the large amounts of organic matter that can accumulate in the soil over extended periods, heath forests are crucial ecosystems for carbon sequestration. These forests are distinguished by their acidic, low-nutrient soils and their dominance by evergreen shrubs and tiny trees. The unique structure of heath forests enables them to store substantial quantities of carbon in both above- and belowground biomass. The slow growth rates and high carbon-to-nitrogen ratios of the evergreen shrubs and tiny trees in heath forests enable them to store more carbon in their tissues than other types of vegetation [7]. In addition, most healthy soils are acidic, which delays the decomposition rate of organic matter, thereby enhancing the carbon sequestration potential of these ecosystems.

Biological carbon capture and sequestration have gained the interest of many stakeholders in Sabah's forestry industry. The Sabah State Government has signed a Nature Conservation Agreement (NCA) with Singapore-registered company Hoch Standard Pte Ltd. This profit-sharing agreement is based on carbon trading and monetizing other non-carbon and natural capital from 2 million ha of Sabah's Forest reserves designated under the NCA. Carbon trading involves the buying and selling carbon credits, which permit companies and other organizations to emit carbon dioxide or other greenhouse gases. The market-based system aims to reduce emissions that contribute to global warming. The Sabah Forest policymakers could earn carbon credits for storing carbon or reducing greenhouse emissions by monetizing protected areas under the Sabah Foundation, including ICCA. In addition, carbon is linked to natural capital that is commercially viable and recognized. Hence, this study could provide a management option for ICCA to increase aboveground forest production and promote long-term carbon storage underground. Understanding the role of soil as a carbon reservoir in a forest ecosystem, particularly the heath forest, is important for carbon modeling and would facilitate decision-making in forest management and policy development.

EXPERIMENTAL

Study Area

ICCA comprises 30,000 hectares of undisturbed rainforest located in Ulu Kinabatangan, situated at 5° 15′ 93″ N, 116° 92′ 64″ E (Figure 1). It is in the Yayasan Sabah Forest Management Area,

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approximately 80 km south of Telupid. The Sabah state government gazetted half of ICCA as a Class 1 (Protection) Forest Reserve 2009. ICCA encompasses several different forest types, including lowland dipterocarp forests and rare lower montane heath forests, ranging from 250 to 1,000 meters above sea level (m a.s.l.).

(a) (b)

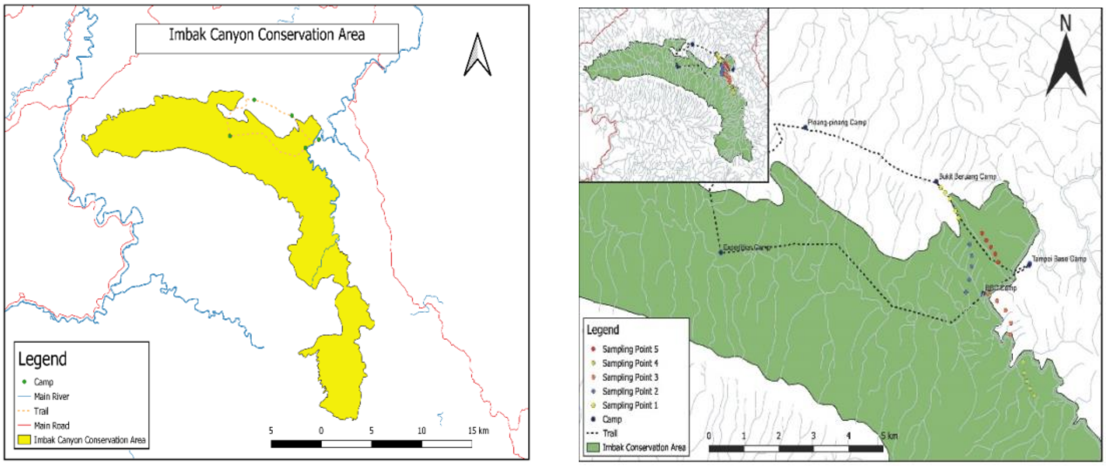

Figure 1. Map of Study Area and Sampling Locations

Sampling Design

Soil sampling was carried out in the study area from the 3rd until the 6th of October 2022. Five sampling points were established in every 250 m interval for each sampling location (Figure 1b). Each sampling point's geographical position and elevation were recorded using the Global Positioning System (GPS), Garmin GPSMAP® 64s. Several photographs of the surroundings of the sampling locations were taken for reference (Figure 2). A soil sample with three replicates for each sampling point is taken as vertical depth increment undisturbed cores at 20 cm depth extracted with a soil auger. Then, the samples were thoroughly mixed and bulked into one composite sample of about 1 kg. Using a stainless-steel core, we randomly collected the soil for bulk density from undisturbed soil within each sampling location. Next, the soil samples were air dried, placed in a labeled heavy-duty clear plastic bag, and transferred to the Soil Laboratory at Kompleks Sains & Teknologi (KOMSAT) in UiTM Sabah Branch.

Soil Analysis

To determine each collected soil sample's SOC, TC, and TN, 10 g of sub-samples were taken from the labeled sample, transported to the Chemical Section in Forest Research Centre (FRC), Sandakan, and analyzed in the laboratory. Percentage moisture content (% MC) was determined by oven-drying a subsample to constant weight to correct measurements on an oven-dry basis. The soil samples were oven-dried at 40°C overnight and lightly ground using mortar and pestle to pass through a 100-mesh sieve (0.45 mm opening) to obtain a fine subsample for microscale analyses. TC and N were measured simultaneously on the LECO CN928 Series Combustion Analyzer (Leco, MI, USA).

Meanwhile, TOC was determined titrimetrically using the rapid dichromate oxidation method adapted from the Walkey-Black procedure. A detailed analysis description can be found in Nelson & Sommers (1982) [8]. In this research, the calculations of the C/N ratio were made based on Kirby et al. (2011) [9]. Soil bulk densities are used to calculate soil C stock. Soil C stock is the product of soil organic C concentration, soil depth, and bulk density.

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Bulk density of each sample is calculated based on the following equation:

$$\text{BD (g cm}^{-3}\text{)} = \text{(M (g))} / \text{(VC (cm}^{-3}\text{))} \qquad \text{Equation 1}$$

Where BD is bulk density (g cm^{-3}), M is the mass of dry-weight soil (g), and VC is the volume of core (cm^3).
Soil carbon stock ton of carbon per hectare calculated based on the following equation:

$$\text{Soil organic carbon (tC ha}^{-3}\text{)} = \text{BD (g cm}^{-3}\text{) x SD (cm) x OC (\%)} \qquad \text{Equation 2}$$

Where BD is bulk density (g cm^{-3}), SD is the depth of soil (cm), and OC is the content of organic carbon (%)

Statistical Analyses

Shapiro-Wilk Test is used to verify the data normality. The data normality condition was not met for the values of C/N ratio ($p < 0.05$. Hence, the log transformation was conducted. The significance difference of BD, SOC, TN, TC, and C/N ratio was tested using ANOVA at a 5% significance level. The correlation test was applied to determine the relationship between the variables. SPSS software (IBM SPSS Statistics, IBM Corporation, Version 26 was used for statistical data analysis.

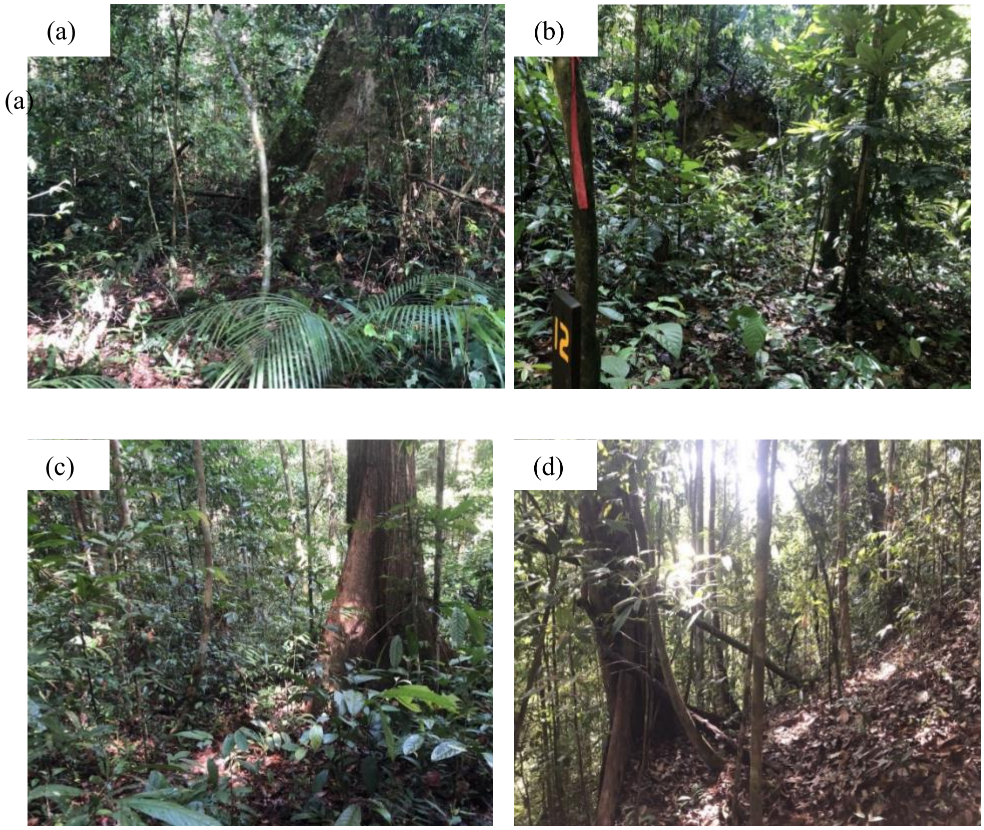

Figure 2. Sampling Points (a) 120 m a.s.l. (b) 220 m a.s.l. (c) 350 m a.s.l. (d) 500 a.s.l.

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RESULTS AND DISCUSSION

This research demonstrated the highest C/N ratio of 146 in the lowland dipterocarp forest at Nepenthes trail (Table 1). Our study observed that SOC consistently exhibited a decreasing pattern and increased C/N ratio (Figure 3a). The higher the C/N ratio, the slower the decomposition rate. The high C/N ratio may lead to prolonged decomposition and contribute to the low SOC content of the soil in the Nepenthes trail. Our study revealed that the BD of the soil was negatively correlated, r = - 0.8809 with SOC (Figure 3b), and corroborates with the findings that stated that as the bulk density decreases, the amount of soil organic carbon tends to increase [10]. The highest SOC, 2.5%, was found at the highest elevation, and the lowest SOC, 1.22%, was recorded at the lowest elevation of the Nepenthes trail (Figure 3a). Similar findings were reported by Xiao et al. [11], who stated that forest soil C density in Beijing increases with increasing elevation. The decomposition process is slower as higher C amounts are found at high elevations. Soils at lower elevations hold significantly lower C content than soils at higher elevations at both the forest exterior and interior [12,13].

The SOC value showed a strong linear relationship (r = 0.9731) with the elevation (Figure 3c). This means that the SOC increases when the altitude increases in the forest. Our findings validate the study from Gachhadar et al. [14]. The increase in tree diameter would influence the SOC as the competition among tree species increases with tree diameter; the natural shedding of lower branches will increase. Thus, more deadwood material would be present on the forest floor, consequently increasing the amount of C [15,16]. It was also proven that the highest BD was demonstrated in the Nepenthes trail, indicating poor soil SOC retention (Table 2). The bulk density of the soil is considered extremely high because the measured value is greater than 1 g/cm³, indicating compacted or dense soil structure, which can impact root growth and water infiltration (Table 1). Hence, the lowland dipterocarp forest in the Nepenthes trail should be restored as soon as possible.

Nonetheless, the strong negative correlation between BD and SOC indicates that SOC was inversely related to BD, as SOC experienced a decrease with an increase in soil BD. As SOC is governed by almost 58% of soil organic matter (SOM), the SOM and BD were observed to be inversely proportional in this study. The Nepenthes trail, representing the lowland vegetation forest, has exhibited extremely low TN and TC. The low levels of TN in the Nepenthes trail, at 0.006%, may be due to the rapid uptake of N into the plant biomass (Table 1).

Table 1: Summary of the analysis results of TN, TC, SOC, C/N, BD, and Soil Carbon

Sampling Location (Trail)	TN (%)	TC (%)	SOC (%)	C/N	BD (g cm^{-3})	Soil Carbon Stock (tC/ha)
Nepenthes	0.006	0.876	0.564	146	1.486	16.76

In the present study, the lowland dipterocarp forest in the Nepenthes trail is in the transition to the Kerangas forest or heath forest, and it is characterized by sandy soil texture in layers 0-20 cm (Figure 4b). The discovery of groups of pitcher plants in the Nepenthes trail at 220 m a.s.l. elevation has underpinned the transition of a lowland dipterocarp forest into a heath forest (Figures 4a and 4b). It also has slow litter decomposition rates due to low-quality litter, low pH, poor soil retention, and low soil availability of nitrogen [17]. Poor nutrient content and TN with a higher C/N ratio and acidic soil of heath forest would contribute to lower variations of plant species and growth that will cause lower accumulation of SOM and BD [18].

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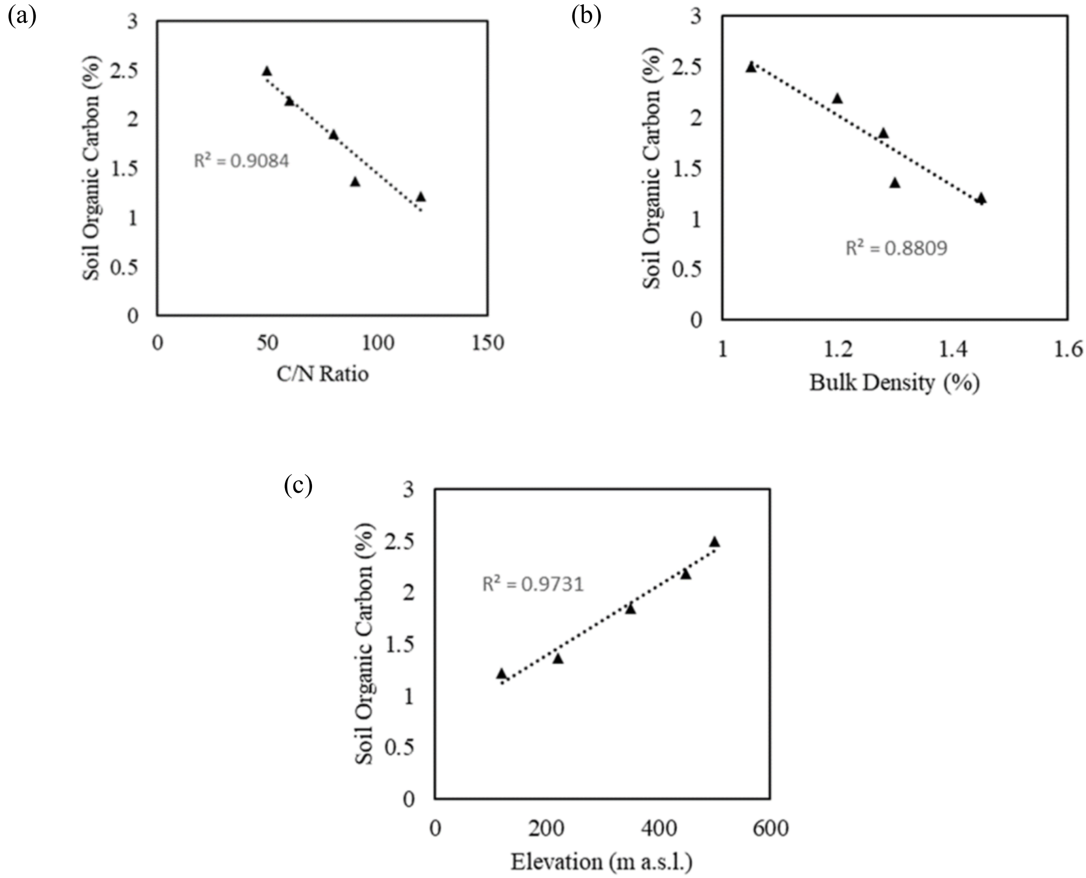

Figure 3. Correlation between (a) elevation (a.s.l.), (b) bulk density, and (c) C/N ratio with soil organic carbon

The ANOVA test shows that there was a significant difference in SOC content, C/N ratio, and BD ($p < 0.05$) across the four different vegetations at a 5% level of significance (Table 2). The differences can be attributed to the unique characteristics of each sampling point. Variations in root structure, organic matter input, microbial activity, litter quality, and human or animal influence contribute to these observed differences. These differences highlight the importance of vegetation in shaping soil properties and influencing ecosystem functions.

Natural succession is remarked as the best approach in rehabilitation, as a restoration of the heath forest ecosystem [19,20], which the ICCA management should investigate and integrate into their strategic management plan. The higher the C/N ratio, the slower the decomposition rate. The high C/N ratio may lead to prolonged decomposition and contribute to the low SOC content of the soil in the Nepenthes trail. This could be demonstrated by the highest amount of C/N recorded in the Nepenthes trail, with 146. Acidic soils in the Nepenthes trail may also be the key factor that impedes the carbon-use efficiency of decomposer microorganisms in decomposing soil litter. Studies have demonstrated that heath forests can sequester substantial carbon over time, particularly in the soil.

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(a) (b)

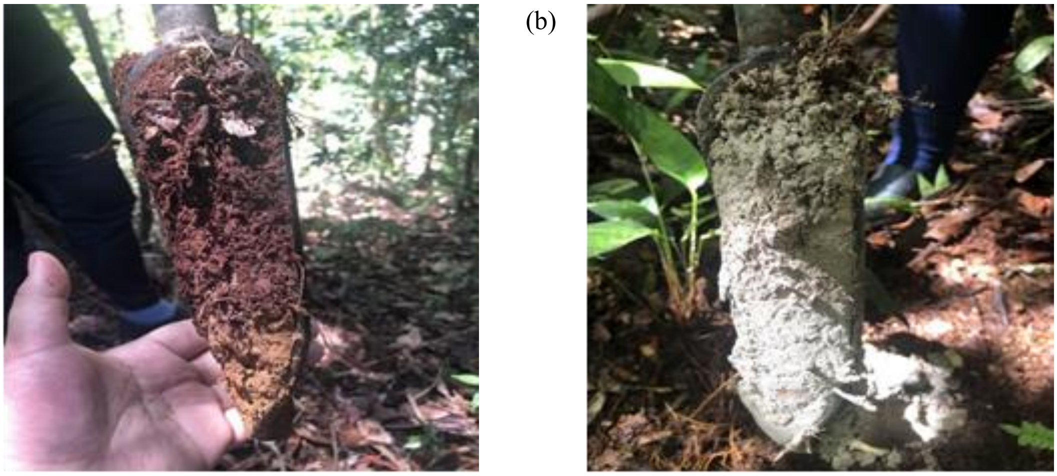

Figure 4. Soil sample at (a) 120 m a.sl and (b) 220 m a.sl.

Table 2. ANOVA Test of TN, TC, SOC, C/N, and BD

Sampling Location (Point No.)	**TN (%)**	**p-value**	**TC (%)**	**p-value**	**S.O.C (%)**	**p-value**	**C/N**	**p-value**	**BD (g cm⁻³)**	**p-value**
1	0.01	0.068	1.215	0.053	1.215	0.0290	1.45	0.010	1.45	0.002
2	0.004		0.786		1.3653		1.3		1.3	
3	0.050		2.821		1.85		1.28		1.28	
4	0.060		3.912		2.186		1.2		1.2	
5	0.038		0.912		2.5		1.05		1.05	

While we acknowledge the importance of additional soil properties such as pH, temperature, moisture content, Total Organic Carbon (TOC), electrical conductivity, Cation Exchange Capacity (CEC), and soil organic matter, these parameters were not included in the present study due to a strategic focus on evaluating soil bulk density and related physical properties. Nonetheless, we aim to provide a more comprehensive soil analysis by including these crucial parameters in subsequent research. By incorporating these additional parameters in future research, we can provide a more holistic understanding of the soil's chemical and physical properties, thereby enhancing the robustness of our findings.

CONCLUSION

A substantial output of this research could help ICCA develop targeted management strategies to enhance soil carbon sequestration through forest restoration and rehabilitation, particularly in pristine heath forests. By focusing on these fragile ecosystems, ICCA can ensure the long-term sustainability of their carbon storage capacity. Heath forests contribute significantly to climate change mitigation by sequestering carbon in both above- and belowground biomass. Protecting and restoring these forests can

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help maintain their capacity for carbon sequestration and assure the continuation of other ecosystem services.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted without any self-benefits or commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

Jacqueline Joseph conceived the idea, designed the study, conducted the experiments/analysis, interpreted the results, and wrote the manuscript.

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