Simulation Study on Peak Path of Tourism Carbon Emissions Introduced by System Dynamics and Panel Threshold Model

Xiaoying Xu[1]
[1]School of Cultural Tourism & Health and Wellness, Liaoning University of International Business and Economics, Dalian 116052, Liaoning, China
Corresponding author: Xiaoying Xu (e-mail: phenixdun2026@163.com)

ABSTRACT The nonlinear processes that influence the carbon emission of a tourism industry are varied, such as economic growth, technology and energy structure and their peaking path and threshold process is not well understood. The paper combines system dynamics and panel threshold models: First, a system dynamics model of tourism carbon emission is developed, which includes economic, energy, carbon sink, and policy subsystems, simulating the changes in carbon emission intensity in the period 2005-2050; second, using a sample of panel data of 30 provinces (2005-2025), a dual threshold model is applied to study the Findings reveal that in the baseline scenario, the peak of carbon emission by tourism will come in (438 million tons); the coefficient of increase of tourism income per capita has two levels: 28,100 yuan and 51,700 yuan, and the coefficient is 0.342 (significant at the 1% level) in the lower section and -0.072 (not significant) in the high section. In the combined scenario, the peak is shifted to 2029 and the peak value is reduced to 343 million tons and carbon emissions in 2050 is 268 million tons and the transportation sector is the sector which has made the greatest reduction in the peak (reducing by 23.4 percent). System dynamics coupled with threshold model could be an effective way to describe the phased nature and dynamic trajectory of tourism carbon emissions.

INDEX TERMS tourism carbon emissions,system dynamics,panel threshold model,scenario simulation,low-carbon tourism

I. INTRODUCTION

THE fast growth of the tourism industry has greatly contributed to regional economic expansion and job creation, yet the energy use and emission of green house gases have attracted a lot of concern. Due to factors like transport, accommodation, catering services, and operations in scenic areas, carbon emissions associated with tourism are ever increasing and this presents new challenges to the global climate governance. Within the framework of the carbon neutrality objectives, the correct representation of the dynamic development of tourism carbon emissions, the determination of its staged nature, the development of achievable peak emission trajectories have become the main research problems in the field of sustainable tourism development. The carbon emission system of tourism is very dynamic, nonlinear and complicated. The economic development of tourism and emission of carbon do not have a direct linear relationship but depends on the interaction of various factors, such as technological advances, energy portfolio, consumption habits, and environmental policies. The internal feedback processes and threshold-hysteresis effects of such complex systems are typically difficult to capture using traditional econometric approaches. System dynamics techniques are more effective in dealing with multivariate, multi-loop, and nonlinear socioeconomic systems, and in tracing the long-term process of dynamic evolution; and panel threshold models can effectively estimate important thresholds and determine nonlinear relationships between variables. These two approaches can be used together to uncover the inherent processes of tourism carbon emission and forecast peak patterns with various policy interventions.

The key aims of this research are: to build a system dynamics simulation model of peak tourism carbon emissions to describe the causal feedback relationship between tourism economy, energy consumption, and carbon emissions, to use a panel threshold model to analyze the threshold effect of tourism carbon emissions and the identification of the key thresholds to transform the influencing processes, to model multiple development scenarios to simulate the peak time and peak level of tourism carbon emission under various pathways, The findings of the research can offer both theoretical and quantitative ground to the tourism management departments to develop scientific and effective carbon emission reduction policies.

II. RELATED WORK

The tension between the recovery of the tourism industry and the global carbon neutrality target is becoming increasingly prominent. How to quantify and mitigate the carbon emissions and ecological footprint caused by tourism activities has become a frontier issue in environmental economics and sustainable tourism research. Ehigiamusoe et al. [1] found that the tourism industry itself increases carbon emissions and ecological footprint, but in countries with a high level of globalization, the negative impact of tourism on the environment is significantly reduced. Mansourihanis et al. [2] used machine learning algorithms to conduct high-resolution spatial distribution simulation and time trend analysis of tourism-related carbon emissions. Razzaq et al. [3] distinguished between the positive and negative impacts of tourism development and green innovation, and assessed their short-term and long-term asymmetric effects on economic growth and carbon emissions respectively. Raihan et al. [4] analyzed the long-term cointegration relationship and causal direction between tourism, economic growth, energy use and carbon emissions. Based on global multi-country panel data, Kayani et al. [5] used fixed effects models and system GMM estimation methods to control endogeneity and heterogeneity and empirically tested the direct effects of each variable on carbon emissions.

Kumail et al. [6] analyzed the long-term equilibrium and causal relationship between tourism, economic growth, energy consumption and carbon emissions based on time series data of Pakistan from 1972 to 2019. Blázquez et al. [7] screened and analyzed a number of empirical studies on tourists' willingness to pay carbon compensation and identified key factors affecting willingness. Leal Filho et al. [8] sorted out carbon emission reduction measures in the aviation industry and evaluated their technical feasibility and emission reduction potential. Aini [9] combined panel data regression and case comparison analysis to evaluate the quantitative relationship between tourism growth, economic output, employment rate and carbon emissions in many Southeast Asian countries and identified best practices. Raihan and Tuspekova [10] used ARDL boundary test and dynamic ordinary least squares (DOLS) to estimate the long-term elasticity of renewable energy consumption, forest area, technological innovation and carbon emissions. Existing studies have made important progress in measuring, driving factors and nonlinear effects of carbon emissions in the tourism industry, but most of them are concentrated on static panel regression or time series cointegration analysis, which makes it difficult to reveal the dynamic feedback mechanism and threshold transformation law inside the system. This paper introduces system dynamics and panel threshold models to reveal the nonlinear dynamic mechanism of tourism carbon emissions and to design differentiated peaking paths.

III. METHODS

A. CONSTRUCTION OF SYSTEM DYNAMICS MODEL

In the present study, the dynamic model of tourism carbon emissions took shape has four interrelated modules: the tourism economy subsystem, the energy consumption subsystem, the carbon emission subsystem, and the policy regulation subsystem. To ensure model transparency and reproducibility, the causal relationships and feedback structures are visualized through a Causal Loop Diagram (CLD) (see Figure 1) and a Stock-Flow Diagram (SFD) (see Figure 2). These diagrams define the mathematical boundaries and integration logic of the system. The key variables of the tourism economy subsystem are total tourism revenue, tourism added value, the number of tourists arriving, and per capita consumption of tourism. Total tourism revenue is the sum of domestic tourism revenue and inbound tourism revenue and it is improved by various factors including the level of economic development, disposable income of the residents and convenience of transport. The positive feedback loop (R1) of this subsystem is defined by the following logic: Total Tourism Revenue $\rightarrow$ Investment Capacity $\rightarrow$ Facility Quality $\rightarrow$ Tourism Attractiveness $\rightarrow$ Number of Tourists $\rightarrow$ Total Tourism Revenue. Mathematically, the reinvestment in facilities is expressed as $I(t) = \alpha \cdot R(t)$, where R is revenue and α is the reinvestment coefficient. This cycle facilitates the continuous expansion of the tourism economy. At the same time, a negative impact of economic growth in tourism is also possible, namely consumption of resources and contamination of the environment.

The subsystem of energy consumption includes the four key areas of energy consumption that are transportation, accommodation facilities, catering services, and tourist attractions. The tourism carbon emissions are the highest in the transportation sector and it encompasses air, rail, road, water transportation modes. The heating, cooling and provision of hot water to guest rooms are the leading sources of energy used by accommodation facilities. Food processing and cold storage are part of the energy use of catering service sector. There is also a demand of energy in cable cars and sightseeing vehicles in tourist attractions. The enhancement of energy efficiency creates a negative feedback mechanism (B1) in this subsystem. As technological advancement increases, the energy intensity per unit of tourism activity decreases, formulated as $EI(t) = EI_0 \cdot e^{-\gamma t}$, where γ represents the rate of technological progress. This mechanism acts as a critical constraint on the total growth of emissions despite increasing tourism demand [11,12].

The carbon emissions subsystem calculates the CO2 emissions generated by the tourism activities, using the IPCC-recommended approach of combining the activity levels with emission factors. This subsystem has carbon sink absorption where the carbon absorption capacity of tourism areas is influenced by factors like forest cover. The policy regulation subsystem has three types of policy variables, which are technological upgrading, structural optimization,

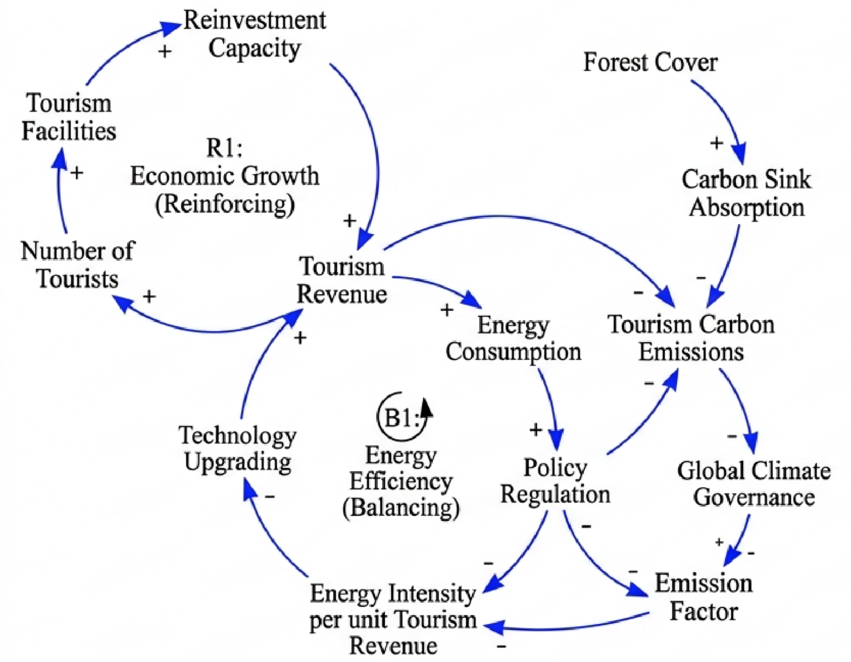

FIGURE 1. Causal Loop Diagram (CLD) of Tourism Carbon Emission System

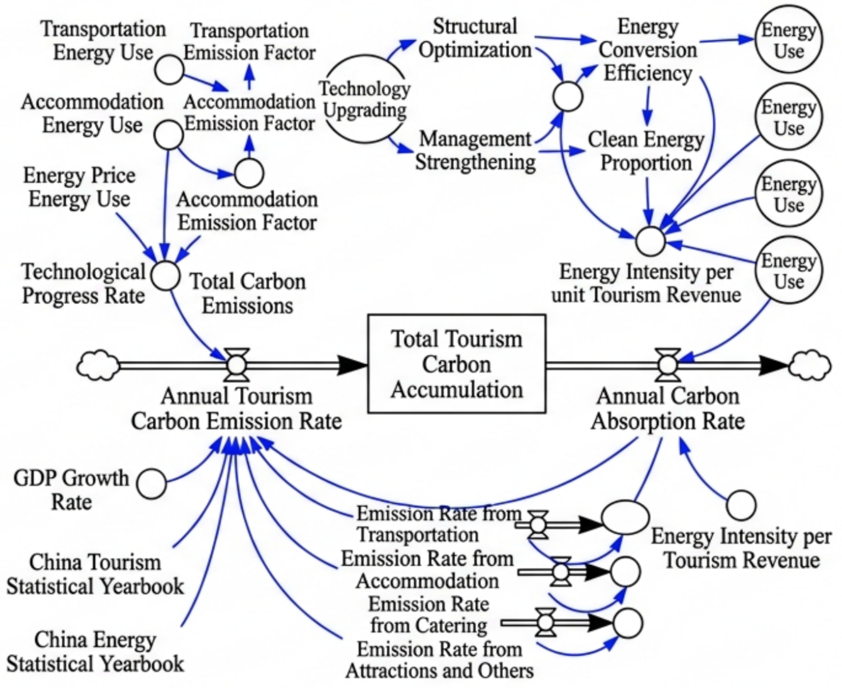

FIGURE 2. Stock-Flow Diagram (SFD) of Tourism Carbon Emission System

and management strengthening. These variables affect the key rate variables and level variables within the energy consumption and carbon emission subsystems. By adjusting the policy intensity parameters in the Stock-Flow model, the simulation can trace the nonlinear shifts in the system's state variables, such as Total Carbon Accumulation (S), where $\frac{dS}{dt} = \text{EmissionRate} - \text{AbsorptionRate}$. This allows for the modification of the evolutionary course of the entire system under different intervention scenarios.

The time horizon of the model is determined as the period between 2005 and 2050, where the period between 2005 and 2025 would be the period of calibration of the model and 2026-2050 would be the period of simulation and prediction. The key input parameters of the model are macroeconomic variables (GDP growth rate, urbanization rate, energy price index, and technological progress rate), tourism-specific variables (tourism revenue elasticity, energy intensity per unit of tourism revenue). The parameters are based on the calibration outcomes of the annual "China Tourism Statistical Yearbook," and China Energy Statistical Yearbook, and other sources.

B. PANEL THRESHOLD MODEL SETTING

The panel threshold model, proposed by Hansen in 1999, is used to identify structural breakpoints in the relationship between variables. This study uses this model to examine the nonlinear relationship between tourism economic growth and carbon emission intensity. The explained variable is tourism carbon emission intensity, defined as carbon dioxide emissions per unit of tourism added value (tons/10,000 yuan). The core explanatory variable is per capita tourism revenue (10,000 yuan/person), and the threshold variable is also set as per capita tourism revenue. While using the same variable for both the regressor and the threshold is consistent with the investigation of the Environmental Kuznets Curve (EKC) logic, potential endogeneity was addressed. To ensure the reliability of the threshold estimates, we performed robustness checks using a one-period lagged per capita tourism revenue as an alternative threshold variable, which yielded consistent structural breakpoints. Control variables include technological level (energy conversion efficiency of tourismrelated industries), industrial structure (the proportion of tertiary industry added value to GDP), urbanization rate (the proportion of urban population), environmental regulation (the proportion of pollution control investment to GDP), and openness to the outside world (the proportion of tourism foreign exchange earnings to total tourism revenue).

The baseline form of the panel threshold model is set as a single-threshold model. If it passes the test, double or triple thresholds are further tested. The threshold effect is tested using the bootstrap method, constructing

the likelihood ratio statistic through repeated sampling. The threshold estimate is determined by minimizing the sum of squared residuals.

In terms of data sources, carbon emission data were estimated based on the energy consumption of tourism departments in each province, and energy consumption data came from the detailed data of relevant departments in the "China Energy Statistical Yearbook". Per capita tourism revenue was calculated by dividing the total tourism revenue of each province by the total number of tourists. The time span was from 2005 to 2025, with a total of 21 annual observation periods and 630 sample observations from 30 provinces. All nominal variables were deflated with 2005 as the base year [13].

C. SCENARIO DESIGN AND SIMULATION SCHEME

To evaluate the effects of different policy intervention combinations, this study designed five typical development scenarios: the baseline scenario continues the current development trend, with an average annual growth rate of tourism revenue set at 5.5% and an average annual increase in energy conversion efficiency of 1.2%; the technology upgrading scenario assumes that the average annual increase in energy conversion efficiency is revised upward to 2.5%, and the proportion of clean energy increases by an average of 2.0 percentage points per year; the structural optimization scenario assumes that the proportion of public transportation trips gradually increases from 45% to 65%, and the proportion of low-carbon accommodation facilities increases from 30% to 50%; the management strengthening scenario assumes that energy prices rise by an average of 3% per year, and carbon emission intensity constraints are included in the assessment of local governments; the comprehensive scenario implements the above three types of policies simultaneously, and selects the optimal combination. Specifically, this scenario integrates the high-intensity parameters: an energy conversion efficiency growth rate of 2.5%, a clean energy share increase of 2.0% per year, a public transportation structure target of 65%, and a mandatory 3% annual energy price adjustment.

The simulation ran from 2005 to 2050, with a simulation step size of one year. Initial model conditions were set based on actual data from 2005, and open boundary assumptions were used for boundary conditions. Model validation employed a historical data fitting method, comparing the simulation outputs from 2005 to 2025 with the actual values. The goodness of fit for key indicators was above 90%, indicating that the model has good simulation accuracy.

IV. RESULTS AND DISCUSSION

A. SYSTEM DYNAMICS SIMULATION RESULTS

In the scenario of the baseline, the total carbon emissions of tourism in China are characterized by an inverted U-shaped curve, with the curve rising up and falling down. The simulation results indicate that the total volume of tourism carbon emissions will increase steadily from 152 million tons in 2005 to a peak of 438 million tons in 2034. Concurrently, the tourism carbon emission intensity is projected to decrease from 0.76 tons/10,000 yuan in 2005 to 0.31 tons/10,000 yuan by the peak year. The carbon intensity of tourism will gradually reduce to 0.6 to 0.76 tons/10,000 yuan in 2005, 0.31 to 0.19 tons/10,000 yuan in 2034 and 2050 respectively. The fact that there has been a constant decrease in the carbon intensity as well as the original increase and subsequent reduction in overall emissions is an indication that technological advancements have slightly neutralized the growth in emissions that has been caused by the growth in tourism.

Transportation continues to be the biggest source of carbon emissions by the tourism industry, and its contribution to total carbon emissions is steadily growing by between 52-60 percent. The share of accommodation dropped to 21 per cent as compared to 25 per cent, catering was stagnant at about 12 per cent, scenic spots and other sectors lost their share which was about 11 per cent to 7 per cent. The intensity of carbon emission and the most rapid increase are air travel, which is now the primary contributor to the rise in the portion of emissions in the transportation sector.

Three effects influence the peak of the tourism carbon emissions: the tourism demand growth effect, the energy efficiency improvement effect, and the energy structure cleanup effect. The growth effect of tourism demand is a positive driver so it contributes significantly during the initial stages, the growth effect of energy efficiency is a negative driver so its contribution is steadily growing, and the energy structure cleanup effect contribution increases more rapidly in the later stages. The peak time and level are the result of the combined effects of these three effects. In the baseline scenario, the effect of increase in demand in tourism prevails up to the year 2034 after which the negative driving effect overtakes the positive driving effect and carbon emission levels off and start to decrease.

B. PANEL THRESHOLD MODEL ESTIMATION RESULTS

The threshold effect was tested using the Bootstrap method with 300 repeated samplings. The results showed that the F-statistic for the single-threshold model was 45.32 (p-value less than 0.01); the F-statistic for the double-threshold model was 23.67 (p-value 0.02); and the triple-threshold model failed the test. Therefore, the double-threshold model was adopted. The estimated threshold values were 28,100 yuan and 51,700 yuan, respectively. Based on these two threshold values, the sample was divided into three intervals: low tourism income (per capita tourism income less than 28,100 yuan) accounting for 32%, medium income (28,100 yuan to 51,700 yuan) accounting for 48%, and high income (above 51,700 yuan) accounting for 20%.

The parameter estimation results of the dual threshold model are shown in Table 1.

Table 1 shows that the coefficient of influence of per capita tourism revenue on carbon emission intensity decreases as income level increases. The coefficient in the low interval is 0.342 (significant), indicating that when per capita tourism revenue is below 28,100 yuan, a 1% increase in tourism economic growth leads to a 0.342% increase in carbon emission intensity. The coefficient in the middle interval drops to 0.186 (significant), a decrease of approximately 45.6%. The coefficient in the high interval turns negative (-0.072) but is not significant, indicating a possible decoupling trend. Technological level is significantly negative in all intervals, and the absolute value of the coefficient increases with income level, indicating that the contribution of technological progress to reducing carbon emission intensity increases with economic development. Urbanization rate is significantly positive in the low and middle intervals, but not significant in the high interval. Environmental regulation is significantly negative in the middle and high intervals, while openness to the outside world is significantly negative only in the high interval.

C. COMPARISON OF PEAK PATHS UNDER DIFFERENT SCENARIOS

The peak paths for tourism carbon emissions differ significantly across the five scenarios. Table 2 summarizes the key indicators for each scenario.

Under the technology upgrade scenario, the peak year is 2031, with a peak of 392 million tons, a reduction of 10.5% from the baseline. The emission reductions in this scenario mainly come from the transportation sector, whose peak carbon emissions decrease from the baseline of 263 million tons to 231 million tons, contributing approximately 65% of the total emission reductions. Under the structural optimization scenario, the peak year is 2032, with a peak reduction of 7.5%, and the effects are mainly reflected in the medium to long term. The management enhancement scenario has limited peaking effects, with a reduction of only 3.9%. The comprehensive scenario, incorporating all three policy scenarios, advances the peak year to 2029, with a peak of 343 million tons, a reduction of 21.6%, and carbon emissions are expected to decrease to 268 million tons by 2050, resulting in a cumulative emission reduction of 3.54 billion tons.

Table 3 shows the peak carbon emissions of different sectors under the overall scenario.

The transportation sector is projected to achieve the most significant mitigation, with a peak reduction of 23.4%, and the peak emission date moved forward from 2033 to 2028. The accommodation sector will see its peak emission date moved forward from 2035 to 2030, with a peak reduction of 18.7%. The food and beverage sector will reduce emissions by 15.2%, and tourist attractions and other sectors by 19.8%. The parameters for the composite scenario are lower than the target values in the International Energy Agency's 2050 net-zero emissions roadmap, demonstrating technical feasibility. In terms of economic feasibility, the net life-cycle benefit is positive.

Correlation analysis between the threshold model findings and scenario simulation results reveals that provinces in the low tourism revenue range should focus on introducing energy-saving technologies to help them overcome the first threshold; provinces in the medium range represent the optimal window of opportunity for implementing emission reduction policies; and provinces in the high range are nearing decoupling, with policy focus shifting towards deep decarbonization. The comprehensive scenario is applicable to peak emission path design at the national level.

TABLE 1. Parameter estimation results for the panel threshold model

Variable name	Low interval coefficient	t-value	Middle interval coefficient	t-value	High interval coefficient	t-value
per capita tourism revenue	0.342**	2.87	0.186*	2.14	-0.072	-0.98
technical level	-0.215**	-3.21	-0.237**	-3.56	-0.263**	-3.89
Industrial structure	-0.098	-1.65	-0.124*	-2.18	-0.156*	-2.43
urbanization rate	0.176*	2.23	0.143*	2.01	0.095	1.34
Environmental regulations	-0.087	-1.34	-0.112*	-2.05	-0.138*	-2.27
Opening up to the outside world	-0.052	-0.89	-0.078	-1.32	-0.104*	-2.01
constant term	1.235**	4.56	1.018**	3.98	0.876**	3.45

Note: ** and * indicate significance at the 1% and 5% levels, respectively.

TABLE 2. Key Indicators for Peak Tourism Carbon Emission Pathways under Different Scenarios

Scenario Name	Peak Year	Peak carbon emissions (100 million tons)	Peak change rate (%)	Carbon emissions in 2050 (100 million tons)	Cumulative emission reductions (100 million tons)
Baseline Scenario	2034	4.38	—	3.96	—
Technology upgrade scenario	2031	3.92	-10.5	3.21	18.6
Structural optimization scenario	2032	4.05	-7.5	3.38	14.2
Management reinforcement scenario	2033	4.21	-3.9	3.67	8.5
Comprehensive Scenario	2029	3.43	-21.6	2.68	35.4

TABLE 3. Peak carbon emissions of the tourism sector under the comprehensive scenario

department	Baseline scenario peak year	Peak Years in Combined Scenario	Peak change rate (%)	Main emission reduction pathways
Transportation	2034	2028	-23.4	Electrification and optimization of travel structure
stay	2035	2030	-18.7	Energy efficiency improvement and clean heating
FOOD	2032	2029	-15.2	Energy-saving equipment and localized food ingredients
Scenic spots and others	2036	2031	-19.8	Smart management and clean energy

V. CONCLUSION

This study constructs a simulation framework for peak carbon emissions in tourism that integrates system dynamics and panel threshold models, addressing the challenge of traditional methods in characterizing the nonlinear dynamic evolution and threshold transition mechanisms of carbon emission systems. Scenario simulations reveal the differences in peak time and peak level under various policy interventions, identify two key threshold values for per capita tourism revenue, and clarify the differentiated focus of emission reduction policies at different development stages. Limitations of this study include the model parameters being primarily based on historical data and literature calibration, limiting its responsiveness to sudden technological breakthroughs or extreme policy shocks, and failing to fully consider the heterogeneity of tourist behavior and the complex impact of international tourism flows. Future research could introduce machine learning methods to optimize parameter estimation, combine micro-survey data to characterize tourists' low-carbon preferences, and extend the model to cross-national comparative studies to enhance its universality.

AUTHOR CONTRIBUTIONS

Xiaoying Xu designed, collected and analyzed the data, and drafted the manuscript. Xiaoying Xu conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Xiaoying Xu participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

FUNDING

This research received no external funding.

ACKNOWLEDGEMENTS

Not applicable.

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