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Smart energy management in renewable microgrids: integrating IoT with TSK-fuzzy logic controllers

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ABSTRACT

Hybrid microgrids powered by renewable energy sources are gaining popularity globally. Photovoltaic (PV) and permanent magnet synchronous generator (PMSG)-based wind energy systems are widely used due to their ease of installation. However, wind and solar energy are unpredictable, leading to fluctuating power generation. Simultaneously, load demand varies randomly, making it necessary to integrate storage devices to maintain a balance between generation and consumption. To enhance system economy, a small battery is combined with a hydrogen-based fuel cell and electrolyzer for efficient energy storage and management. A robust energy management system (EMS) is critical to ensure power quality and reliability across all microgrid components. Maximum power point trackers (MPPTs) are employed to maximize renewable energy utilization. Frequency stability and ensuring power balance is important in autonomous microgrids, especially during rapid load or source variations. This paper presents a novel fuzzy rule-driven Takagi-Sugeno-Kang (TSK) controller for the EMS, ensuring fast, precise responses and improved microgrid reliability.

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1. INTRODUCTION

The global electricity demand is rising rapidly, driving the adoption of renewable energy sources for a quality power supply [1]. Standalone microgrids with multiple integrated renewable sources, like solar and wind, offer a feasible solution. Combining sources ensures reliability, addressing variability issues inherent in single-source renewable energy systems [2], [3]. Hence, integrating two or more renewable energy sources is essential to enhance system reliability and address the variability of individual sources.

Photovoltaic (PV) and wind energy are widely available renewable sources, with permanent magnet synchronous generators (PMSG) ideal for medium-scale wind applications due to direct coupling [4], [5]. Energy storage is crucial for stability amidst fluctuating solar irradiance and wind speeds. While batteries are commonly used, they require frequent replacement and high maintenance, increasing long-term costs. Integrating electrolyzers and fuel cells alongside small batteries can enhance cost-effectiveness and stability [4]. Batteries address transient changes, while proper coordination control ensures energy balance and power quality in microgrid systems, optimizing performance and reliability.

Proportional-integral (PI) controller gains, fixed for specific conditions, are unsuitable for dynamic microgrids with renewable sources, electrolyzers, fuel cells, batteries, and varying loads. Takagi-Sugeno-Kang fuzzy (TSK-fuzzy) controllers address this by dynamically adjusting gains during sudden changes, ensuring fast response [6], [7]. While PV, wind, batteries, and electrolyzers provide active power, reactive power demands are met by the inverter through the proposed controller [8], [9]. Additionally, the microgrid's active power is balanced by regulating frequency at the point of common coupling (PCC).

Key points of paper:

- Optimized maximum power point tracking (MPPT): The implementation of MPPT for both PV and wind systems, utilizing IoT sensors, minimizes costs while maximizing energy harvesting. This approach ensures both systems operate at maximum efficiency under varying environmental conditions.
- Advanced IoT-enabled TSK-fuzzy controllers: The use of TSK-fuzzy logic controllers enables real-time, adaptive control of the microgrid, providing rapid responses to changes in generation and load. This enhances stability, improves power quality, and increases reliability across all operating conditions.
- Inverter-based frequency and reactive power compensation: The inverter is responsible for maintaining frequency regulation and reactive power compensation, critical for meeting load demands and ensuring voltage stability within the microgrid. The proposed controller efficiently manages these functions, ensuring seamless operation.
- Hybrid energy storage system for cost-effectiveness: By combining a small battery with fuel cells and electrolyzers, the proposed system reduces long-term operational costs while maintaining a reliable energy supply. This hybrid approach leverages the fast response of batteries with the long-term storage capabilities of hydrogen technologies.

2. METHOD

2.1. System description

Photovoltaic (PV) and wind systems use a power optimizer for solar panels with a perturb and observe (P&O) algorithm [10], utilizing boost converters connected to a DC-link. A bidirectional DC-DC converter manages battery charging/discharging. A buck converter interfaces the electrolyzer with the DC-link to enhance hydrogen production, while a boost converter connects the fuel cell (FC) due to its lower operating voltage. Electrolyzer-generated hydrogen and oxygen are stored for FC usage. AC loads connect to the DC-link via a 3-phase 5-level H-bridge inverter, with an LC filter at the PCC to reduce harmonics [11], [12]. The microgrid's block diagram is shown in Figure 1.

Several related systems have been presented recently. Preview study [13], [14], novel controllers for coordinated energy management in smart grids were implemented, excluding electrolyzers and fuel cells. In [15], [16], PV-based systems with electrolyzers and fuel cells were studied, but wind energy and the quality of power at the grid interconnection point were omitted. Bhanutej and Naidu [17] presented a seven-level power inverter for PV, wind, and battery systems, without addressing electrolyzers or fuel cells. The integration of batteries in DC microgrids powered by solar and wind was explored in [18], but electrolyzers were excluded. Islanding microgrids in [19] lacked electrolyzers, fuel cells, and EMS. Grid-interactive PV-wind systems in [20] were non-standalone. Preview study [21], DC microgrid EMS ignored fuel cells and electrolyzers, while [22] focused on reactive power but missed electrolyzers and fuel cells. None utilized TSK-fuzzy controllers or multilevel inverters for improved response and voltage.

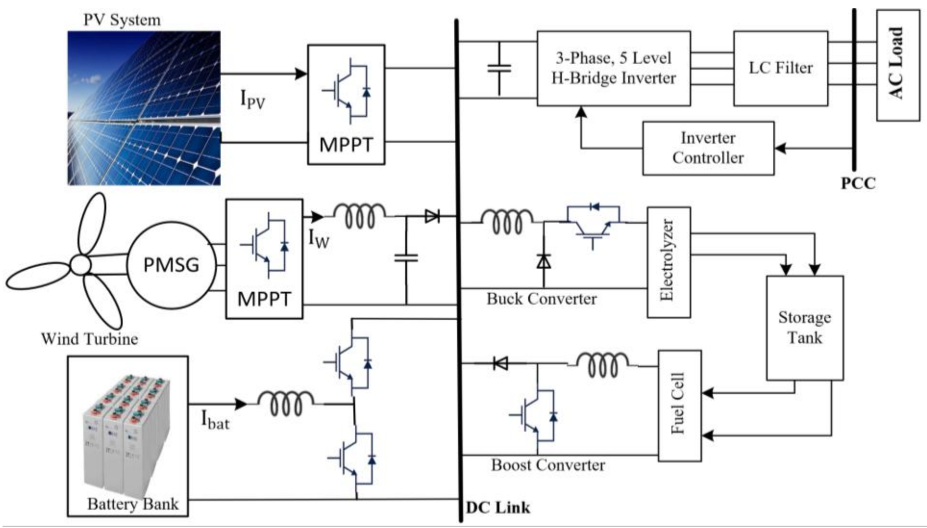

Figure 1. PV, wind, fuel cell, electrolyzer, and battery-based hybrid standalone microgrid

2.2. Different controllers
2.2.1. TSK fuzzy controller

The inability to adapt gain values makes the PI controller less responsive to sudden changes. During random fluctuations, TSK-fuzzy systems adjust in real time to deliver accurate reference outputs. To enhance responsiveness, an artificial neural network (ANN) training algorithm is integrated with the rule-based TSK fuzzy controller [23], [24]. Figure 2 shows the block diagram, and Figure 3 shows the weight distribution of TSK rules.

The mathematical expressions of the TSK-fuzzy system are given by (1)-(3).

$$f_1 = p_1X_1 + q_1X_2 + r_1 \tag{1}$$

$$f_2 = p_2X_1 + q_2X_2 + r_2 \tag{2}$$

$$Y = W_1^n f_1 + W_2^n f_2 \tag{3}$$

The constants $p1,2$; $q1,2$; $r1,2$ are tuned parameters, with weights updated by a trained ANN for fast response. This TSK-fuzzy model can be applied in microgrid converter controllers, using the error signal as input to generate the relevant reference signal.

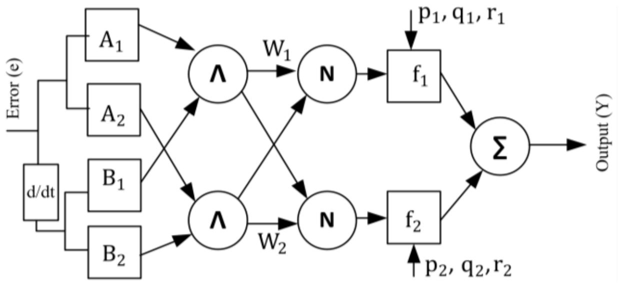

Figure 2. ANN interfaced TSK-fuzzy system

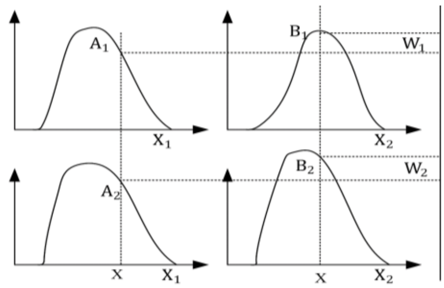

Figure 3. TSK-fuzzy rules-weight

2.2.2. DC side controllers

The relationship between power and speed in wind turbines, and power versus voltage in PV systems, is nonlinear, requiring appropriate MPPT converters with controllers to maximize power extraction. A boost converter with a P&O algorithm is used for the PV system to achieve this. The connection between the PV system and the DC-link is established via a boost converter, and instead of using multiple voltage sensors provides the DC-link voltage input for the MPPT controller. The simple layout of the P&O algorithm for PV is shown in Figure 4. For wind turbines, maximum power is extracted at a specific speed, which must be controlled. Since the wind turbine is directly coupled to the PMSG, the turbine speed is regulated by controlling the PMSG speed. To minimize the number of converters, a controllable rectifier converts the three-phase output from the PMSG to DC and regulates the current to maintain the turbine's optimal speed. The P&O algorithm generates pulses (6 pulses, S_w) based on the DC current from the PMSG, which is supplied to the DC-link. The algorithm of P&O and the controller for generating pulses for the rectifier are shown in Figure 4. Since the MPPT converter outputs differ, a diode is used to transfer the specified current input to the DC-link.

The voltage at the DC-link should be stabilized at the desired reference point. Power mismatch between generation (PV and wind) and load affects the DC-link voltage, with higher generation leading to higher voltage. In response to power imbalances, a battery is connected to the DC-link through a bidirectional converter for controlled charging and discharging. The reference current for the battery is derived through a TSK-fuzzy controller that monitors the DC-link voltage against its target value. A hysteresis controller generates pulses for the DC-DC converter by comparing the reference battery current to the actual battery current.

In a steady state, the battery should neither charge nor discharge. This is managed by the fuel cell (FC) or electrolyzer, based on power mismatch. The TSK-fuzzy controller generates pulses for the boost converter (for FC) and buck converter (for electrolyzer) by comparing the battery current to zero. The system can respond to both positive and negative battery currents instantly. Figure 5 illustrates the associated DC-link voltage controller.

2.2.3. AC side controllers

Space vector pulse width modulation (SVPWM) reduces total harmonic distortion compared to conventional inverters. A 5-level inverter is designed for intermediate power-level applications requiring high-quality power, and SVPWM enhances its performance [25], [26]. In this paper, a 5-level H-bridge configuration operating with space vector modulation is employed to convert and provide AC power at the PCC for various AC loads. The block diagram is shown in Figure 6.

Once the DC-link voltage is stabilized, the PCC voltage can be controlled through the inverter. The microgrid frequency is crucial, as active power demands affect frequency at the PCC. The active load current is derived by comparing the actual frequency with its reference value. The RMS voltage at the PCC is regulated to manage and compensate reactive power. The real and reactive current references are evaluated against the measured DQ components at the PCC, and the resulting error is processed by TSK-fuzzy controllers to generate control voltages. A comprehensive diagram of the 5-level inverter controller is provided in Figure 7, with pulse sequences depicted in Figure 8.

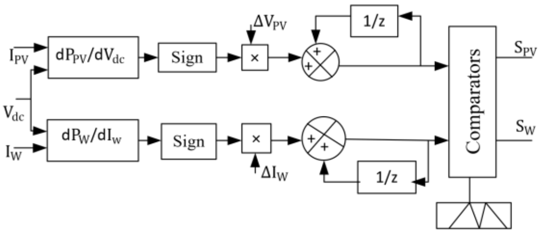

Figure 4. MPPT controllers on the P&O algorithm

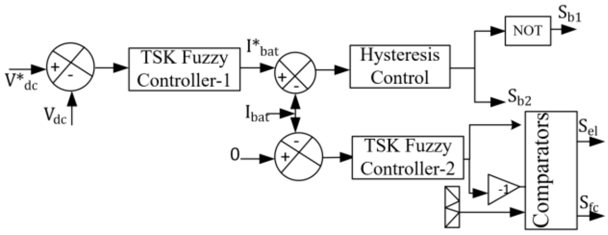

Figure 5. Controller of DC-link voltage

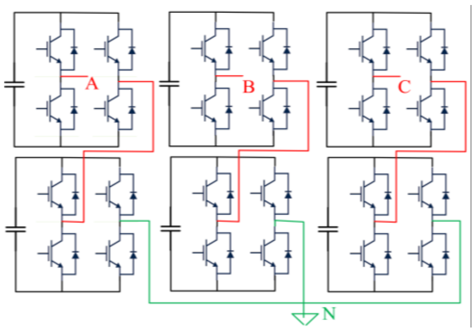

Figure 6. 5-level H-type bridge inverter for 3-phase

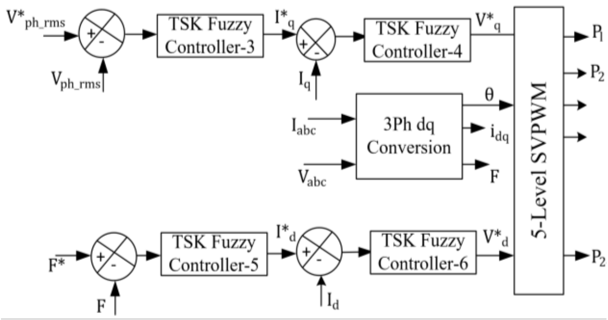

Figure 7. Inverter control scheme

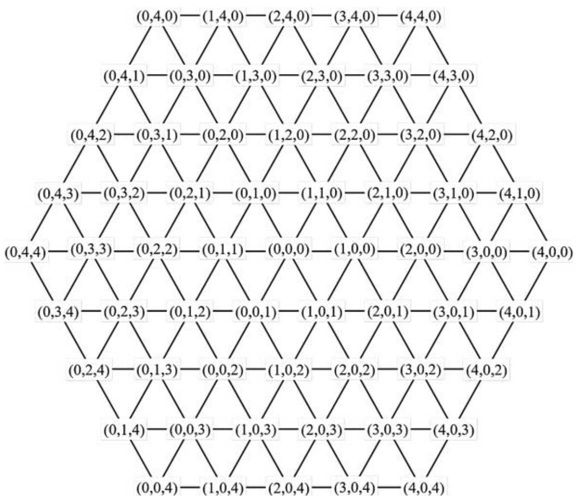

Figure 8. 5-level inverter sequence for space vector

3. RESULTS AND DISCUSSION

3.1. Case 1: Frequency response under load changes at the PCC

In this case, the system's performance is evaluated under a substantial load variation of 200% at the PCC, with a constant total generation of 9 kW throughout the analysis. The initial load at the PCC is set at 4 kW, with the following steps implemented, facilitated by IoT-enabled sensors and controllers:

- Step 1: An 8 kW three-phase load is connected suddenly at 1.0 to 3.0 seconds.
- Step 2: The 8 kW three-phase load is disconnected abruptly at 3.16 seconds.

During these load transitions, IoT sensors detect real-time changes in load conditions and communicate these to the central controller. A significant drop in frequency occurs when the load is connected, reflecting a momentary imbalance between generation and consumption. However, the IoT-enabled controller rapidly adjusts system parameters, stabilizing the frequency back to its reference value of 50 Hz within a short time frame. Conversely, when the load is disconnected, IoT monitoring systems capture the sharp increase in frequency due to the sudden reduction in demand.

The frequency response throughout these load changes is shown in Figure 9. Notably, the frequency variation remains below 1% during all transitions, indicating the robustness of the proposed IoT-enhanced inverter controller in maintaining frequency stability within standalone microgrids. The absence of a connection to a larger power grid makes frequency control critical, as it directly influences the active power balance. The control scheme, leveraging TSK-fuzzy controllers and IoT data analytics, enables rapid frequency adjustments while keeping the RMS voltage at the PCC stable.

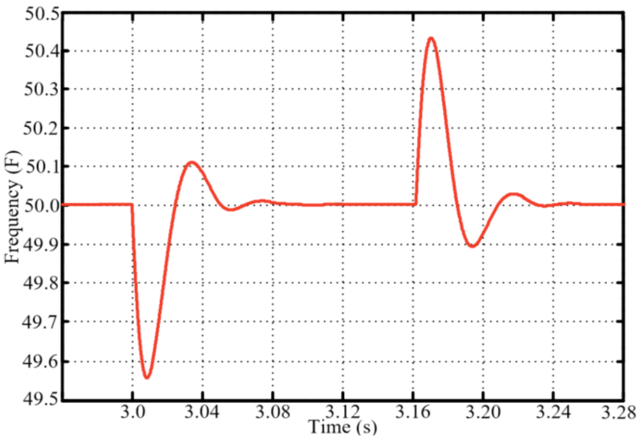

Figure 9. Frequency response at PCC during a change in load

3.2. Case 2: System response to variable conditions

Figure 10 shows the response of the standalone microgrid under various dynamic changes, including shifts in solar intensity, wind speed, and load connected at the PCC across different time intervals. The performance of the battery, fuel cell, and electrolyzer is analyzed during these fluctuations, all managed through IoT-connected devices that provide real-time monitoring and control capabilities. The timings for variations in sunlight intensity and wind velocity are set at 1.0 to 1.5 seconds and at 3.0 seconds, respectively. The wind turbine modeled with two inertial masses prevents an abrupt decrease in power output from the PMSG when the wind speed drops.

Key observations from the response are as follows:

- At t < 0.5 seconds: The load initially applied at the PCC is 1.5 kW, while the PV plant and wind generation operate at maximum capacity, monitored by IoT sensors. Observation: The total generation exceeds the load significantly, resulting in surplus power consumed by the electrolyzer, indicated by negative power readings. IoT systems alert the controller to adjust electrolyzer operation dynamically.
- At t = 1 second: The load increases from 1.5 kW to 5 kW. Observation: The battery begins discharging to meet the increased load; however, generation still surpasses consumption, leading to a decrease in electrolyzer power consumption. The IoT system provides real-time data, allowing for momentary adjustments in electrolyzer output to stabilize power flow.
- At t = 1.5 seconds: A reduction in solar irradiance from 1000 to 700 W/m² occurs. Observation: The battery supplies power by discharging to maintain system balance, as the electrolyzer's response is

delayed. IoT analytics help predict the necessary discharge rate to stabilize the system, ensuring that generation remains above load.

– At t = 2 seconds: A substantial load increase from 5 kW to 12.5 kW is implemented. Observation: The battery rapidly responds to the demand surge; however, initial generation is insufficient to meet the load. The battery discharges while the electrolyzer's power consumption falls to zero. The controller, empowered by IoT data, activates the FC to fulfill the load requirement, albeit with a delay in power output generation. IoT systems enable real-time adjustments, allowing the electrolyzer to gradually increase its generation capacity while the battery discharge levels decrease to zero as per the control strategy.
– At t = 3 seconds: A decrease in wind speed from 12 m/s to 5 m/s is observed. Observation: The power output from the PMSG declines gradually due to the two-mass drive system. The IoT-connected control system allows for seamless communication between devices, increasing the generated output from the fuel cell to maintain power balance.
– At t = 4 seconds: The load decreases from 12.5 kW to 7 kW. Observation: With sufficient generation capacity available, the fuel cell ceases to produce power, and the surplus energy is absorbed by the battery and electrolyzer, as needed. IoT systems ensure that these adjustments happen promptly and efficiently.

The corresponding responses of the DC-link voltage, modulation indexes of the inverter, and RMS voltage at the PCC are detailed in Figures 11(a)-11(c), respectively. These figures illustrate the system's adaptability and stability during various operational scenarios, highlighting the efficacy of the proposed IoT-enhanced control strategy in managing power flows within the standalone microgrid. The integration of IoT technology not only facilitates real-time monitoring and control but also enhances the overall reliability and efficiency of the energy management system.

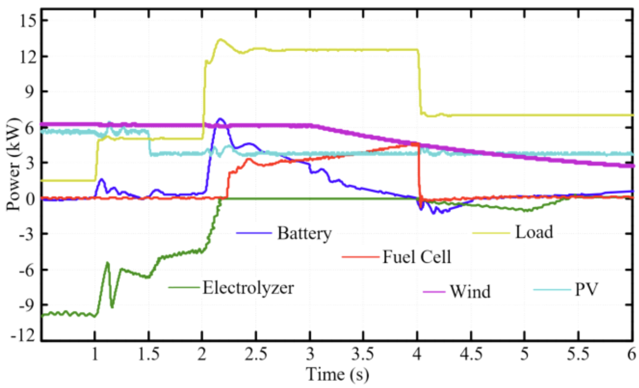

Figure 10. Powers for a standalone microgrid

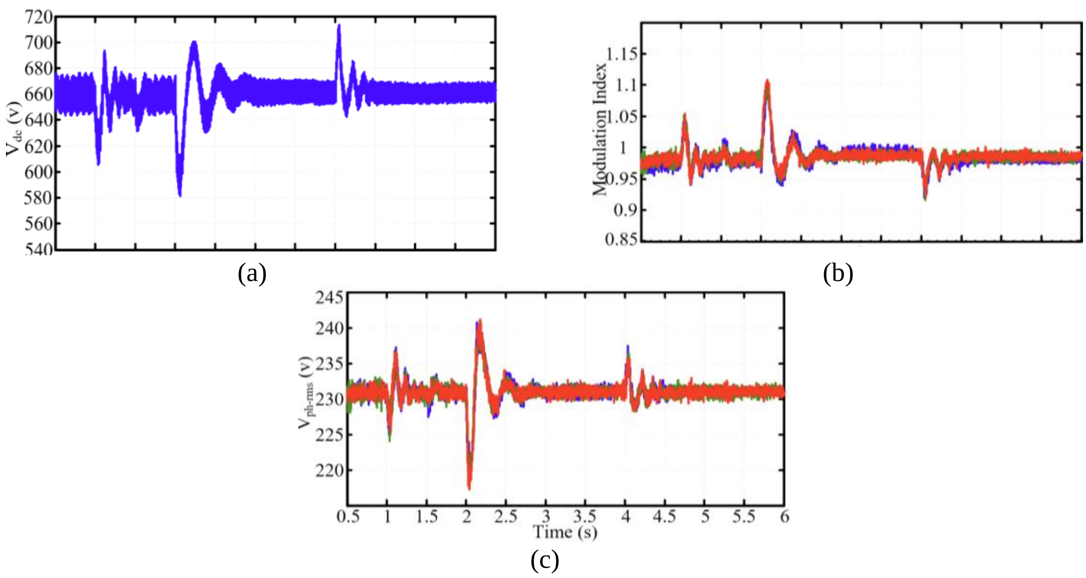

Figure 11. Response of (a) DC-link voltage, (b) modulation indexes, and (c) phase RMS voltages at PCC

4. CONCLUSION

This paper focuses on hybrid microgrids powered by sustainable energy sources like solar PV and PMSG-driven wind energy systems. Due to the unpredictable nature of wind power and solar power, energy storage devices such as small batteries, fuel cells, and electrolyzers are integrated for power balance. A Takagi Sugeno Kang (TSK) fuzzy-based energy management system is used to improve power quality and reliability. The system includes MPPT for PV and wind, TSK-fuzzy controllers for fast responses, and a coordinated energy management strategy.

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The authors declare that no funding was received for this work.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Moazzam Haidari	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Vivek Kumar		✓	✓			✓	✓	✓	✓	✓	✓	✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

This study did not generate or analyze any new data; therefore, data availability is not applicable.

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