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Comparison of acrylic and zinc blade materials on the performance of Darrieus vertical axis wind turbine

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ABSTRACT

The performance of vertical axis wind turbine is strongly influenced by blade characteristics, yet the effect of blade material on turbine performance remains relatively underexplored, particularly for small scale Darrieus type turbines. This study experimentally investigated the influence of acrylic and zinc blade materials on the aerodynamics and energy conversion performance of a three bladed Darrieus vertical axis wind Turbine. A laboratory-scale experimental setup was employed to evaluated turbine rotational speed, torque, and electrical power under a controlled wind speed of 4.3 m/s. The results demonstrate the blade material significantly affects the turbine's ability to extract and convert wind energy. The acrylic blade turbine achieved a power coefficient (C_p) of 0.293 and an overall conversion efficiency 62.81%, compared with 0.208 and 47.11%, respectively, for the zinc bladed turbine. The acrylic configuration therefore provided approximately 25% higher overall performance than zinc configuration. These findings experimentally validate the importance of blade material selection in the design of small scale Darrieus wind turbines and indicate that acrylic can provide a more effective alternative to zinc for improving wind energy conversion under low speed operating conditions. The results provide practical guidance for material selection in the development of lightweight, low speed vertical axis turbines for decentralized and small scale renewable energy applications.

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1. INTRODUCTION

The continuous growth of population and industrial activity has resulted in increasing global electricity demand and has accelerated the transition toward cleaner and more sustainable energy sources [1]-[3]. Fossil fuels remain a major component of the global energy mix and are associated with greenhouse gas emissions and air pollution [1], [4]. Consequently, renewable energy technologies have received increasing attention, with wind energy representing a promising option because of its availability, technological maturity, and potential for decentralized electricity generation [2], [5], [6].

For urban and campus environments, wind resources are generally characterized by relatively low wind speed and frequently changing wind directions. These conditions make vertical axis wind turbines (VAWTs) attractive because they can accept wind from multiple directions and can be installed in location where conventional horizontal axis wind turbines (HAWTs) may be less practical [5]-[7]. Among VAWT configurations, the Darrieus turbine is widely investigated because its lift based operating principle and curved blade configuration can provide relatively high aerodynamic performance compared with drag based turbines such as Savonius Type, [5], [6], [8]-[13]. However, Darrieus turbine performance is highly independent on design and operating parameters including airfoil shape, blade number, pitch angle, and blade structural characteristics [8], [14]-[17].

Previous studies have primarily investigated Darrieus turbine performance through blade geometry optimization, computational fluid dynamics (CFD), aerodynamic modeling, and structure analysis [8], [14]-[17]. These studies have provided valuable insight into the effects of airfoil configuration, blade shape, and operating conditions on aerodynamic performance. However, comparatively less attention has been given to the experimental effect of blade material on the actual energy conversion performance of the small scale Derrius turbines. In particular, many investigations concerning materials properties have relied on numerical or theoretical approaches, while experimental comparison between materials with substantially different density and stiffness under identical operating conditions remain limited. This creates an important research gap because blade material does not merely determine structural strength, it also influences rotor mass, rotational inertia, starting characteristics, vibration, and consequently the turbine's ability to extract energy under low-speed conditions [14], [15], [18]-[23].

To address this gap, the present study experimentally compares two blade materials, acrylic and zinc, while maintaining the same aerodynamic configuration. Acrylic has substantially lower density than zinc, whereas zinc provides considerably higher stiffness. These contracting properties provide a suitable basis for experimentally evaluating how the mass and mechanical characteristics the blade influence turbine performance. Both blade types where fabricated using the same symmetrical NCA 0018 airfoil profile so that differences could be primarily attributed to blade material [8], [11], [10]. This experimental design provides a more direct comparison than simulation-based studies because the influence of material properties is evaluated through the actual mechanical and electrical response of the turbine.

The objective of this study is therefore to experimentally quantify the effect of blade material on the performance of a three Darrieus VAWT operating under low-speed wind conditions. The investigation evaluates rotational speed, torque, electrical output power, power coefficient (*Cp*), and overall energy conversion efficiency. Experiments were performed at a controlled wind speed 4.3 m/s, with a blade pitch angle of 32° and measurement distance of 10 cm from the airflow source. Each configuration was tested three times to improve measurement consistency and reduce the influence of airflow fluctuations and experimental uncertainty [15], [24]-[28].

The contribution of the study is the experimental validation of the role of blade material in the performance of small-scale Darrieus VAWT under low wind speed conditions. By comparing acrylic and zinc blades with identical aerodynamic geometry and operating conditions, the study distinguishes the influence of material related characteristics from that of blade geometry. The results are expected to provide an experimental basis for future development of lightweight composite blades with improved stiffness to mass ratios and potentially enhanced energy conversion performance [13], [15], [20], [29].

2. METHOD

This study employs an experimental laboratory-based approach to investigate the influence of blade material on the performance of a Darrieus-type vertical axis wind turbine (VAWT) under low wind speed conditions. The wind turbine employed in this study is a Darrieus-type vertical axis wind turbine (VAWT) with a three-bladed symmetrical configuration using a NACA 0018 airfoil profile [1], [15], [21]. This configuration was selected due to its capability to operate at relatively low wind speeds, provide acceptable starting torque characteristics, and achieve satisfactory efficiency for small-scale energy applications [2], [6], [7].

The rotor consists of three identical blades mounted symmetrically around a vertical shaft to ensure balanced rotation and uniform aerodynamic performance during operation. The three-blade configuration is designed to provide stable rotational motion while maintaining consistent aerodynamic loading across the rotor. The detailed turbine geometry and design parameters are summarized in Table 1, while the schematic diagram of the system is presented in Figures 1 and 2.

The experimental investigation was conducted under controlled laboratory conditions using an axial fan as an artificial wind source. The fan was positioned at a fixed distance of 10 cm from the turbine rotor to generate a uniform airflow with a constant wind speed of 4.3 m/s [24], [26]. The blade pitch angle was maintained at 32°, and the turbine shaft was mechanically coupled to an AC generator with a rated output voltage range of 12 V–220 V through a pulley transmission system [12], [15]. This laboratory-scale approach ensures stable airflow conditions and high repeatability of measurements [19], [26], [30], [31].

Table 1. Turbine and experimental parameters

Parameter	Symbol	Acrylic	Zinc	Unit
Material weight		0.138	0.140	kg
Average torque	T	0.2	0.16	N-m
Rotation speed	N	45	40	rpm
Wind speed	V	4.3	4.3	m/s
Turbine radius	R	0.145	0.145	m
Turbine Blade Wide	D	0.18	0.18	m
Turbine blade height (diameter)	H	0.31	0.31	m
Number of blades	n	3	3	-
Blade pitch angle	θ	32	32	°
Air density	ρ	1.225	1.225	kg/m^3
Generator output power (rated)	P_{gen_1}	4.4	3.3	W
Turbine pulley diameter	D_1	8	8	cm
Generator pulley diameter	D_2	5	5	cm

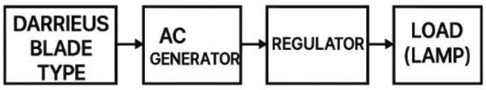

Figure 1. Flowchart of the wind turbine prototype design scheme

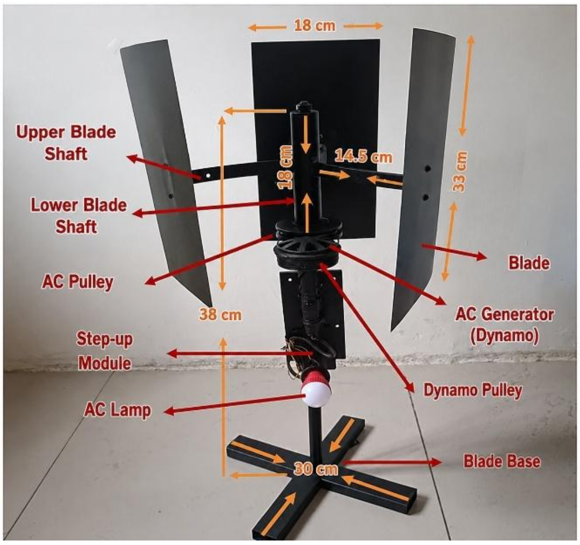

Figure 2. PLTB prototype design

Two different blade materials were used in this study, namely acrylic and zinc, to evaluate the influence of material properties on turbine performance. The physical properties of the materials are as follows: Acrylic: density of 1.18 g/cm^3 and elastic modulus of 3.2 GPa and Zinc: density of 7.14 g/cm^3 and elastic modulus of 108 GPa [15], [18]. Both blade types were fabricated with identical dimensions and the same NACA 0018 airfoil geometry to ensure that any differences in performance are solely attributed to the material characteristics [15], [18]. The prototypes of both blade configurations are illustrated in Figure 3.

The experiment was conducted under controlled laboratory conditions. An axial fan was positioned at a fixed distance of 10 cm from the turbine to generate a constant wind speed of 4.3 m/s. The turbine shaft was connected to an AC generator using a pulley transmission system. The experimental steps are as follows: i) The turbine was placed facing the airflow source; ii) The fan was operated to produce a constant wind speed of 4.3 m/s; iii) The turbine rotation drove the generator via the pulley system; iv) Rotational speed, torque, and electrical output power was measured; v) Each experiment was repeated three times under identical conditions; vi) The results were averaged to reduce random measurement errors and improve accuracy.

(a)

(b)

Figure 3. PLTB Prototype: (a) zinc material type and (b) acrylic material type

This procedure ensures high repeatability and reliability of the experimental data. The experimental procedure was carried out as follows: i) The turbine was placed at a fixed position facing the axial fan; ii) The fan was operated to produce a constant wind speed of 4.3 m/s; iii) The turbine rotation drove the generator via a pulley system; iv) Key parameters such as rotational speed, torque, and electrical output were measured; v) Each experiment was repeated three times under identical conditions; and iv) The results were averaged to improve data accuracy and minimize random errors. For each test condition, experiments were repeated three times, and the measured values were averaged to obtain representative performance data and reduce the likelihood of random measurement errors [5], [27], [19].

i) Wind power: The performance of the turbine was evaluated using (1), where ρ is the air density (1.225 kg/m³), A is the swept area of the turbine ($D \times H$), and V is the wind velocity (m/s).

$$P_{wind} = 0.5\,\rho A V^3 \quad (1)$$

ii) Mechanical power: The mechanical power generated by the turbine is defined as (2), where T is the torque (N·m), and ω is the angular velocity (rad/s), expressed as (3).

$$P_{mech} = T \times \omega \quad (2)$$

$$\omega = \frac{2\,\pi N}{60} \quad (3)$$

iii) Power coefficient: The C_p, which represents the efficiency of energy conversion from wind to mechanical power, is given by (4).

$$C_p = \frac{P_{mek}}{0.5\rho A V^3} \quad (4)$$

iv) Mechanical efficiency

The mechanical efficiency of the turbine is calculated as (5).

$$\eta_{mech} = \frac{P_{mech}}{P_{wind}} \times 100\% \quad (5)$$

v) Overall system efficiency

The overall efficiency, including generator performance, is expressed as (6).

$$\eta_{tot} = \frac{P_{gen\_2}}{P_{wind}} \times 100\% \quad (6)$$

vi) Generator power with pulley ratio: The generator power from the turbine side is influenced by the pulley ratio and is calculated as (7), where $D1$ and D2 represent the diameters of the turbine and generator pulleys, respectively. The pulley ratio plays a significant role in determining the rotational speed and torque transmitted to the generator.

$$P_{gen\_2} = P_{gen\_1} \times \frac{D_1}{D_2} \quad (7)$$

vii) Tip speed ratio: The tip speed ratio (TSR) is defined as (8), where R is the turbine radius and V is the wind speed.

$$\lambda = \frac{\omega \cdot R}{V} \tag{8}$$

The validation of results was carried out by repeating each experiment three times and averaging the measured values to reduce uncertainty and minimize random errors. The turbine performance was then evaluated by comparing key performance indicators, including mechanical power, C_p, efficiency (η), and TSR. This approach ensures data consistency, improves measurement reliability, and enables an accurate and objective comparison between the performance of acrylic and zinc blade materials.

3. RESULTS AND DISCUSSION

The experimental results indicate that zinc turbine blades are slightly heavier than acrylic blades by approximately 1.4%, which influences rotational inertia and start-up behaviour. The measured torque for the acrylic turbine is 0.20 N·m, while the zinc turbine produces 0.16 N·m. Similarly, the rotational speed reaches 45 rpm for acrylic and 40 rpm for zinc, corresponding to angular velocities of approximately 4.71 rad/s and 4.19 rad/s, respectively. Based on these values, the mechanical power generated by the acrylic turbine is approximately 0.94 W, whereas the zinc turbine produces about 0.67 W, representing an increase of around 40.3%.

Using a swept area of A=0.0558 m^2 and a wind speed of 4.3 m/s, the available wind power is calculated to be approximately 2.77 W. The corresponding Cp is approximately 0.293 for acrylic and 0.208 for zinc. The TSR is calculated as 0.16 for acrylic and 0.14 for zinc. In terms of efficiency, the mechanical efficiency of the acrylic turbine is approximately 34%, compared to 24% for zinc. The overall system efficiency reaches 45.8% for acrylic and 34.4% for zinc, indicating a significant improvement in electrical output performance. A comparison of these parameters is illustrated in Figure 4.

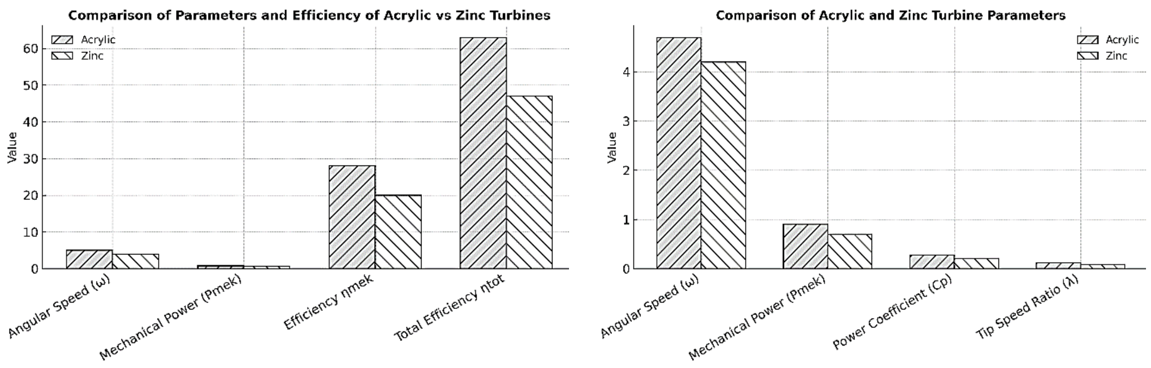

Figure 4. Comparison of parameters and efficiency of acrylic vs zinc turbines

The results clearly demonstrate that blade material has a significant influence on turbine performance under low wind speed conditions. The lighter acrylic blades exhibit lower rotational inertia, enabling improved self-starting capability and faster dynamic response. This leads to higher rotational speed and torque simultaneously, which directly increases mechanical power output.

From an aerodynamic perspective, the higher Cp and TSR observed in the acrylic turbine indicate more effective energy extraction from the airflow. In Darrieus turbines, the continuously varying angle of attack causes fluctuations in lift and drag forces throughout the rotation cycle see in Figure 5. The acrylic blades, due to their lower mass and adequate stiffness, respond more effectively to these dynamic aerodynamic forces, resulting in smoother acceleration and more stable operation. Since all experimental parameters such as wind speed, blade geometry, and pitch angle were kept constant, the observed performance differences can be attributed primarily to material properties.

The wind movement mechanism illustrated in Figure 6 further explains this behaviour. The variation of the angle of attack at different blade positions leads to fluctuating aerodynamic forces, which are better accommodated by lighter blades. This explains why the acrylic turbine achieves higher efficiency despite similar geometric conditions.

The wind movement mechanism that moves toward the Darius turbine is shown in Figure 6. The black circle and dashed line indicate the path of the turbine blade tip as it rotates around a vertical axis with a turbine radius of 0.145 m. The blade's azimuth angle differs by 120 degrees. The airfoil chord direction of the blade is shown in blue, including the effect of a 32-degree pitch angle, making the blade appear slightly tilted. Aerodynamic forces such as lift, drag, and resultant are marked on the outer tips of the blades. The wind direction and speed hitting the turbine are 4.3 m/s from left to right, indicated by the top and bottom dashed lines. The direction and relative wind speed are indicated by the red arrows at each blade tip, explaining where the relative wind is coming from. The angle of attack experienced by each blade relative to the relative wind is -20.5, -337.3, and -456 degrees, with negative values indicating the direction of attack opposite the blade chord orientation. Each blade exhibits a different direction of attack depending on its rotational position. The changing angle of attack throughout the rotation causes the lift and drag forces on the blades to change accordingly. This phenomenon explains why the Darrieus turbine produces fluctuating torque but remains able to rotate efficiently after reaching a certain initial speed.

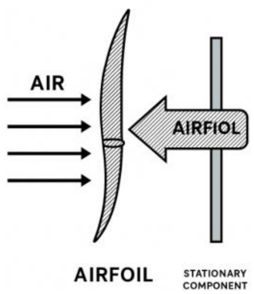

Figure 5. Aerodynamic drag

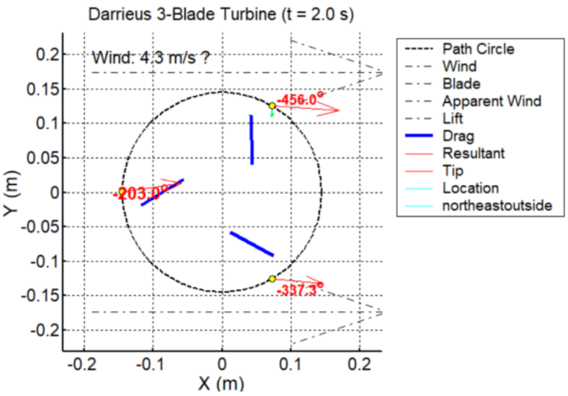

Figure 6. Wind movement mechanism

The obtained results are consistent with previous studies on Darrieus turbines, which report Cp values in the range of 0.25–0.46 and efficiencies of 30–50%, depending on turbine design, blade geometry, and operating conditions. The performance of the acrylic turbine falls within the lower range of these reported values and slightly exceeds the lower bound under certain operating conditions, particularly at low wind speeds. This result indicates that, despite the relatively simple acrylic blade construction, the proposed turbine can achieve a comparable level of aerodynamic performance and demonstrates potential for small-scale wind energy applications.

Most prior research has focused on aerodynamic optimization, such as airfoil shape, blade configuration, and pitch angle control, often using computational fluid dynamics (CFD) approaches. In contrast, experimental investigations on blade material effects remain limited. This study extends the current state of the art by providing direct experimental validation of how material properties influence turbine performance. The results confirm that, beyond geometry and aerodynamics, material selection plays a crucial role in determining efficiency and energy conversion capability see in Table 2.

The findings of this study have important implications for the design and development of small-scale wind energy systems. From a practical perspective, the use of lightweight materials such as acrylic can significantly improve turbine performance in low wind speed environments, making it suitable for urban and campus applications. From a technological standpoint, this study highlights that optimizing blade material is as important as aerodynamic design in achieving high efficiency.

These results suggest that future developments should focus on the application of advanced lightweight composite materials with improved stiffness-to-mass ratios to further enhance turbine performance. Such materials could reduce the structural mass of the blades while maintaining sufficient mechanical strength and rigidity under aerodynamic loading. In addition, integrating optimized blade materials with advanced control strategies could improve the turbine's ability to operate efficiently under varying wind conditions. The combination of material optimization, intelligent control, and hybrid energy systems may therefore provide a pathway toward more efficient, reliable, and sustainable renewable energy solutions.

Table 2. Comparison of previous research on the Darrieus vertical-axis wind turbine

No	Author	Turbine type/blade material	Wind speed (m/s)	Power coefficient (C_p	Efficiency (%)	Main results
1	Islam *et al.* [1]	Straight-bladed Darrieus/Aluminum	4–12	0.30–0.40	35–45	Developed aerodynamic models improving prediction accuracy of Darrieus turbine performance
2	Ackermann & Söder [2]	Darrieus VAWT (general review)	3–15	≤0.40	30–45	Comprehensive overview of wind energy technologies including VAWT potential
3	Pope *et al.* [5]	Darrieus vs HAWT/Composite	5–10	0.25–0.38	30–42	VAWTs show lower C_p than HAWTs but higher suitability for urban use
4	Bedon *et al.* [8]	H-Darrieus/Optimized Airfoil	6–12	0.42	48	Airfoil optimization significantly enhances Darrieus turbine performance
5	A. Bhutta *et al.* [6]	Darrieus & Hybrid VAWT/Various	3–10	0.20–0.40	25–45	Reviewed configurations and design techniques for efficiency improvement
6	Howell *et al.* [7]	Small-scale Darrieus/Aluminum	4–9	0.30	35	Wind tunnel and CFD results show strong correlation at low Reynolds number
7	Burton *et al.* [31]	H-Darrieus/Composite	5–15	≤0.40	40–45	Handbook reference detailing aerodynamic theory and performance limits
8	Das *et al.* [11]	Darrieus Mathematical Model	5–12	0.35	–	Simple analytical model accurately predicts power characteristics
9	Fiedler and Tullis [14]	High-solidity Darrieus/Aluminum	6–10	0.28–0.34	32–38	Blade offset and pitch significantly affect starting torque and C_p
10	Bianchini *et al.* [13]	H-Darrieu/Composite	4–11	0.40–0.45	45–50	Design optimization improves annual energy yield
11	Mohamed [30]	H-Rotor Darrieus/New Airfoils	6–12	0.46	50	Novel airfoil shapes outperform conventional NACA profiles
12	Yang *et al.* [16]	Straight-bladed Darrieus/Aluminum	5–10	0.38–0.42	44	Optimal pitch angle increases torque and C_p
13	Elkhoury *et al.* [19]	Variable-pitch Darrieus/Composite	6–12	0.45	48	Variable pitch significantly enhances performance under unsteady wind
14	Alnaimi *et al.* [24]	Hybrid Solar–Darrieus/Aluminum	3–9	0.35–0.40	40–45	Integrated hybrid system effective for residential power generation
15	Khammas & Nabil [21]	Darrieus–Savonius Hybrid/Composite	3–8	0.42	47	Combined rotor improves self-starting and overall efficiency

4. CONCLUSION

In this work, an experimental investigation was conducted to evaluate the effect of blade material on the performance of a Darrieus-type vertical axis wind turbine under low wind speed conditions by implementing and testing two materials, acrylic and zinc, using identical NACA 0018 blade geometry under controlled laboratory conditions. The results demonstrate that blade material significantly influences turbine performance, where acrylic blades achieved a higher maximum C_p of 0.293 and total efficiency of 62.81% at a wind speed of 4.3 m/s, along with better self-starting capability and rotational stability, while zinc blades, despite producing higher peak torque, showed lower aerodynamic efficiency with a maximum C_p of 0.208 and efficiency of 47.11%, indicating that acrylic provides approximately 25% better performance in converting wind energy into electrical power. These findings provide important experimental evidence addressing the existing research gap, where most previous studies emphasize blade geometry and numerical simulations rather than direct material validation, confirming that lightweight materials with favorable surface characteristics enhance turbine responsiveness and energy conversion efficiency. However, this study is limited to laboratory-scale testing at a fixed wind speed and a single blade configuration, and does not consider long-term structural effects or real environmental conditions. Therefore, future work should investigate a wider range of advanced composite materials with improved stiffness-to-mass ratios, evaluate performance under varying wind conditions and real outdoor environments, and integrate material optimization with aerodynamic design and smart monitoring systems to further enhance the efficiency and applicability of small-scale wind energy systems.

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AUTHOR CONTRIBUTIONS STATEMENT

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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

The data that support the findings of this study are available on request from the corresponding author, [DM]. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

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