Comparative Study of Blade Material Selection for Hybrid Wind-Water Turbine Applications

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Abstract
Hybrid wind–water turbines represent an emerging solution to enhance renewable energy capture across diverse environmental conditions. A key determinant of their efficiency and longevity is the selection of suitable blade materials capable of withstanding both aerodynamic and hydrodynamic forces, as well as environmental stressors such as salinity, moisture, and ultraviolet (UV) exposure. This study presents a comparative evaluation of five candidate materials such as glass fiber-reinforced polymer (GFRP), carbon fiber-reinforced polymer (CFRP), aluminum alloy (6061-T6), stainless steel (316L), and natural fiber composites for hybrid turbine blade applications. The assessment draws upon published mechanical and environmental data to evaluate each material in terms of tensile strength, corrosion resistance, weight, cost, manufacturability, and sustainability. CFRP demonstrates the highest mechanical strength, whereas GFRP offers an optimal balance of performance and cost-effectiveness. Natural fiber composites show strong sustainability potential but limited mechanical reliability. Metallic options provide robustness yet face constraints in weight and corrosion management. No single material proves universally superior; the optimal choice depends on contextual design and operational requirements. GFRP is recommended for general-purpose applications due to its practical balance, while CFRP remains ideal for high-performance conditions. This comparative framework provides a reference for future experimental validation and supports material selection strategies for next-generation hybrid renewable energy systems.

Keywords: Blade material selection; Composite materials; Corrosion resistance; Hybrid wind-water turbine; Sustainable energy systems.

1.0 Introduction
The global pursuit of sustainable energy has intensified research into hybrid renewable systems. Among them, hybrid wind–water turbines have gained attention for their ability to maintain continuous power output by harnessing both wind and water flows. Such systems are particularly advantageous in coastal and riverine regions where dual resources coexist (Katare et al., 2024; Testi et al., 2024; Hossain et al., 2019).

However, hybrid operation presents unique material challenges. Turbine blades must endure alternating aerodynamic and hydrodynamic loads as well as harsh environmental factors such as salinity, humidity, UV radiation, and biofouling all of which can accelerate degradation (Olabi et al., 2021; Safaei & Almalki, 2024). Selecting an appropriate blade material thus becomes critical to ensure durability, efficiency, and cost-effectiveness. The ideal material must balance strength, fatigue resistance, corrosion tolerance, weight, and sustainability (Torres-Madroñero & Alvarez-Montoya, 2020).

Existing studies often focus on either wind or hydro turbines independently, with limited research addressing hybrid configurations where simultaneous air–water exposure occurs. Composite materials like GFRP and CFRP offer excellent strength-to-weight ratios and fatigue resistance (Mohammed & Naik, 2022; Garmode et al., 2022), while metallic options such as stainless steel and aluminum alloys provide high structural integrity and corrosion resistance (Charabi & Abdul-Wahab, 2020). Nonetheless, neither category alone fully satisfies the requirements of hybrid turbine environments (Alam & Iqbal, 2009; Jin et al., 2024).

This study addresses that gap by performing a comparative evaluation of five potential blade materials GFRP, CFRP, aluminum alloy (6061-T6), stainless steel (316L), and natural fiber composites. Each material is assessed against mechanical, environmental, economic, and sustainability criteria to establish a reference for hybrid turbine design. The results aim to guide future experimental validation and optimization in hybrid renewable energy applications.

2.0 Methodology

This study employs a structured comparative review methodology to evaluate potential blade materials for hybrid wind–water turbine applications. The approach is literature-based and qualitative, relying on peer-reviewed journals, technical reports, and engineering standards from reputable databases such as ScienceDirect, Scopus, IEEE Xplore, and Web of Science. Studies from the last 10–15 years were prioritized to ensure relevance to current material technologies and fabrication methods (Olabi et al., 2021; Mohammed & Naik, 2022; Safaei & Almalki, 2024; Cruz & Alves, 2017).

Figure 1 illustrates the comparative evaluation process used to assess candidate materials. The workflow begins by defining key evaluation criteria—mechanical performance, corrosion resistance, weight, manufacturability, cost, and sustainability. Candidate materials are then identified based on their suitability for turbine blades in both wind and hydro environments. Comparative analysis follows, drawing from literature data and engineering standards to examine material performance under hybrid exposure. The process concludes with selecting the most appropriate material according to technical and operational feasibility. This structured approach ensures consistency, objectivity, and application-oriented evaluation.

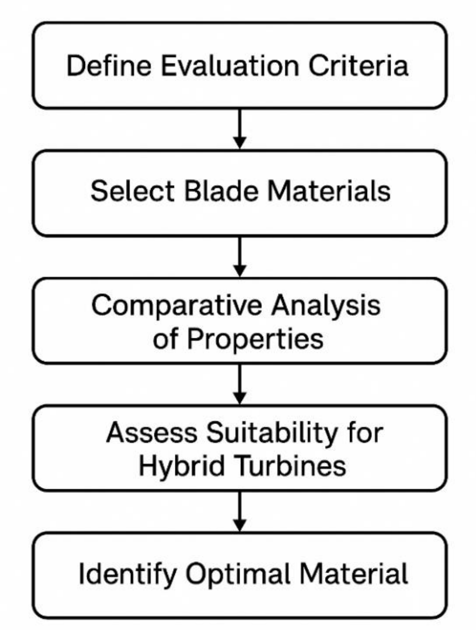

Figure 1: Comparative Evaluation Process

2.1 Material Selection Criteria

To achieve a comprehensive comparison, five primary selection criteria were established based on the functional and environmental demands of hybrid turbine operation:

i. Mechanical Performance: Tensile strength, fatigue resistance, Young's modulus, and impact behavior were prioritized to account for dynamic and alternating loads in wind–water environments (Torres-Madroñero & Alvarez-Montoya, 2020; Garmode et al., 2022).
ii. Corrosion and Environmental Resistance: Resistance to moisture, salinity, UV degradation, and temperature variation was considered crucial for hybrid exposure (Charabi & Abdul-Wahab, 2020; Jin et al., 2024).
iii. Density and Weight: Low-density materials reduce inertial loads and improve energy conversion efficiency, particularly in large-scale blades (Suresh et al., 2024; Asadbeigi et al., 2023).
iv. Manufacturability and Cost: Fabrication ease, availability, repairability, and material cost were evaluated for scalability and economic feasibility (Mohammed & Naik, 2022; Lakshmanan, 2022).
v. Sustainability and End-of-Life Considerations: Recyclability, embodied energy, and environmental impact were reviewed in alignment with global sustainability objectives (Algayal, 2025; Safaei & Almalki, 2024).

2.2 Candidate Materials Reviewed

Five representative materials—both conventional and emerging—were selected for detailed analysis based on their relevance to turbine blade design:

i. Glass Fiber–Reinforced Polymer (GFRP): Offers strong mechanical performance and cost efficiency (Garmode et al., 2022).
ii. Carbon Fiber–Reinforced Polymer (CFRP): Provides exceptional strength-to-weight ratio but at higher cost (Mohammed & Naik, 2022).

iii. Aluminum Alloy (6061-T6): Known for machinability and moderate corrosion resistance in non-saline environments (Charabi & Abdul-Wahab, 2020).
iv. Stainless Steel (316L): Exhibits superior corrosion resistance and structural integrity but with a significant weight penalty (Mehroliya et al., 2021).
v. Natural Fiber Composites (e.g., flax/bio-resin): A sustainable alternative offering biodegradability but limited mechanical robustness (Suresh et al., 2024).

2.3 Data Compilation and Analysis

Data compilation followed a systematic process to ensure transparency and reliability. An initial pool of approximately 140 relevant publications and technical references was identified across major databases. These were filtered by publication year, experimental quality, and direct relevance to turbine blade performance, resulting in 36 core studies forming the analytical foundation. Table 1 summarizes the data acquisition process, showing the database sources, coverage periods, and the number of studies retained after filtering.

Table 1: Data Acquisition Sources and Filtering

Source Database / Reference Type	Years Covered	Initial Papers Collected	Papers Included After Filtering	Example References
ScienceDirect	2010 – 2025	45	12	(Olabi et al., 2021; Mohammed & Naik, 2022)
IEEE Xplore	2010 – 2025	20	5	(Mehroliya et al., 2021)
Scopus	2010 – 2025	35	8	(Suresh et al., 2024)
Web of Science	2010 – 2025	30	7	(Torres-Madroñero & Alvarez-Montoya, 2020)
Standards / Handbooks	N/A	10	4	(ASTM D3039; ISO 527; Callister & Rethwisch, 2020; Strong, 2008)

The filtering process ensured that only high-quality, recent studies were incorporated. Figure 2 schematically illustrates the data acquisition flow, showing progression from broad literature collection to final inclusion for comparative assessment. By integrating consistent mechanical, environmental, and cost data from these validated sources, a robust comparative matrix was developed to evaluate the performance of GFRP, CFRP, aluminum alloy 6061-T6, stainless steel 316L, and natural fiber composites under hybrid wind–water conditions.

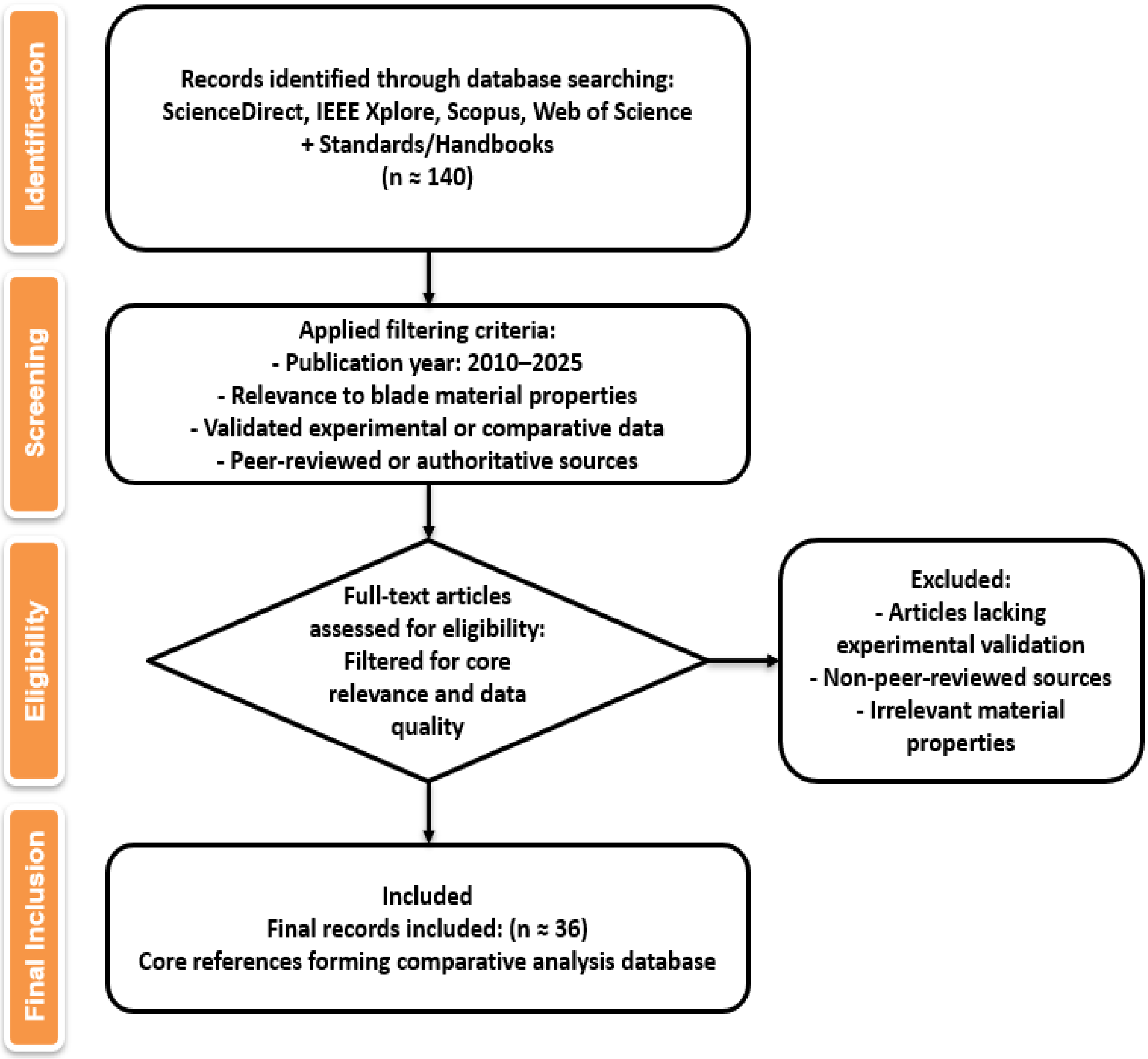

Figure 2: Data Acquisition Flow for Blade Material Review

3.0 Results and Discussion

The performance of hybrid wind–water turbine blades depends on the interplay between mechanical strength, corrosion resistance, manufacturability, cost, and sustainability. Five candidate materials—GFRP, CFRP, aluminum alloy (6061-T6), stainless steel (316L), and natural fiber composites—were evaluated using literature data and engineering standards. CFRP demonstrates the highest tensile strength and fatigue resistance, while GFRP offers a balanced combination of cost-effectiveness and manufacturability. Metallic materials provide structural robustness but are penalized by high density and corrosion issues. Natural fiber composites excel in sustainability but remain limited by low strength and moisture sensitivity.

Table 2: Comparative Properties of Candidate Blade Materials

Property	GFRP	CFRP	Aluminum Alloy (6061-T6)	Stainless Steel (316L)	Natural Fiber Composite (Flax/Bio-resin)
Density (g/cm³)	1.8–2.0	1.6–1.9	2.7	7.9	1.2–1.5
Tensile Strength (MPa)	350–600	600–1200	290–320	485	100–200
Young's Modulus (GPa)	20–35	70–150	69	193	10–25
Fatigue Resistance	Moderate	High	Moderate	High	Low - Moderate
Corrosion Resistance	Good	Good	Fair	Excellent	Good (depends on resin)
UV/Weather Resistance	Moderate (needs coating)	Good	Moderate	Excellent	Low - Moderate
Cost (relative)	Low	High	Moderate	High	Low
Ease of Manufacturing	High	Moderate	High	Moderate	Moderate (varies by resin)
Recyclability / Sustainability	Low (limited recycling)	Low	High	Moderate	High
Suitability for Hybrid Environments	Good	Very Good	Moderate	Good	Fair

As shown in Figure 3, which illustrates the comparative performance of materials across key criteria, CFRP leads in mechanical performance, GFRP demonstrates balanced overall efficiency, and natural fibers perform best environmentally. GFRP thus emerges as the most practical choice for hybrid applications, while CFRP suits high-performance environments and natural fibers offer future sustainability potential.

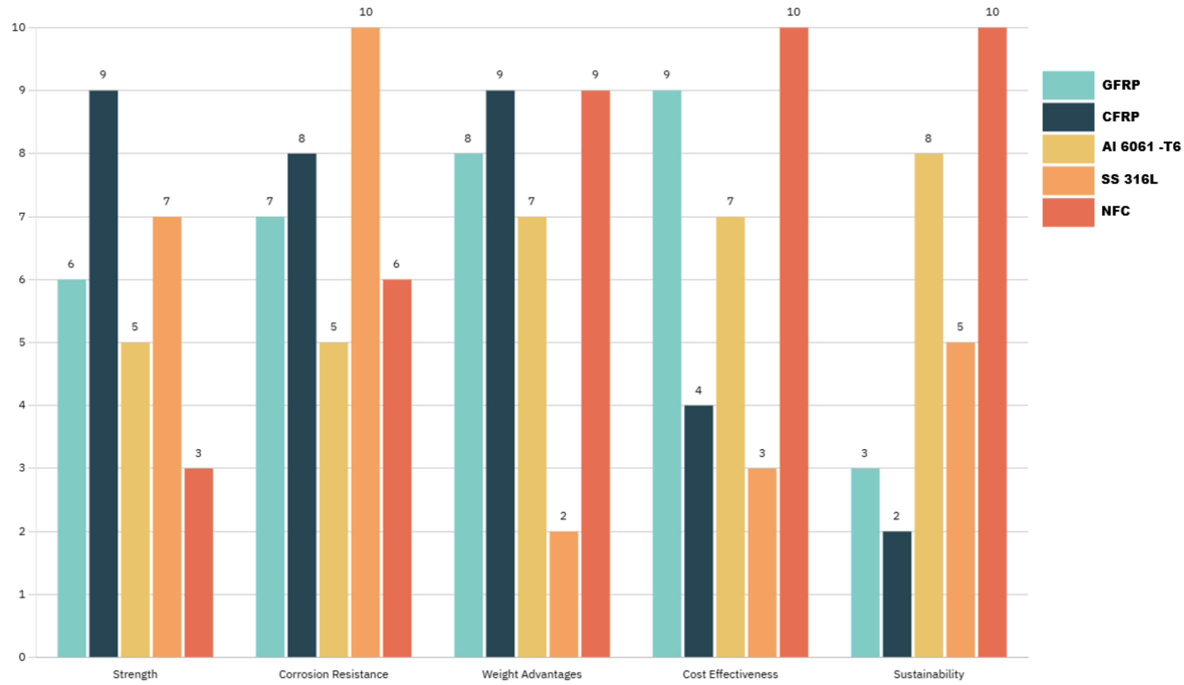

Figure 3: Comparative Evaluation of Blade Materials

3.1 Mechanical Performance

CFRP demonstrates the highest tensile strength (up to 1200 MPa) and stiffness (≈150 GPa), making it ideal for high-load, fatigue-prone hybrid turbines (Mohammed & Naik, 2022). However, its high cost and demanding fabrication limit widespread use. GFRP provides a balanced alternative with tensile strengths of 350–600 MPa, offering reliable fatigue performance, ease of manufacture, and low cost—factors that have driven its adoption in wind and marine systems (Garmode et al., 2022).

Aluminum alloy (6061-T6) combines moderate strength and machinability but requires protective coatings in saline environments. Stainless steel (316L) offers high strength and corrosion resistance yet is hindered by excessive density, which reduces turbine responsiveness. Natural fiber composites, though lightweight and biodegradable, remain limited by low fatigue endurance and moisture sensitivity. Overall, CFRP excels in mechanical performance, GFRP achieves the best practical balance, and metallic or natural alternatives serve niche or sustainability-focused applications.

3.2 Environmental Resistance

Environmental durability is essential for hybrid turbine blades operating in both air and water. Materials must resist corrosion, UV degradation, temperature fluctuation, and biofouling. Table 3 summarizes the relative performance of five candidate materials based on literature and engineering standards (1–10 rating scale).

Table 3: Environmental Resistance Ratings for Hybrid Blade Materials

Material	Salinity	Moisture	UV	Thermal	Hydrolysis	Biofouling	Total
Stainless Steel (316L)	10	9	9	9	10	9	56
CFRP	8	7	8	9	8	7	47
GFRP	7	6	6	7	6	6	38
Aluminum (6061-T6)	5	8	6	7	9	7	42
Natural Fiber (Flax/Bio-resin)	6	3	4	5	3	4	25

Stainless steel (316L) demonstrates the highest overall resistance, making it ideal for marine exposure. CFRP also performs strongly, offering good UV and thermal stability with moderate moisture tolerance. Aluminum provides acceptable performance in non-saline conditions but corrodes under chloride exposure. GFRP offers balanced yet moderate protection, requiring coatings for long-term use. Natural fiber composites, despite being sustainable, remain vulnerable to moisture and UV degradation unless treated. Overall, stainless steel and CFRP are best suited for durability, GFRP offers a cost-effective middle ground, and natural fibers require further development for hybrid environments.

3.3 Cost and Manufacturability

Cost and manufacturability play crucial roles in selecting suitable materials for hybrid turbine blades. As shown in Table 4, GFRP remains the most cost-effective and easily fabricated option due to mature processing methods and good repairability, making it ideal for large-scale production. CFRP, while offering superior strength and fatigue performance, is limited by its high cost and complex curing requirements. Aluminum alloy (6061-T6) provides a favorable balance between cost and manufacturability but needs surface treatment in saline environments. Stainless steel (316L) ensures durability and corrosion resistance but is heavy and expensive to machine, making it more suitable for structural supports. Natural fiber composites are the most sustainable and affordable, though their variability and limited repairability hinder industrial scalability. Overall, GFRP offers the best trade-off between cost, fabrication ease, and reliability, while CFRP and aluminum serve specialized performance-oriented applications.

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Table 4: Cost and Manufacturability Indicators of Candidate Materials

Material	Cost	Manufacturability	Repairability	Notes
GFRP	Low	High	High	Widely available, easy fabrication
CFRP	High	Moderate	Moderate	Requires advanced curing technology
Aluminum 6061-T6	Moderate	High	High	Easily machinable, coating required
Stainless Steel 316L	High	Moderate	Moderate	Durable but heavy and costly to shape
Natural Fiber Composites	Low	Moderate	Low	Sustainable, variable quality

3.4 Sustainability and Lifecycle Considerations

Sustainability is a key factor in hybrid turbine material selection, influencing environmental impact and long-term feasibility. Table 5 summarizes the recyclability, carbon footprint, and end-of-life handling of the five candidate materials. Natural fiber composites rank highest in sustainability with low embodied carbon and biodegradability, making them ideal for small or modular systems. Aluminum and stainless steel also perform well, offering high recyclability and long service life despite higher production energy demands. In contrast, GFRP and CFRP exhibit poor recyclability due to thermoset resin matrices, leading to landfill disposal or energy-intensive recycling processes.

Table 5: Sustainability and Lifecycle Indicators of Candidate Blade Materials

Material	Recyclability	Carbon Footprint (kg CO_2/kg)	End-of-Life Handling	Overall Rating
GFRP	Low	20–25	Landfill	★★☆☆☆
CFRP	Low	25–30	Emerging pyrolysis	★★☆☆☆
Aluminum 6061-T6	High	10–12	Closed-loop recycling	★★★★☆
Stainless Steel 316L	High	15–18	Re-melting reuse	★★★☆☆
Natural Fiber Composite	High	5–7	Biodegradable	★★★★★

Overall, natural fiber composites and aluminum demonstrate the strongest sustainability performance, while GFRP and CFRP require improved recycling technologies to align with circular economy principles. As hybrid turbine systems evolve, integrating recyclable or biodegradable materials will be vital for minimizing lifecycle impacts and achieving long-term environmental goals.

3.5 Overall Suitability for Hybrid Turbine Blades

When evaluated across technical, economic, and environmental metrics, CFRP is the optimal choice for high-performance, high-reliability hybrid blades, particularly in harsh offshore or estuarine environments (Mohammed & Naik, 2022). However, its high cost restricts widespread adoption. GFRP provides the most practical solution, balancing performance and affordability, and remains the industry standard in mid-sized wind and marine blades (Garmode et al., 2022). Natural fiber composites offer promise for small-scale or modular hybrid systems where sustainability and cost are prioritized, but further R&D is required to address their durability (Suresh et al., 2024; Algayal, 2025). Aluminum and stainless steel, while strong and reliable, are less suitable for full-scale blade applications without design adaptations due to their mass or corrosion profiles (Charabi & Abdul-Wahab, 2020; Torres-Madroñero & Alvarez-Montoya, 2020). This analysis reinforces the need for context-driven material selection, weighing environmental exposure, lifecycle performance, and cost to guide optimal hybrid blade design.

4.0 Conclusion

This study compared five potential materials—GFRP, CFRP, aluminum alloy (6061-T6), stainless steel (316L), and natural fiber composites—for hybrid wind–water turbine blades using a multi-criteria evaluation of mechanical, environmental, economic, and sustainability factors. CFRP exhibited the highest mechanical and fatigue performance, while GFRP provided the best balance between strength, cost, and manufacturability, making it the most practical choice for general hybrid turbine applications. Metallic materials offered robustness but were limited by density and corrosion challenges, and natural fiber composites, though environmentally superior, require further improvement for structural reliability.

Ultimately, the selection of blade materials should align with operational conditions, environmental exposure, and sustainability objectives. GFRP remains the most viable for broad implementation, with CFRP suited to high-performance environments and natural fibers representing the most promising path toward sustainable innovation. Future research should focus on experimental validation and advanced recycling methods to enhance both material efficiency and environmental compatibility in next-generation hybrid turbines.

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Author Contributions
M.F. Mohd Yunus: Conceptualized The Study, Designed The Comparative Evaluation Framework, Prepared The Initial Manuscript Draft; **S.N.T.M Yasin:** Literature Review, Data Analysis, And Manuscript Refinement; **I.Ismail:** Reviewing and Editing; **R. J. Soriano**:Reviewing.

Conflicts of Interest
The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its Submission and declare no conflict of interest in the manuscript.

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