

# Influence of Wettability Characteristic on Biofouling Resistance of Polytetrafluoroethylene (PTFE) and Polyvinylidene Fluoride (PVDF) Film Embedded on Glass Fiber

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**ABSTRACT**

Biofouling is a persistent issue for marine structures, reducing operational efficiency and increasing maintenance costs. Antifouling coatings prevent the accumulation of fouling organisms by forming physical barriers that inhibit the attachment of microorganisms, contaminants, and particles. However, conventional coatings often face limitations such as environmental degradation, frequent reapplication, and limited durability. This study examines the role of surface wettability in biofouling resistance by comparing polytetrafluoroethylene (PTFE) and polyvinylidene fluoride (PVDF) films embedded with glass fiber (GF) to uncoated GF as a reference system, focusing on the influence of hydrophobic and hydrophilic properties. Contact angle measurements revealed distinct wettability characteristics: PTFE/GF exhibited high hydrophobicity (125.95°), while PVDF/GF (59.4°) and GF (63.1°) were hydrophilic. After 120 days of seawater exposure, PTFE/GF displayed the lowest biofouling growth (35.6%), significantly outperforming PVDF/GF (89.6%) and GF

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(94.7%). PTFE/GF also demonstrated self-cleaning capabilities, with fouling levels decreasing from 57.8% at 60 days to 35.6% at 120 days, emphasizing its durability and efficiency in harsh marine environments. The superior antifouling performance of PTFE/GF is attributed to its hydrophobicity, low surface energy, and the "lotus effect," which repels water and prevents microbial adhesion by allowing water droplets to bead and roll off, carrying away debris. In contrast, the hydrophilic PVDF/GF promotes water spreading, encouraging microbial attachment and biofilm formation, resulting in greater fouling growth. This study highlights the critical role of hydrophobicity in antifouling coatings, demonstrating that materials like PTFE significantly enhance biofouling resistance. These findings provide a foundation for developing durable, efficient antifouling solutions tailored to the challenging conditions of marine environments.

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## INTRODUCTION

Biofouling, the buildup of marine organisms like algae and barnacles on submerged objects, is a widespread problem. Surfaces such as ship hulls, offshore platforms, and underwater pipelines are particularly prone to biofouling [1], leading to decreased efficiency, corrosion, and increased resistance [2]. Biofouling is a complex process that varies significantly depending on the location, involving over 4,000 different types of marine organisms [3]. The four (4) main groups of macro-fouler that most significantly affect marine devices and structures deployed at sea are mussels, bryozoans, calcareous tubeworms, and acorn barnacles. Biofouling growth involves the colonization of macrofouling species, such as macroinvertebrates and macroalgae, along with microfouling organisms like viruses, bacteria, cyanobacteria, fungi, protozoa, and microalgae [3]. Macrofouling includes non-calcareous algae, sponges, anemones, tunicates, hydroids, and calcareous hard-fouling creatures, including acorn barnacles, mussels, and tubeworms [3]. The development of biofouling on submerged surfaces is affected by various factors, including the surface's physicochemical properties [4], chemical composition [5,6], surface roughness [7], porosity [8], hydrophobicity [9], and pH [10]. However, knowledge on how these factors operate in marine environments remains limited.

The growth of biofouling on a surface is influenced by various factors, including the type of surface, the characteristics of the surrounding environment, and the properties of the fouling organisms [11]. The initial stage of biofouling is conditioning, during which organic and inorganic molecules accumulate on the surface, creating a suitable environment for the attachment of fouling organisms [3]. The second stage is attachment, where these fouling organisms adhere to the conditioned surface through various mechanisms, including physical adhesion, chemical bonding, and electrostatic interactions [3,12].

The third stage involves colonization, a complex process typically broken down into four main phases. Although this process is often described as following a linear progression from stage to stage, this "successional" model may oversimplify the development of biofouling communities [3,12]. Contemporary research supports a more dynamic and probabilistic paradigm, where the absence of one stage does not preclude the occurrence of others. For example, certain bryozoan and barnacle species can colonize a surface without the presence of a conditioning biofilm [3]. Consequently, the type and number of unrelated organisms that may adhere to or colonize the substrate are critical factors in the colonization process [3]. Additionally, foulants can form aggregations, such as marine snow, which float in the water column and eventually settle on substrates. Once attached, organisms like invertebrate larvae and algal spores embedded within the marine snow begin to grow [3].

To reduce the adverse effects of biofouling, strategies such as applying antifouling coatings, antibacterial coatings, using biofouling-resistant materials, and performing mechanical cleaning are commonly employed [1,13]. Antifouling coatings are widely used in the marine industry to prevent the growth of marine biofouling, with some coatings designed to release biocidal compounds onto surfaces exposed to seawater [14].

Polymer coatings, particularly those with engineered surface properties, offer a promising avenue for biofouling prevention. Polytetrafluoroethylene (PTFE), polydimethylsiloxane (PDMS), polyether sulfone (PES), and polyvinylidene fluoride (PVDF) are frequently used as coatings to prevent marine biofouling [1]. These coatings prevent biofouling by providing unfavorable sites for attachment, low surface tension, and resistance to chemicals and weathering.

Among these, polytetrafluoroethylene (PTFE) and polyvinylidene fluoride (PVDF) have gained attention due to their unique chemical and physical characteristics. PTFE is known for its extreme hydrophobicity, making surfaces with low surface energy that repel water and biofouling agents [15]. Its chemically inert nature resists microbial degradation, making it an ideal choice for long-term marine applications. The smooth surface of PTFE, combined with its antifouling properties, makes it effective against macrofouling species such as barnacles and mussels. However, its promise under varying environmental conditions, such as zones with high bacterial loads, remains underexplored [16]. Conversely, PVDF offers a balance of mechanical strength, durability, and chemical resistance, allowing it to survive harsh marine conditions [17]. Although considered as hydrophobic, new research and experimental findings, including in this study, show that PVDF exhibits hydrophilic behaviours under certain conditions. This hydrophilicity allows the formation of a hydration layer on the surface, deterring biofilm formation by creating a physical barrier against adhesion [18]. Its hydrophilic nature improves resistance to bacterial attachment, making it particularly suitable for microfouling mitigation in biomedical or low-salinity environments. Therefore, the objective of this research is to evaluate and compare the wettability property of PTFE and PVDF film characteristics which can effectively prevent the growth of biofouling.

## METHODOLOGY

Materials used in this study were woven GF, PTFE film and PVDF. Woven GF (15cm x 21cm) was supplied by Innovative Pultrusion Sdn Bhd, while PTFE film was supplied by Vistec Technology Sdn Bhd. PVDF was provided by Teguh Sainstek Sdn Bhd.

### *The Fabrication of Glass Fibre (GF) Reinforced PU composite*

A two-part polyurethane (PU) resin (Willkat) was mixed in a 1:2 ratio (A:B). A layer of glass fibre (GF) was placed in a square mold, followed by pouring the resin evenly. Another GF layer was added on top, and the sample was left to cure at room temperature for 24 hours. The weight ratio of GF to resin was maintained at 40:60.

### *Preparation of PVDF film*

PVDF was dissolved in dimethylformamide (DMF) and stirred at 60°C for 24 hours [19]. The solution was sonicated to remove air bubbles and cast onto a glass plate using a 100 µm gap glass rod. The plate was immersed in deionized (DI) water at 25°C for 24 hours to initiate phase inversion. Afterward, the membrane was dried at room temperature for characterization

### ***Fabrication of GFRP with PTFE and PVDF***

The PTFE film was put in the bottom layer of a squared mould. Then, Willkat resin in 1:2 ratio was poured and uniformly distributed in the mould. Then, the prepared GFRP was placed on top and left to cure at room temperature for 24 hours. The same step was repeated for PVDF film.

### ***Field Testing***

Field testing for this study was carried out at the Marine Materials and Structures Research Site UiTM, located on Pulau Tuba, Langkawi, Malaysia. This location was chosen as field testing because of the high growth of biofouling. The testing involved observing the biofouling growth on the samples due to constant seawater exposure for 0, 14, 28, 60, 90, and 120 days [20]. The degree of biofouling growth was compared between GF (reference sample), PTFE/GF and PVDF/GF based on the observation. The three (3) samples were placed on a custom rack and submerged in seawater. Before submersion, images were taken to record the initial condition for each sample at 0 day. After 14 days of submersion, the rack was removed from the seawater and the samples were extracted for visual inspection and data collection. During this process, the images were captured to see the changes on the biofouling growth. These images were then analyzed using ImageJ software to assess changes over time. This process was then repeated at each designated interval, enabling a thorough assessment of the sample's performance over the testing period.

### ***Contact Angle Testing***

Contact angle measurements assessed the wettability of all samples. A droplet of water was placed on the surface, and the angle between the droplet and the surface was measured using a goniometer [21]. Surfaces were cleaned prior to testing to ensure accuracy. Smaller contact angles indicated higher wettability, while larger angles suggested lower wettability. Standardized droplet size and placement ensured consistency across measurements. Characterization of surface wettability based on the contact angle result could be referred at Table 1.

Table 1. The characterization of surface wettability [22]

No	Angle	Description
1	Between 0 ° and 10 °	Surface wettable, super hydrophilic water spreads out completely when it meets the surface.
2	Between 10° and 90 °	Surface wettable, hydrophilic
3	Between 90 ° and 150 °	Surface not wettable, hydrophobic
4	Between 150 ° and 180 °	Ultra hydrophobic surface, completely liquid-repellent, lotus effect

## **RESULTS AND DISCUSSION**

Surface wettability plays a crucial role in the colonization of fouling organisms, spanning a range from hydrophobic (water-repellent) to hydrophilic (water-attracting) surfaces. Hydrophobic surfaces are characterized by low wettability and low surface energy, whereas hydrophilic surfaces have high wettability and higher surface energy [9]. On hydrophobic surfaces, water droplets tend to "bead up," reducing the contact area between the water and the surface. In contrast, hydrophilic surfaces promote the even spreading of water droplets across the surface.

A key feature of hydrophobic surfaces, especially those that are hydrophobic, is their self-cleaning property, often referred to as the "lotus effect." On hydrophobic surfaces, where contact angles exceed 150°,

water droplets roll off the surface rather than spread out. [23] As the droplets move, they pick up dirt, debris, and even microorganisms, effectively cleaning the surface. This self-cleaning mechanism can significantly reduce biofouling by preventing the accumulation of organic matter and fouling organisms, which require stable attachment points to colonize [24].

For instance, hydrophobic surfaces, with contact angles greater than  $150^\circ$ , display a strong resistance to water, effectively repelling it [25]. On the other hand, hydrophilic surfaces, defined by contact angles less than  $10^\circ$ , show an exceptional ability to attract and spread water [26]. These differences in surface behaviour directly affect the adhesion of biofouling organisms. Hydrophobic surfaces may prevent the accumulation of fouling by limiting the interaction with water and fouling organisms, while hydrophilic surfaces might inhibit attachment by maintaining a stable water layer that impedes organism-surface contact [27]

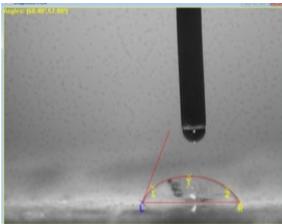
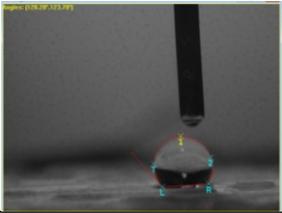
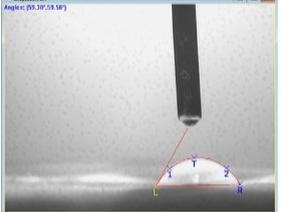
These variations in wettability, as measured through contact angles, highlights the importance of surface design in controlling biofouling in marine environments. Both hydrophobic and hydrophilic surfaces offer unique strategies for fouling management, depending on the specific environmental and operational context. The self-cleaning properties of hydrophobic surfaces offer a passive and energy-efficient method to prevent and mitigate fouling accumulation.

Table 2 illustrates the wettability characteristics of different materials, measured by contact angle. Glass fiber (GF, reference) has a contact angle of  $63.1^\circ$ , indicating a hydrophilic surface. This moderately hydrophilic behaviour allows water to spread across the surface, which may slow biofouling attachment but not entirely prevent it. GF/PTFE, with a contact angle of  $125.95^\circ$ , is classified as hydrophobic, meaning water droplets "bead up" on the surface, reducing water interaction and limiting organism adhesion, making it more effective for antifouling. In contrast, PVDF/GF's hydrophilic nature (contact angle  $59.4^\circ$ ) facilitates water spreading and microbial adhesion, leading to higher fouling levels.

The GF/PTFE system effectively limits biofouling growth due to its high hydrophobicity and low surface energy, creating an unfavourable environment for fouling organisms. With a contact angle of  $125.95^\circ$ , PTFE surfaces repel water, causing droplets to bead up and minimize interaction with the surface [23]. This disrupts the initial stages of biofouling, as microorganisms require stable water-surface contact to attach and grow. PTFE's hydrophobicity also enables a self-cleaning mechanism known as the "lotus effect." Water droplets rolling off the surface collect debris, organic material, and fouling agents, keeping the surface clean without external intervention [24]. This passive cleaning is especially effective in dynamic seawater environments.

Additionally, PTFE is a polymer composed of a carbon backbone fully surrounded by fluorine atoms ( $-\text{CF}_2-$ ) [28]. This rich fluorine coating is strongly electronegative, forming a protective barrier around the carbon chain. This structure renders PTFE chemically inert and resistant to interactions with polar substances such as water, preventing organic molecules and microbes from adhering and consequently impeding the formation of the initial biofilm. Unlike hydrophilic surfaces like PVDF or unmodified GF, PTFE's water-repellent nature reduces interaction with seawater, further preventing fouling. These properties make PTFE an ideal choice for marine applications, offering superior antifouling performance and reduced maintenance needs over time.

Table 2. Contact angle measurements of different materials

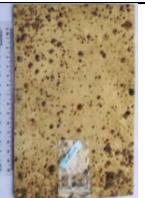
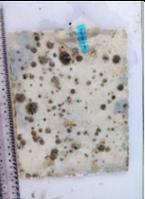
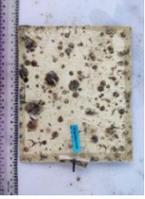
Material	Contact angle image	Contact angle	Result analysis
GF (reference)		63.1° (between 0 ° and 90 °)	Surface wettable (Hydrophilic)
GF/PTFE		125.95° (between 90 ° and 180 °)	Surface not wettable (Hydrophobic)
GF/PVDF		59.4° (between 0 ° and 90 °)	Surface wettable (Hydrophilic)

### **Biofouling growth analysis**

The results of the observations reveal a clear difference in biofouling growth degree between the GF, PTFE/GF and PVDF/GF samples up to 120 days of seawater exposure, as shown in Table 3. Initially, at 0 days, GF and both coatings materials (PTFE and PVDF) were in their pristine state with no significant biofouling growth. However, as the observation period extended to 14 days, those samples began to show initial spots of biofouling growth. The biofouling on GF, PTFE/GF and PVDF/GF appeared similar at this stage.

After 28 days, the difference became more pronounced. The degree of biofouling growth of PTFE/GF exhibited lesser recorded 18.3% compared to the GF and PVDF/GF recorded 21.9% and 32.8% respectively, with some areas of the PTFE/GF remaining relatively clear. This difference highlights the effectiveness of the PTFE as coating material in reducing biofouling. As analysed in Table 2, The PTFE's hydrophobic nature and low surface energy contribute to its self-cleaning abilities, making it more challenging for fouling organisms to adhere and accumulate on the surface.

Table 3. Biofouling growth progression images for 4 months

Material/ Days	0	14	28	60	90	120
Glass Fibre (control)	 0%	 0.9%	 21.9%	 77.1%	 87.1%	 94.7%
Glass / PTFE	 0%	 1.1%	 18.3%	 36.8%	 57.8%	 35.6%
Glass / PVDF	 0%	 0.2%	 32.8%	 74.3%	 86.6%	 89.6%

As the observation period reached 60 and 90 days, this trend continued, with PTFE/GF showing significantly less biofouling marked 36.8% and 57.8% respectively. Meanwhile, the degree of biofouling growth for GF marked higher than PVDF/GF at 60 days seawater exposure compared to 14 and 28 days. This situation is attributed to the properties of GF itself which is hydrophilic, and the surface tend to biofouling to attach easily as GF did not have any coating material on the surface. The PTFE/GF superior performance in reducing fouling is attributed to its hydrophobic properties, which provide a slick surface that resists fouling as mentioned in Table 2. In contrast, the PVDF/GF, which are hydrophilic, did not exhibit self-cleaning abilities and showed a higher level of biofouling.

In 120 days, the observations confirmed that the PTFE/GF had a notably lower degree of biofouling growth marked 35.6% compared to the GF and PVDF/GF with 94.7% and 89.6% respectively. This result shows remarkable comparison between those three (3) systems. As the PTFE coating maintained its anti-fouling properties over an extended period, effectively preventing the attachment and growth of fouling organisms, the degree of biofouling growth reduces from 57.8% at 60 days to 35.6% at 120 days. This reduction confirmed PTFE having anti-fouling properties that is self-cleaning.

Overall, the results underscore the importance of selecting appropriate coating materials for biofouling prevention. The PTFE/GF demonstrated superior anti-fouling properties due to its hydrophobic nature and self-cleaning abilities, resulting in reduced fouling and a cleaner surface over time. Conversely, the PVDF/GF, being hydrophilic and lacking self-cleaning properties, showed a higher accumulation of biofouling. Therefore, the utilization of PTFE/GF is better than PVDF/GF for biofouling prevention due to PTFE's high hydrophobicity, low surface energy, and self-cleaning abilities. These properties result in a

surface that resists the adhesion and growth of biofouling organisms over extended periods. In contrast, PVDF/GF's hydrophilic nature, while potentially inhibiting attachment to some degree, does not prevent fouling as effectively, as observed in the field-testing results. Thus, PTFE/GF proves to be a superior choice for antifouling applications.

## **CONCLUSION**

In conclusion, the findings of this study reveal that the PTFE/GF samples exhibited significantly less biofouling formation compared to the PVDF/GF samples as the observation period progressed. The marked difference between the two film suggests that PTFE film are a more favourable choice for anti-fouling applications. PTFE's hydrophobic properties, which result in a low surface energy, contribute to its self-cleaning abilities, making it highly effective in preventing the attachment and growth of fouling organisms. This hydrophobicity not only reduces biofouling but also minimizes maintenance costs and improves operational efficiency in marine environments. In contrast, the PVDF/GF samples, being hydrophilic, did not exhibit self-cleaning properties and showed a higher level of biofouling accumulation. The hydrophilic nature of PVDF facilitates the adhesion of fouling organisms, leading to increased biofouling and potentially higher maintenance needs. Overall, the results underscore the effectiveness of PTFE film in providing superior protection against biofouling, thanks to their low wettability and hydrophobic characteristics. These findings highlight PTFE as a promising material for anti-fouling applications, potentially leading to enhanced efficiency and reduced maintenance costs in marine settings. Further research is needed to explore the underlying mechanisms of PTFE's performance and to optimize its use for anti-fouling purposes. Nevertheless, this study contributes valuable insights into the development of effective and environmentally friendly strategies for managing biofouling in marine applications.

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## **AUTHOR'S CONTRIBUTION**

Muhammad Hazim carried out the research, wrote and revised the article. Mohd Akmal and Aidah conceptualized the central research idea and provided the theoretical framework. Ummu Raihanah and Mohd Afiq designed the research, supervised research progress; Zaidahtulakmal and Mohd Akmal anchored the review, revisions and approved the article submission.

## **CONFLICT OF INTEREST STATEMENT**

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare absence of conflicting interests with the funders.

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