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Effect of Surface Roughness of Pistia Leaves Inspired Surfaces on Oil Contact Angle and Coefficient of Friction under Lubricated Condition

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ABSTRACT

Biomimetics field is getting more interest in engineering purposes. The plant surface roughness existing in nature such as in leaves can be mimicked into artificial technologies. Basically, the surface structures have micro and nano scales in nature and possess properties of interest. Pistia leaves for example have intrinsic of tribology application which have rarely explored. In this study, a preliminary work on 3 types of Pistia leaves inspired surface-based polymer have been conducted to look at effect of surface roughness towards contact angle (CA) measurements and coefficient of friction (COF) under lubricated condition. The surface characteristics were also examined using Variable Pressure Scanning Electron Microscope (VP-SEM). Two different oils namely palm oil and palm oil + TiO_2 were tested on the Pistia leaves inspired surface to measure the CA and COF. It was found that both types of palm oils had distinct CA values and COF towards surface roughness of the Pistia inspired surfaces. A maximum difference of CA and COF were recorded in CA and COF values. The different nanocomposite of Pistia leaves inspired surface were found to affect for both parameters CA and COF under lubricated condition.

1. Introduction

The biological structures of outer surfaces of plants, animals, and insects carry remarkable properties and functions that can inspire a diverse range of valuable biomimetic applications. For decades, they have become a crucial source for technological advances, providing new insights into useful artificial design structures. Surface analysis of bio-inspired, as a new branch of Tribology, studies the imitation of biological systems for required functional properties [1].

In recent years, there has been an increasing interest in the surface analysis based on bio-inspired or biomimetics field among scientist and researchers, contributing to exponential growth in the biomimetic market. Nosonovsky and Bhushan reported that the profits gained from the sales of the 100 largest biomimetic products were approximately US $1.5 billion for the years 2005-2008 3. In

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2018 alone [2], the global biomimetics market size had reached tens of millions of US and is projected to hit $1 trillion for both products and services by the end of 2025. The annual sales are expected to continue to increase dramatically. Many biological materials have remarkable properties that can hardly be achieved by conventional engineering methods.

Surface characteristic and surface analysis based on bio-inspired studies cover a wide range of research topics [3,4]. It affects several fields of applications with significant scientific, social, and economic impacts on life quality. Biomimetic is also of environmental importance. For example, it addresses the interfacial phenomenon affecting many natural ecological processes in which surface wetting plays a vital role. Special wetting properties and roughness observed in biological surfaces can inspire the development of novel artificial materials with various types of special wettability. This environmental application can only be made possible by the recent advancements in tribology, where they provide elucidation on the natural mechanisms of special wetting properties and surface roughness.

The study of bio-inspired surfaces characteristics based on plants leaf has not widely explored. Plant such as lotus has been investigated in many studies and the findings from the Lotus Effect have been established and converted into artificial technology which has allowed the creation of self-cleaning, self-healing, anti-fogging, anti-fouling, anti-impurity, anti-sticking, and waterproof [5-7]. This encouraged researchers to make something new and useful from plant leaf into inspired surfaces. Hence, in this study, the effect of surface roughness of the Pistia Stratiotes called as "Kiambang" leaves inspired surfaces is investigated.

However, up to now, far too little attention has been paid to its surface analysis [8,9]. Surface roughness and surface texture are two different things. Surface roughness can be measured with the help of suitable instruments but surface texture is not measurable. The microstructures on the surface texture such as diameter and length can be measured using SEM and digital microscope. Roughness always has an absolute value while surface texture depends only on requirements and human perception. In the previous studies [10-13], surface roughness and surface texture (surface topography) gave influence to the wetting behaviour either CA or COF of a surface. The value of surface roughness indicates the smooth to very rough of the surface [14]. A profilometer is one of the equipment that can measure the surface roughness. There are two types of profilometer namely non-contact profilometer and contact profilometer. Non-contact profilometer uses a light beam spot to the sample while contact profilometer uses a stylus to measure the surface roughness. Generally, it can be used for hard materials like steel, composites or ceramics. It is not suitable for soft material.

Previous study was proven that the fabricated surface texture with different micro/nanostructures at different materials greatly influences the contact angle values [11]. They found that the contact angle was sensitive to the microstructures of the lotus inspired surface at the different shape of microstructures. Water contact angle increase when the microstructure surface is rough. In term of COF, a small-scale study by the previous researchers found no strong correlation exists between surface roughness and COF under both dry and lubricated conditions for the surfaces investigated [15]. Their study showed that COF significantly depends on surface texture when compared to the surface roughness (Ra) of the harder steel material. This view is supported who wrote that surface texture is one of the most important factors that influence the COF during sliding [16]. Conversely, some of the available literatures have proven that COF depends on both surface texture and surface roughness of the investigated surfaces [12,17,18]. Thus, the perception of surface textures, in addition to surface roughness, should be considered to understand the frictional analyses either in mechanical or biological system [16].

Many efforts have been made to obtain artificial surfaces with biomimetics micro-nano textures using a variety of methods such as the sol-gel method [19], photolithography [20], micro-contact printing [21,22], and chemical vapor deposition [23,24].

Hence, inspired by the biomimetics study, the fabrication of the Pistia Stratiotes was successfully fabricated using a casting method of high-grade silicone to investigate the effect of surface roughness of the nanocomposites materials towards CA and COF. The nanocomposites products were finally produced to compare the novel nanocomposites (filled by graphene, multiwalled carbon nanotube (MWCNT), and nanoclay of pistia-inspired surface).

2. Methodology

The mixture of silicone which are part A and part B were then poured over the biological plant leaves templates. After 48 h of curing at room temperature, solidified silicone mould was peeled off from the template, thus a negative replica of pistia leaves template surface was obtained. The outline of the fabrication procedures for both positive and negative biomimetic hairy structures of pistia leaves inspired surfaces comprising various micro and nanostructures is schematically shown in Figure 1.

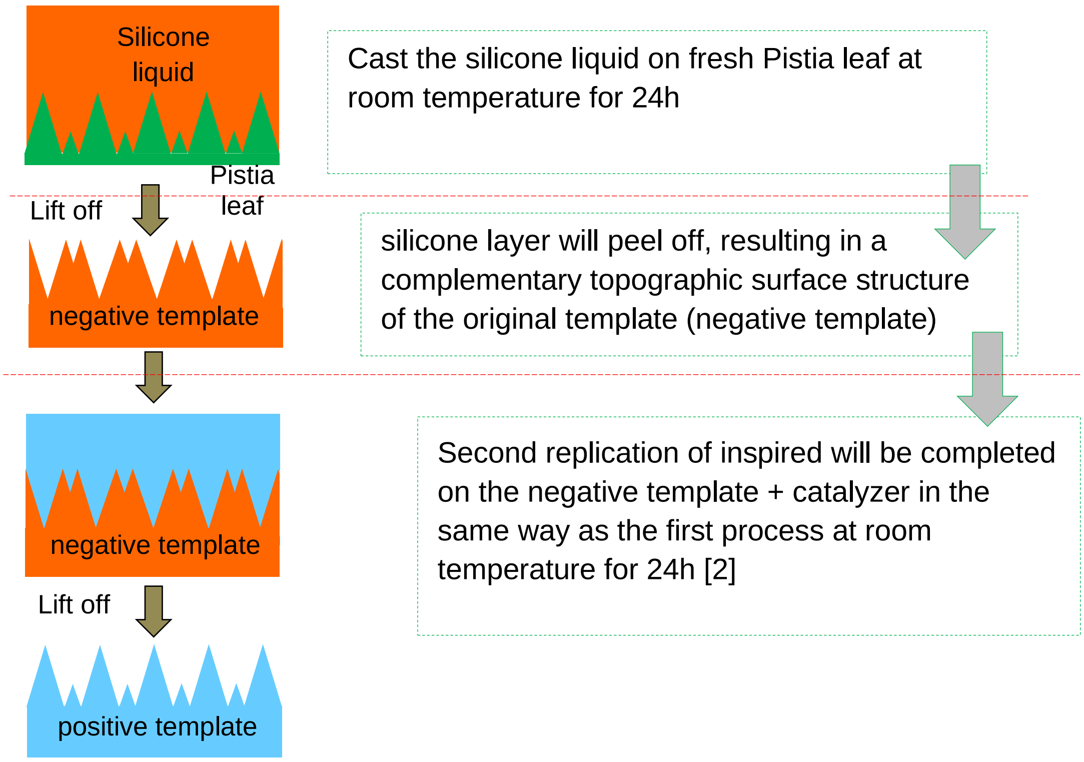

Fig. 1. Schematic diagram of Pistia mould and inspired fabrication

The morphological study was conducted using Variable Pressure Scanning Electron Microscopy (VP-SEM) of Hitachi SU1510 at 1.5 kV with 500 μm magnifier under low vacuum. Fabricated bio-inspired pistia surface, the bio-inspired nanocomposites surfaces were sputter-coated with platinum to impart electrical conductivity and reduce charging artifacts during high resolution electron imaging applications using Auto Fined Coater of Jeol-JFC1600. Figure 2(a) until (c) present the results obtained from the VP-SEM analyses of the size of surface microstructures of the graphene-filled, MWCNT-filled, and nanoclay-filled of pistia leaves-inspired surfaces.

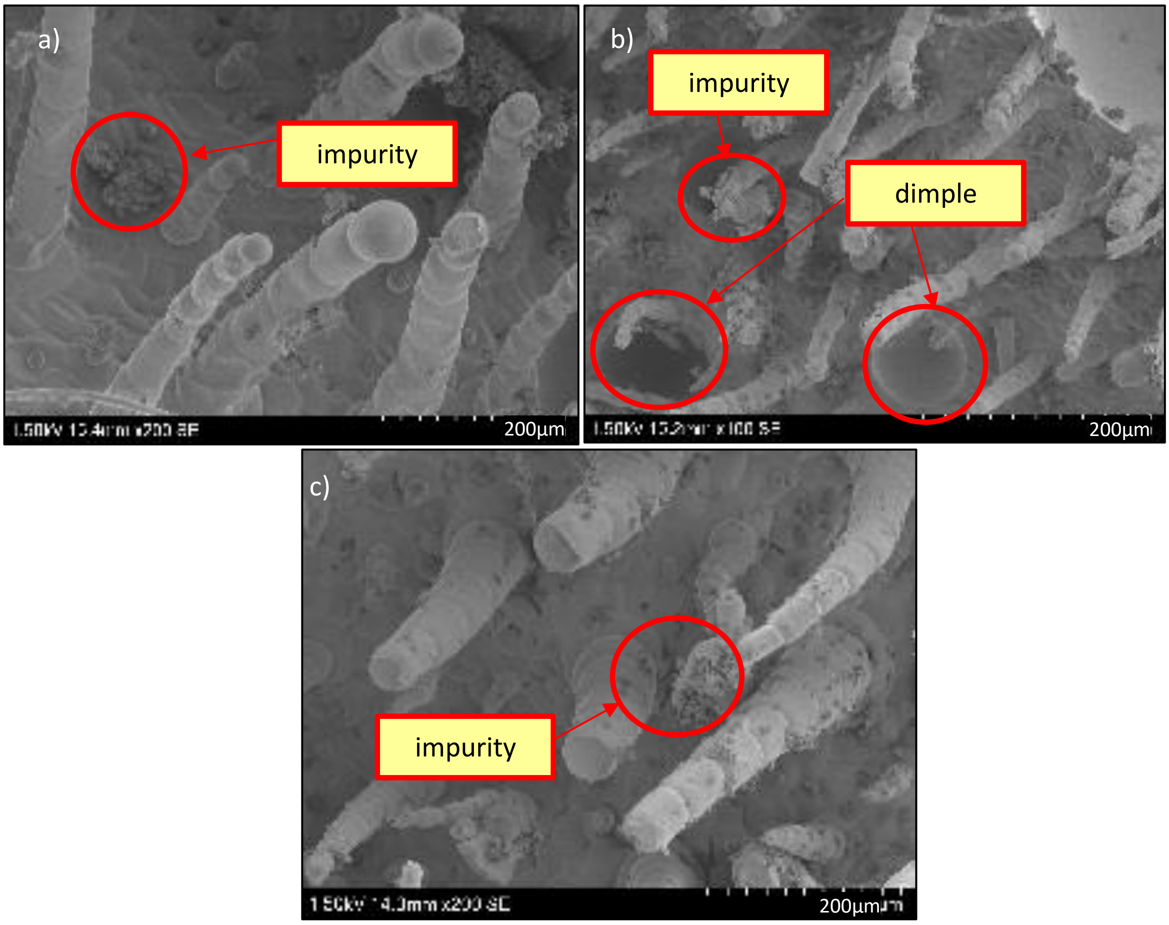

Fig. 2. VP-SEM Image of a) Graphene-filled of Pistia leaves inspired; b) MWCNT-filled of Pistia leaves inspired and c) Nanoclay-filled of Pistia leaves inspired

An optical non-contact method is preferred for measuring the surface topography of the Pistia leaves inspired. Schematic diagram of Alicona InfiniteFocus 3D optical microscope as presented in Figure 3, which employs the technique of focus variation combined with small depth of focus measure surface [25], was used to measure surface topography of all inspired leaves of this study in 3D. The nanocomposite of bio-inspired pistia leaves surfaces was sputter-coated with platinum using Auto Fined Coater of Jeol-JFC1600 for the factor quality of the inspired surfaces. Magnification of 5x was selected to scan the images. The total scanned area was 6 mm*200 µm. The vertical resolution was 25 nm and the lateral resolution was 3 µm. Coaxial light and ring light were used to illuminate the test surface to measure the textures. After scanning, a line was drawn directly on the scanned surface to extract the surface profile along the line. The length of the line was about ± 2 mm**.**

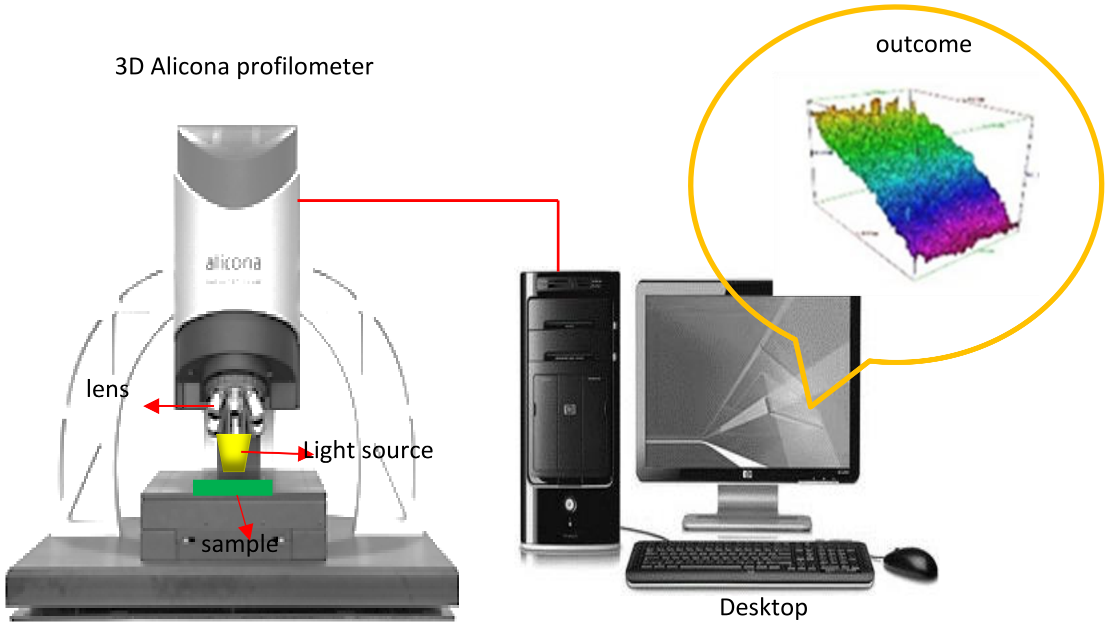

Fig. 3. Schematic diagram of Infinite Focus Alicona profilometer surface topography machine

The oil CA of Pistia leaves inspired surfaces was determined on fully developed leaves by measuring the static contact angles of oils droplet with 2 µL of volume droplet by using a horizontal microscope equipped with a contact angle meter (model OCA 15EC) at ambient temperature. This experiment was conduct in accordance to ASTM D7334. The oil droplet rate was controlled by motor-driven syringe. To obtain an even surface, parts of the leaf blade were affixed to sample table manual moveable with double sided adhesive tape in horizontal and precise adjustable in vertical (z-axis) via hand wheel. The liquid was injected automatically on the leaves surface and it was left for 10 s before the image is being captured. CA value was obtained by the sessile drop method. Figure 4 shows the schematic diagram of contact angle meter.

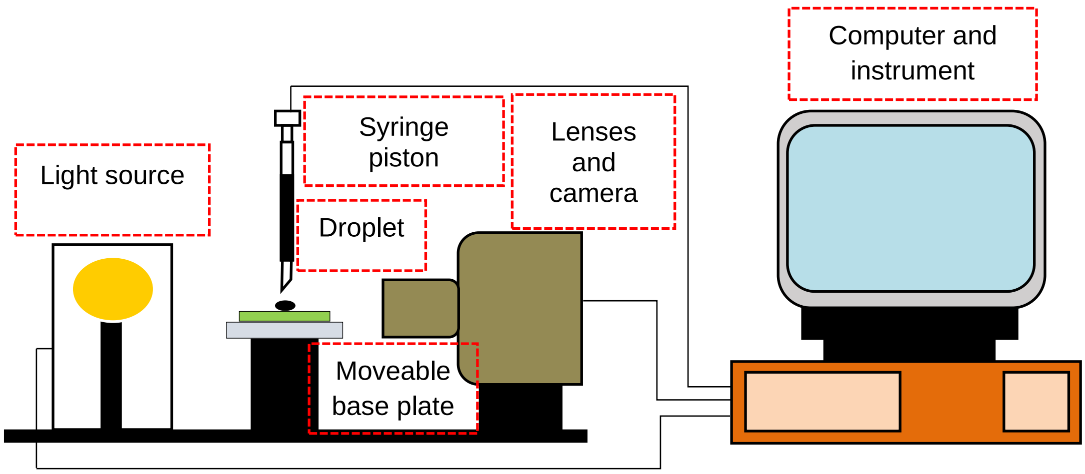

Fig. 4. Schematic diagram of contact angle measurement by using contact angle meter

A schematic diagram of bespoke apparatus for measuring the static COF has been designed due to soft, small and fragile samples of real pistia leaves as shown in Figure 5. In this case, it was continued for COF investigation on pistia leaves inspired surface. This method was recommended where they claimed that the method was more accurate than the prototype sliding friction tester due to good repeatability in determining the COF [26]. The 265 g of wooden block with 3.0*2.0*1.0 cm of dimension was used to fix the sample onto slide of the incline plane. Two different oils (palm oil and palm oil + TiO_2) were used at room temperature of 25 ºC ± 1 ºC and precaution was taken to avoid the possible oil suction effect. The 0.4 ml of oil was slowly applied on the sample using a syringe. Before the experiments began, the weight of wooden block with fix samples was taken using a weighing scale. Then, the block with tapered end (45 º) was manually moved forward until the sample started to slide. The angle at the moment of initial movement of the samples was measured to calculate the COF of the material using Eq. (1) [27]. Each experiment was repeated 7 times to establish an average value.

$$mg \sin \theta = \mu \, mg \cos \theta \qquad (1)$$

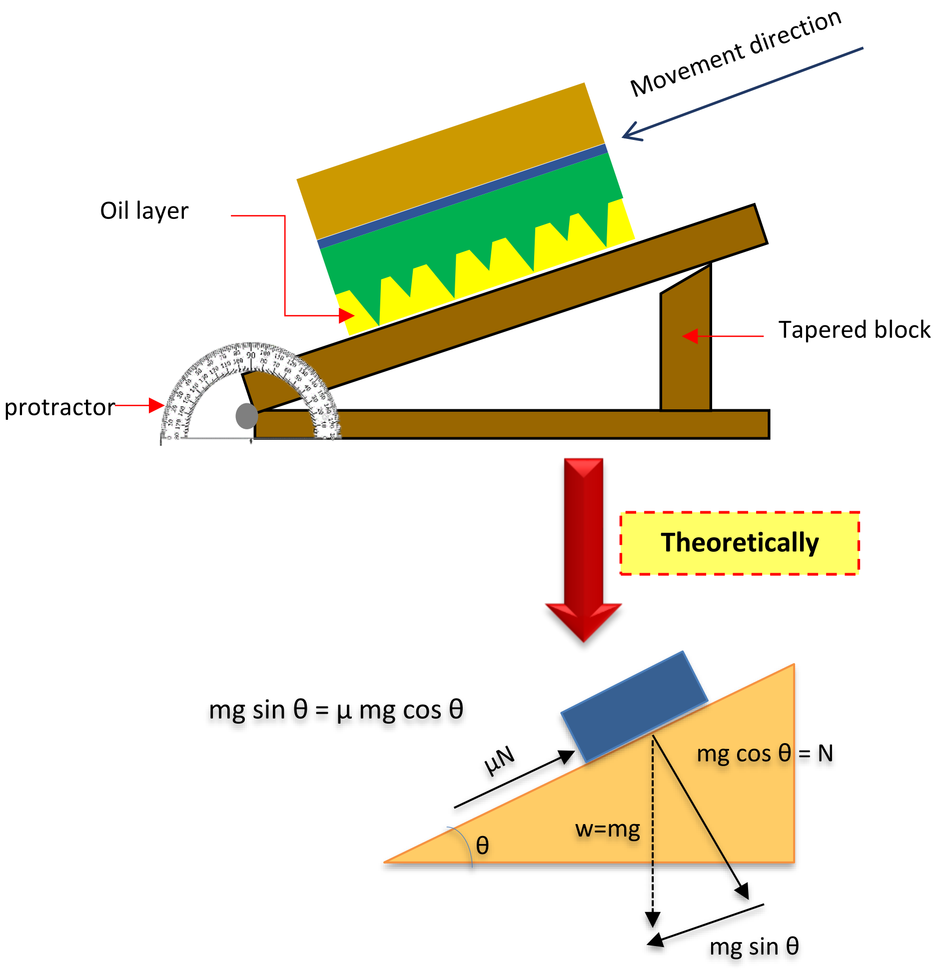

Fig. 5. Schematic diagram of COF measurement for Pistia leaves inspired surfaces

3. Results

3.1 Surface Roughness Analysis on COF Value

The average COF values with respect to surface roughness for various Pistia-inspired materials under lubricated conditions are shown in Table 1. Each data point corresponded to average friction values recorded at the moment the sample began to slide, which was defined as static COF. As shown in Table 1, surface roughness (Ra) values for different nanocomposites surfaces of pistia's leaves-inspired were compared to each other. Previous studies have shown that COF depends on surface roughness [12]. Table 1 shows nanoclay-filled required a larger friction force than the graphene-filled surface for both palm oil and palm oil + TiO_2. The lubricated contact area of the nanoclay-filled might be lower than that of graphene-filled, resulting in higher COF value. In the case of Pistia-inspired surfaces, COF depends on surface roughness; the lower the surface roughness, the lower the COF under lubricated condition. Table 1 also presents that nanoparticle of TiO_2 in palm oil also influence the COF value. Palm oil + TiO_2 gave the lowest COF value at all three nanocomposite inspired surfaces. These results were supported by the previous study [28]. However, one parameter is not sufficient to characterize the roughness. Some unwanted particles and impurities that exist on the inspired surface have caused the values of COF and surface roughness to be affected. Based on the VP-SEM examination (Figure 2(b) and (c)), some of the dimples were discovered on certain inspired-surfaces due to the presence of bubbles during curing process.

Table 1
Surface roughness and static COF values at lubricated condition of Pistia-inspired

	Surface roughness, Ra (µm)	COF	
		Palm oil	Palm oil + TiO_2
Graphene-filled	14.841	0.3198	0.3049
MWCNT-filled	12.726	0.328	0.3149
Nanoclay-filled	15.007	0.3866	0.361

3.2 Surface Roughness Analysis on CA Value

Table 2 shows the relationship between the contact angle of oils and surface roughness. It is seen in Table 2 that the CA of oil (wettability) was affected by the surface roughness. The CAs of the palm oil and palm oil + TiO_2 increased as the surface roughness of the inspired surface increased. The contact angle values ranged from 8.32° to 23.72°. According to Table 2, nanoclay-filled inspired surfaces obtained the highest CA of palm oil and palm oil + TiO_2 with the second highest in surface roughness. Nanoclay-filled of inspired surfaces showed weaker surface energy than the liquid surface tension of the related oils. A possible explanation for this case is the effect of surface texture (microstructures) on the CA. Concerning the texture shape, the maturity Pistia leave exhibited a more apparent effect on wettability behaviour. Surprisingly, Pistia-inspired surfaces demonstrated fluctuating data of surface roughness and CA. However, using the Wenzel theory mentioned in the literature, roughness factor, *r* is most important in determining the wettability of the rough surface [29,30].

Table 2
Surface roughness and contact angle (CA) at lubricated condition of Pistia-inspired

	Surface roughness (Ra), µm	CA (°)	
		Palm oil	Palm oil + TiO_2
Graphene-filled	14.841	13.40	8.32
MWCNT-filled	12.726	14.67	8.76
Nanoclay-filled	15.007	23.72	9.76

3.3 Surface Roughness Factor, R Analysis

Roughness is a different term with roughness factor. Roughness refers to microstructure size of a surface with the dimension of length [31]. In this case, the roughness factor for the nanocomposite Pistia-inspired surface decreased as the CA of oil decreased, as presented in Table 2 and Table 3. This is because of good agreement with Wenzel state, which is CA depends on the roughness factor, *r* [32]. The Eq. (2) (roughness factor equation) also stated that roughness increases hydrophobicity if the angle of smooth surface, θ^{o} is greater than 90^{o} while the contact angle for the rough surface decreases as the roughness factor, *r* increases [33].

$$\cos\ \theta_a = r \cos\ \theta_s \tag{2}$$

where ϑ_a is the apparent contact angle and ϑ_s is contact angle on an ideally flat surface.

Table 3
Roughness factor, *r* of nanocomposites Pistia-inspired surface

	Roughness factor, *r*	
	Palm oil	Palm oil + TiO_2
Graphene-filled	1.142	1.136
MWCNT-filled	1.248	1.267
Nanoclay-filled	1.175	1.359

4. Conclusions

The outcome of this investigation shows that both parameters of CA and COF could be consider affected to surface roughness value of Pistia inspired surfaces. A good agreement has been achieved with independent means of measurement. It was believed that the microstructure of the Pistia leaves is the most important effect on the oil wettability based on CA value.

The tribological property such as friction has been compared under lubricated condition. A good agreement has been achieved where palm oil + TiO_2 gave the lowest values of COF at graphene-filled of pistia inspired surfaces (0.3049). Overall, the Pistia-inspired surfaces showed significant improvement in COF, contact angle, and surface roughness compared with the real Pistia leaves.

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