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Wettability Property In Natural Systems: A Case of Flying Insects

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Abstract

Recently, scientists have demonstrated that material surfaces in nature that possess special wettability properties are composed of micro- and nanostructures. In this study, we focused on the importance of surface structures in determining the wettability of wings of the flying insect species: Idea malabarica, Lucilia sericata and Chrysomya marginalis. Scanning Electron Microscopy (SEM) analysis indicates the different nano-/micro- structures identified on the wings. Surface roughness which plays a role in influencing the wettability was theoretically estimated from the SEM images. While the spherical liquid water droplets used for testing wettability were observed to float on the surface of the Idea malabarica and Lucilia sericata wings, the surface of the Chrysomya marginalis wing was made completely wet. The super-hydrophobicity of the Idea malabarica wing as compared to the near-hydrophobicity/mild hydrophilicity of the Lucilia sericata wing and the distinct hydrophilicity of the Chrysomya marginilis wing could be attributed to its complicated composition of nano-/microstructures and higher surface roughness value.

INTRODUCTION

Super-hydrophobicity is a surface-morphology linked phenomenon recurrent in nature, one through which water striders float and move on water surface; lotus leaves are self-cleaning, and butterflies avoid sticking of their wings [1]. Recently, the surface morphologies of underwater creatures and plants have been widely investigated for their superhydrophobic properties [2-4]. Interest in these types of surface properties have grown over the past years due to the understanding of the criteria for forming such surfaces and the recognition of its potential. The superhydrophobic materials have found applications in anti-corrosive coatings, microfluidic devices, printing techniques, optical devices, etc. [5]. In many of these applications, the presence of an air layer trapped inside the rough surface can reduce liquid penetration.

To characterize the hydrophobicity of a material surface, the contact angle (CA) as well as the contact angle hysteresis has to be considered [6]. The contact angle is the angle at which the liquid/vapor interface meets a given solid. The Young equation is the most important yet the simplest relationship to describe the balance of forces acting on a liquid droplet spreading on a surface. The contact angle (θ) of a drop is related to the interfacial energies acting between the solid-liquid (γ_{SL}), solid-vapor (γ_{SV}) and liquid-vapor (γ_{LV}) interfaces and is described by equation 1 [7].

$$\cos(\theta) = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}} \qquad (1)$$

Equation 1 is strictly valid only for surfaces that are smooth, chemically homogeneous, and do not change by possible interactions with the probing liquid. Yet surfaces in nature are not perfectly smooth as described by Young, thus considering the surface roughness, Wenzel proposed a model to describe the contact angle θ' of a rough surface by modifying Young's equation as [8],

$$\cos(\theta') = \frac{r(\gamma_{SV} - \gamma_{SL})}{\gamma_{LV}} = r\cos(\theta) \qquad (2)$$

where r is the roughness ratio factor. Besides these factors used in evaluating hydrophobicity, it is essential to consider the shape of the liquid droplet on the surface. When liquid water spreads over a surface without the formation of droplets, the surface is said to be hydrophilic. This implies that the forces associated with the interaction of liquid water with the surface are greater than the cohesive forces associated with the bulk droplet of liquid water. Surfaces with very high water contact angles particularly larger than 150° are usually called superhydrophobic (SH) surfaces. Those with contact angles 150° < θ < 90° are hydrophobic while those with θ < 90° are deemed hydrophilic [5].

Recently, researchers have turned to insects due to their naturally developed water-repellent surfaces to create surfaces with better hydrophobic properties. The natural species which exhibit water contact angles higher than 150° have water repellent surfaces in that the water droplets roll off the surface at a small tilt angle (sliding angle), thereby removing contaminates from the surface (self-cleaning). One such example is the superhydrophobicity of butterfly wings which takes advantage to reduce dust particle contamination and enhance flight capability. The group of Barthlott studied the surface structures and wettability of 97 insects' wings. They found different families with highly hydrophobic wings including mayflies, dragonflies, stoneflies, lacewings, scorpionflies, alderflies, caddisflies, butterflies, moths and houseflies. Various morphologies were reported, such as cloth-like microstructures, hairs and scales [9].

It can be inferred therefore that the hydrophobicity of insects' wings is well documented, yet the reported studies do not include the wings of the insects; *Idea malabarica*, *Lucilia sericata* and *Chrysomya marginalis*. Hence the present study investigating the nano-/microstructures on the wings of these flying insects and correlating these to each's observed surface roughness and wing wettability.

MATERIALS AND METHODS

The wings of the studied insects were acquired from the Cape Town city of Strand (South Africa). Prior to carbon coating in an Emitech K950x high vacuum turbo system, the wings were air dried and cut out using a razor blade. The specimens were placed on conductive carbon-stickers and carbon coated to prevent charging so as to enhance the image quality. The nano-architectures of samples were examined using the Nova NanoSEM Scanning Electron Microscope (SEM). Optical imaging of the samples was performed with an Olympus Bx 61 optical microscope. Imaging of wettability on the different insect wings was carried out using a Pointgrey USB 3.0 digital camera operating with FlyCapture® SDK 2.7.3 software.

RESULTS AND DISCUSSIONS

Wing Surface Morphology via SEM and Optical Microscopy

As shown in Figure 1, liquid water droplets were placed on the surface under study and the contact angle measured. The contact angle measurement defines the angle between the liquid water droplet's edge and the solid surface beneath it. In Fig.1, the liquid water droplet on the *Idea malabarica* wing shows a contact angle of ~ 157°on the surface of the wing and ~ 82° on the visually smooth vinyl-covered bench top. The morphological structures observed in the SEM image contain voids separated by cross-ribs and longitudinal ridges [10]. The surface of the wing is decorated with complicated composition of nano-/microstructures (a), which affect its interaction with the liquid water droplet. The micro-/ nano-scale structures in the cuticle layers enhance hydrophobicity, thereby enabling droplets of water to roll off the wing and remove any dirt. Besides this feature, the surface roughness equally plays a critical role in influencing the super-hydrophobicity of the wing.

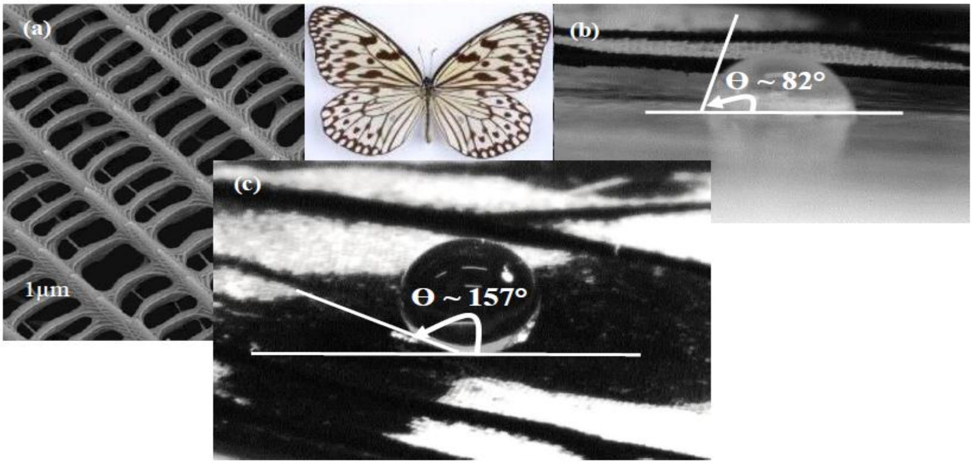

Figure 1: (a) The Scanning electron microscopy image on the wings of *Idea malabarica* showing the nanostructures of cross-ribs separated by longitudinal ridges, (b) water droplet on the bench and (c) water droplet on wings of the butterfly.

Lucilia sericata (Diptera: Calliphoridae) is an ubiquitous fly that belongs to a group of necrophagous insects that are dependent on decomposing flesh to complete their life cycle [11]. The larvae have created a niche in therapeutic options for wound treatment. *Lucilia sericata* is the scientific name for the green blowfly (inset Fig. 2a), a member of the *Calliphoridae* family [12]. It is found in the United States, Southern Canada, Australia, and several South and Central American countries and is among the insects normally used in forensic entomology, [13] medical [14] and veterinary science [15]. It (inset Fig. 2a) feeds on carrion, faeces, and garbage [16]. The SEM image of *Lucilia sericata* reveals microscale setae structures (Fig.2b) which are mainly bent at the tip, similar to high aspect needles. In addition, fine nano-grooves (Fig. 2d)) are observed on the microscale setae. Such micro- and nanoscale structures help surfaces to repel water easily. This feature likely contributes to the near-hydrophobic/hydrophilic property of the wing observed in Fig. 2c. The droplet is observed to sit on the wing for longer than 5 min without wetting the surface. It is clear that the contact angle (~ 74°) between the water droplet and the wing surface of this flying insect species is significantly less than that on the wing of the *Idea malabarica* (Fig. 1c).

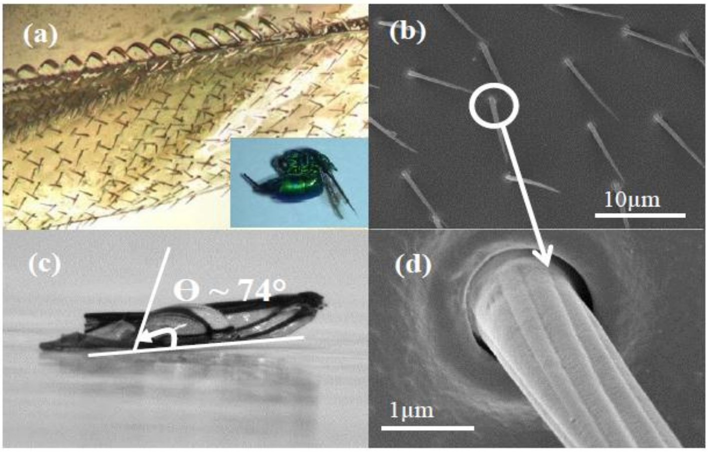

Figure 2: (a) The optical image, (b) scanning electron microscopy image and (c) hydrophobic property on adult *Lucilia sericata* (d) nano-groove.

The wetting property on the surface of the large blow fly known as *Chrysomya marginalis* is illustrated in Fig. 3. The blow fly belongs to the family *Calliphoridae*, and is a slightly larger than normal fly with a shiny blue colour on its body. Its surface morphology as evident in the SEM image (Fig. 3b, c) reveals mole –like structures.

These structures on the wing surface of the *Chrysomya marginalis* do not hold liquid water for long. The wing easily gets wet within the first minute pointing to the strong hydrophilic nature of the wing surface (Fig. 3d). The relatively smooth nature of the wing surface with small mole-like structures and a visible absence of air pockets are likely factors contributing to the strong hydrophilicity/wettability of this species' wing. To corroborate these observations a numerical analysis of the surface roughness of the insect wings was carried out based on the SEM images.

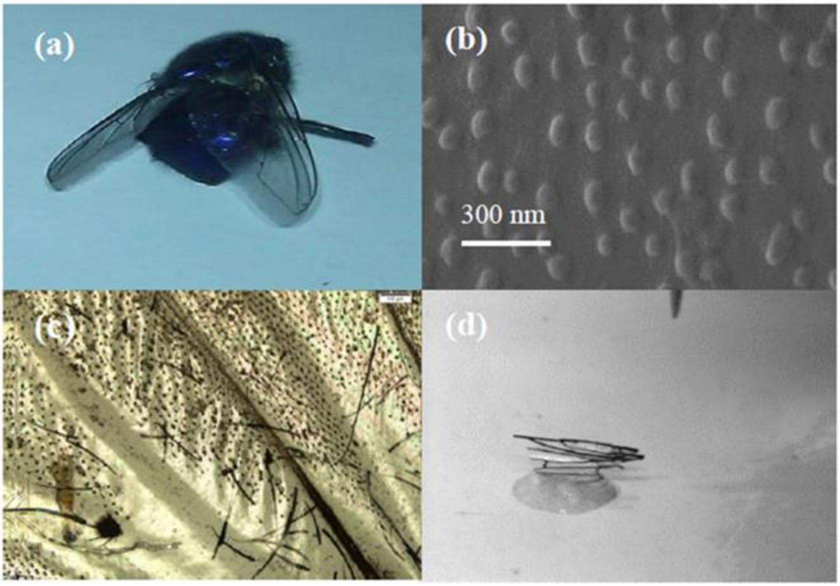

Figure.3: (a) *view of Chrysomya marginalis*, (b) the scanning electron microscopy image, (c) optical image, (d) hydrophilic behaviour of the wings of *Chrysomya marginalis.*

Surface roughness

Surface roughness is known to influence the wettability of different surfaces [17]. The modeling of profile roughness starts from the definition of a mean line, which is parallel to the geometrical profile such that the area of solid above it is equal to the area of void below it. Roughness parameters can be divided into average roughness parameters, statistical parameters, random process parameters and fractal parameters. However, the two widely used average roughness parameters are centre line average (Ra) and root mean square (Rq). An increase in roughness leads to larger surface area and also higher hydrophobicity [17]. Table 1 gives the theoretical values of the roughness parameters estimated using Gwyddion (32) free software. The results indicate the super-hydrophobic, near-hydrophobic/mildly hydrophilic and distinctly hydrophilic natures of the *idea malabarica*, *Lucilia sericata and Chrysomya marginalis* respectively. These roughness results coupled with SEM results and the wettability tests confirm that wings with greater surface roughness exhibit higher hydrophobicity/anti-wetting properties.

Roughness parameters	Insect type		
	Idea malabarica	*Lucilia sericata*	*Chrysomya marginalis*
Roughness average (Ra)	8.6	4.0	2.9
Root mean square roughness(Rq)	12.1	5.6	4.7
Skewness (Rsk)	0.042	0.616	1.866
Kurtosis (Rku)	5.223	7.090	20.949

Table 1: Roughness parameters estimated from the images of the insects under investigation

In estimating the surface roughness of the insects studied, the following digitally modified 3-D images (Fig.4) were obtained from the SEM images. Evidently, the *Idea malabarica*, has micro-/ nano-scale structures while the surface of the *Lucilia sericata* consist of cones (arising from setae) and *Chrysomya marginalis* is made of mole-like structures. Also, the greater roughness of the *Idea malabarica* wing can be visually assessed.

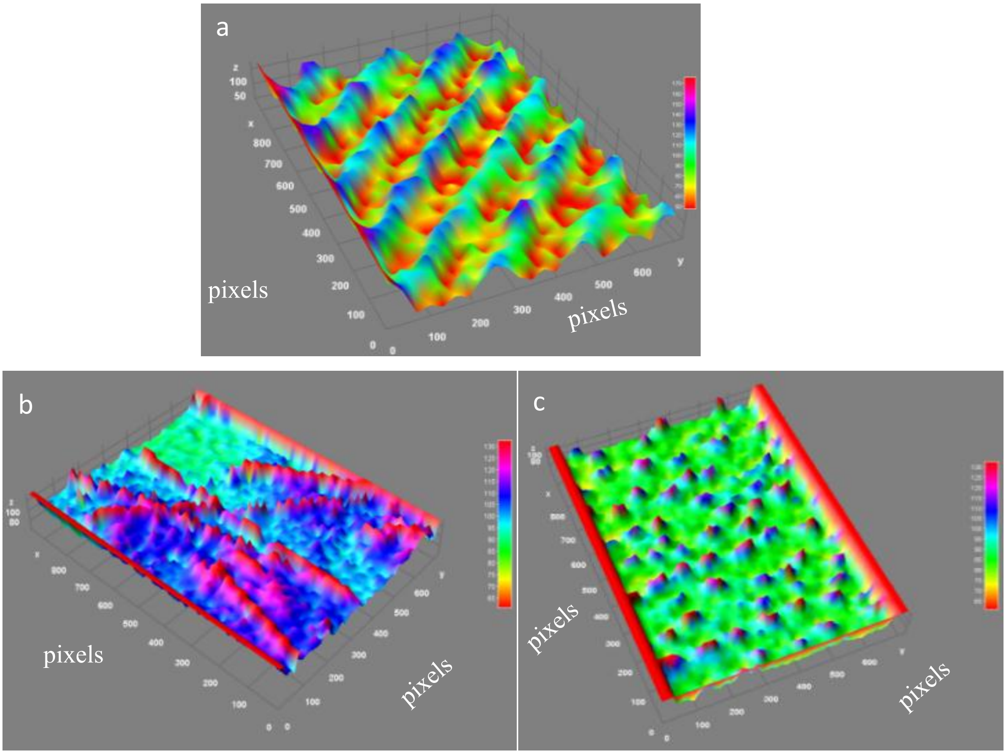

Figure 4: 3D mode of the SEM images displaying the grooves on the surfaces of (a) *Idea malabarica*, (b) *Lucilia sericata* (c) *Chrysomya marginalis*,

CONCLUSION

The experimental methods of SEM and optical microscopy coupled with numerical analysis enables comparison of the surface roughness and wettability properties on wings of the flies; *Idea malabarica*, *Chrysomya marginalis* and *Lucilia sericata*. The greater superhydrophobic/anti-wetting property of *Idea malabarica* can be ascribed to its surface composition of nano-/microstructures which trap air pockets under incident water droplets to form a water-repelling composite surface. In the case of *Lucilia sericata*, the microscale setae with fine-grooves observed on its wing surface likely contribute to its mildly hydrophilic property, as these give rise to the trapping of air that tends to promote hydrophobicity. On the other hand, the mole-like nanostructures observed on the wings of *Chrysomya marginalis* make for a smoother/less rough surface (devoid of air pockets) that contributes to its strongly hydrophilic behaviour. Though *Lucilia sericata* and *Chrysomya marginalis* belong to the same family, the difference in their surface structure compositions and surface roughness clearly affect their wettability with the wings of the former being less wettable (more hydrophobic). This study which shows that surface architectures and surface roughness play an important role in creating water-repellent surfaces can be applied to developing man-made self-cleaning surfaces.

Acknowledgments

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