ABSTRACT

Nature has consistently served as a source of inspiration for scientific and technological progress, particularly in surface wettability and biomechanics. Natural surfaces like plant leaves, insect wings, and bird feathers exhibit exceptional wetting and dewetting behaviours, resulting from their distinctive micro- and nanoscale textures and chemical compositions, which govern solid-water interfacial interactions [1]. Wettability is characterized by Young's equation, which relates the contact angle (CA) to the interfacial tensions of the three phases: solid-liquid (γ_{SL}), liquid-air (γ_{LA}), and solid-air (γ_{SA}) [2]. The contact angle, formed between the tangents of the solid-liquid and liquid-gas interfaces, is referred to as Young's contact angle or simply the contact angle for smooth surfaces. Surfaces with a contact angle CA $< 90°$ are termed hydrophilic, while those with $90° <$ CA $< 145°$ and CA $> 145°$ are classified as hydrophobic and superhydrophobic, respectively [2]. Such surfaces are accordingly known as hydrophilic, hydrophobic, and superhydrophobic surfaces. A superhydrophobic surface with contact angle hysteresis (CAH), defined as the difference between the advancing and receding contact angles [2], below 10° is categorized as a superhydrophobic self-cleaning surface [3]. On such surfaces, water droplets roll off easily due to minimal surface contact area. When the contact angle formed along the three-phase contact line (TCL) is uniform, the wetting is referred to as isotropic wettability. However, when the contact angle is non-uniform or directional along the TCL, it is called anisotropic wettability [1, 4]. It should be noted that surfaces can be described as anisotropic in terms of non-uniform or directional texture. However, in wettability studies, the term "anisotropy "specifically refers to non-uniform or asymmetric wettability. The natural leaf surfaces surfaces may possess multiscale or hierarchical structures. Depending on the scale of texture, surfaces can exhibit single-level, two-level, three-level, or multilevel textures [1]. To explain wettability on textured surfaces, two basic models have been proposed: the Wenzel model and the Cassie-Baxter model [3]. The Wenzel model describes a collapsed wetting state where

the liquid droplet penetrates and fills air pores, grooves, or textures. In contrast, the Cassie-Baxter model explains a suspended wetting state where the liquid droplet remains atop the texture, not filling the air voids, pores or grooves. However, these models are limited to single-level textures. Many natural surfaces, such as leaves, petals, or feathers, exhibit multilevel textures [1, 3]. The wettability of such surfaces can be explained by combining the Wenzel and Cassie-Baxter models, leading to composite states like Wenzel-Cassie, Wenzel-Wenzel, Cassie-Wenzel, and Cassie-Cassie models [5]. The lotus leaf exhibits isotropic superhydrophobicity due to its uniform hierarchical micro- and nanoscale two level texture that demonstrates Cassie-Cassie wetting state, offering a low-adhesion interface with water. This allows droplets to retain a nearly spherical shape and roll off at slight tilts, a phenomenon known as the "*lotus effect* "[3]. Similarly, rose petal exibits uniform two level micro-nano texture which demostrates isotropic superhydrophobicity but with strong adhesion fetures known as "*Rose petal effect* "[3]. Apart from isotropic wetting, anisotropic superhydrophobicity has gained more attention for applications in liquid control along specific direction. In contrast, rice leaves were shown anisotropic superhydrophobicity with Cassie-Cassie wetting state due to striated three level micro-nano textures [4]. When a droplet impacts a non-wetting solid surface, it undergoes a bouncing effect that can be characterized by the Weber number (We), which represents the relative importance of the droplet's inertial forces and surface tension, affecting its deformation, rebound dynamics, or breakup upon impact [6]. In addition to bioinspired surfaces and droplet wetting-dewetting, the electrowetting (EW) offers a dynamic approach to controlling liquid curvature using electric fields. Essentially, electrowetting alters surface energy at the solid-liquid interface using an electric field [7].

This thesis explores the wettability of natural leaf surfaces textures, biomimicry through electrospinning and soft lithography, and electrowetting-based liquid lensing phenomena. The surface texture and wetting aspects of leaf surfaces, such as *Ziziphus mauritiana* (Indian Jujube), *Gladiolus hortulanus* (Sword Lily), *Kalanchoe fedtschenkoi*, *Mesua ferrea* (Cobra Saffron), and *Litchi chinensis* (Lychee) specimens, were examined, emphasizing the origin of their hydrophilic to superhydrophobic responses. Inspired by their unique surface constructs and textures, biomimetic techniques were employed through distinct approachs. Additionally, theoretical treatments have been adopted to correlate the wetting characteristics with the surface texture.

The abaxial *Ziziphus* leaves displayed a hairy, matted, single-level surface structure with fiber diameters ranging from ∼5.6 to 7.1 μm, exhibiting isotropic superhydrophobicity. Water contact angles (WCA) greater than ∼143° and contact angle hysteresis (CAH) values between ∼30° and ∼46° were observed across tender, mature, and senescent leaf states. With a WCA of ∼151° tender leaves exhibited maximum superhydrophobicity, with roll-off angles increasing from approximately ∼21° to 33°. In contrast, mature and senescent leaves showed strong adhesion, preventing droplet roll-off even at a ∼90° tilt. To biomimetically replicate the leaf microstructure, electrospun polyvinylidene fluoride (PVDF) fibers with an average diameter of ∼4.3 μm were fabricated. These microfibers demonstrated similar superhydrophobicity (WCA ∼145.7°) and high adhesion (CAH ∼49.4°) features. The nonwoven, yarn-like structure of the PVDF fibers fits well with the worm-like chain model, characterized by discrete segment length, persistence length, as well as bending angle.

In addition to isotropic wettability, the sword lily leaves possess three-level surface textures and offer anisotropic superhydrophobicity and unidirectional self-cleaning behaviour. Water droplets exhibit more favorable wetting and rolling behaviour in the striation (parallel) direction, with contact angles (WCAs) ranging ∼ 143°–147° as compared to ∼ 156°–169° in the perpendicular direction. The roll-off angles were in the ranges of ∼ 8°–23° and ∼ 16°–41° in the parallel and perpendicular directions, respectively. These differences are attributed to air entrapment within the micro-nanotexture and three-phase contact line pinning along the striated height barriers. Further, a biomimicked polystyrene construct was developed using soft lithography which clearly demonstrate adequate in terms of surface texture and micro constructs.

In addition to the static WCAs and droplet rolling behaviour, droplet impact studies were also carried out on both superhydrophobic surfaces (one with low adhesion and one with high adhesion) and two hydrophobic surfaces (both with high adhesion), for specific leaf surfaces, *Kalanchoe*, *Ziziphus*, *Mesua*, and *Litchi*. The impacting water droplet with low weber numbers (We ∼2.8, 14.4, 25.8) displayed complete rebound characteristics on *Kalanchoe* leaf surface (WCA ∼156°, CAH ∼5°) due to low adhesion nano-structured surface. However, *Ziziphus* abaxial leaf surface (WCA ∼151°, CAH ∼30°) exhibited partial rebound state. The transition from the Cassie to the Wenzel state is expected during droplet impact on matted *Ziziphus* leaf surface. The other two hydrophobic leaves (*Mesua*: WCA ∼146°, CAH ∼39°, *Litchi*: WCA ∼130°, CAH ∼32°) offered completely rebound feature of the droplets. The effects of surface inclination (tilting angle, T.A.) that is the oblique droplet (We ∼25.8) while making impact on low and high adhesion surfaces, have revealed that the contact time would drastically decrease with increase of T.A. from ∼0°-30°. This is due to the rapid detachment caused by asymmetric spreading and retraction.

In the electrowetting phenomena, we investigate two aspects: (i) the planar liquid lens experiment and (ii) a numerical simulation of an adaptive liquid lens using COMSOL Multiphysics® software. The planar liquid lens experiment uses two oil media (silicone oil and mineral oil) with a conducting KCl saltwater droplet. As voltage increases, the contact angle of the droplet decreases, altering the interface curvature and focal length. The simulation models an adaptive liquid lens with insulating liquids (silicone oil, *n*-hexadecane, and *n*-tetradecane) in a chamber with hydrophobic dielectric surfaces (Parylene-C and Teflon-AF), showing how applied voltage modulates the lens curvature and focal length. The focal length varied across the applied voltage range, with a discontinuity near the curvature switching point. The effects of voltage and dielectric thickness on the focal length transition were also examined, offering insights into the challenges of developing industrial-grade liquid lenses.

Keywords: Contact angle, Superhydrophobicity, Bioinspired, Biomimicking, Electrospinning, Microfibers, Anisotropic wettability, Soft-lithography, Liquid lens, Electrowetting.

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