STUDY OF DROPLET IMPACT ON FLEXIBLE SURFACE

Thesis submitted towards partial fulfillment of the requirements for the award of the Degree of Master of Technology in Nano Science and Technology

By

AYAS KUMAR DAS

Registration number: 163811 of 2022-23

Class Roll No: 002230701006

Examination Roll No: M4NST24006

Under the guidance of

Prof. Swarnendu Sen

Prof. Ranjan Ganguly

Prof. Apurba Kumar Santra

School of Materials Science and Nanotechnology Jadavpur University

Kolkata - 700032, India

School of Materials Science and Nanotechnology Jadavpur University

Kolkata - 700032, India

CERTIFICATE OF RECOMMENDATION

We hereby recommend that the thesis entitled as "**STUDY OF DROPLET IMPACT ON FLEXIBLE SURFACE**", prepared by **AYAS KUMAR DAS** (Class Roll No: **002230701006**, Registration No. **163811of 2022-23**, Examination Roll No. **M4NST24006**) under our guidance, be accepted in partial fulfillment of the requirement for the award of the Degree of Master of Technology in Nano Science and Technology from the School of Materials Science and Nano Technology of Jadavpur University.

HOD / Director
Dr. Mahua Ghosh chaudhuri,
School of Materials Science and Nano Technology,
Jadavpur University

Thesis Advisor
Dr. Swarnendu Sen Professor,
Department of Mechanical Engineering,
Jadavpur University

Thesis Advisor
Dr. Ranjan Ganguly Professor,
Department of Power Engineering,
Jadavpur University

Thesis Advisor
Dr. Apurba Kumar Santra Professor,
Department of Power Engineering,
Jadavpur University

Dean - FISLM,
Jadavpur University, Kolkata – 700 032

School of Materials Science and Nanotechnology Jadavpur University

Kolkata - 700032, India

CERTIFICATE OF APPROVAL

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School of Materials Science and Nanotechnology Jadavpur University

Kolkata - 700032, India

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I hereby declare that this thesis titled "**STUDY OF DROPLET IMPACT ON FLEXIBLE SURFACE**" contains literature survey and original research work by the undersigned candidate, as part of my Degree of Master of Technology in Nano Science and Technology.

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.

Name (Block Letters) : AYAS KUMAR DAS

Class Roll No : 002230701006

Registration No : 163811 of 2022-23

Examination Roll No : M4NST24006

Signature Date

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1 INTRODUCTION

1.1. Motivation

Droplet impact is a common physical occurrence in many industrial and natural processes. Examples include pesticide splashing and raindrops landing on insect wings on the food business, coffee stains, plant leaves, and inkjet printing [1] Droplet-substrate interaction physics has drawn interest from a variety of scientific fields, including materials science, aerospace, healthcare, electronics, coatings, and printing. The following physical phenomena were shown in earlier research about droplet impact on rigid substrates: deposit (adhesion), breakup (fragmentation), immediate splash, corona splash, partial bounce, and complete bounce. The interaction between the droplet impact mechanism and the elasticity of the material makes the physical process of a droplet impact on an elastic material much more difficult [2-6]. A substrate's mechanical characteristics, such as its material stiffness and elasticity, will be crucial to the intricate physical process involved in the droplet impact into soft materials [7-8]. These factors are in addition to the substrate's roughness and chemistry [9]. Soft substance displays a Young's modulus of elasticity between 1000 Pa and 1 MPa[10]. Soft material is classified as flexible and elastic material. The mechanics of droplet impact on stiff surfaces have been thoroughly researched; however droplet impact on a flexible surface has not attracted a lot of interest [11-12]. These effects may have biological ramifications, such as how raindrops affect leaves, and they may be significant for industrial uses, such as piezoelectric raindrop energy harvesters [13-15]. A surface or substance that can withstand bending or deformation without losing its structural integrity is referred to as a flexible substrate. It usually has a certain degree of rigidity or stiffness. When it comes to flexible substrates, surface deflection and oscillation are important factors that change the dynamics of impact. On the other hand, low stiffness or rigidity and natural complaints are characteristics of a soft substrate. Soft substrates can be bent or stretched significantly without producing large restoring forces because of their high deformability. There are, however few, earlier research on droplet impact on elastic surfaces, including droplets bouncing on a soap film [16], striking rain [17], and affecting a circular membrane [18]. Research has also been done on the effects of droplets on soft polydimethylsiloxane (PDMS) surfaces [19, 20]. However, the response of hydrophobic elastic surfaces to droplet impacts has not been examined. The capillary deformation caused by interfacial forces, which can alter the static contact angle, its hysteresis, and the droplet impact phenomenon, is the primary distinctionbetween soft and stiff substrates [21].

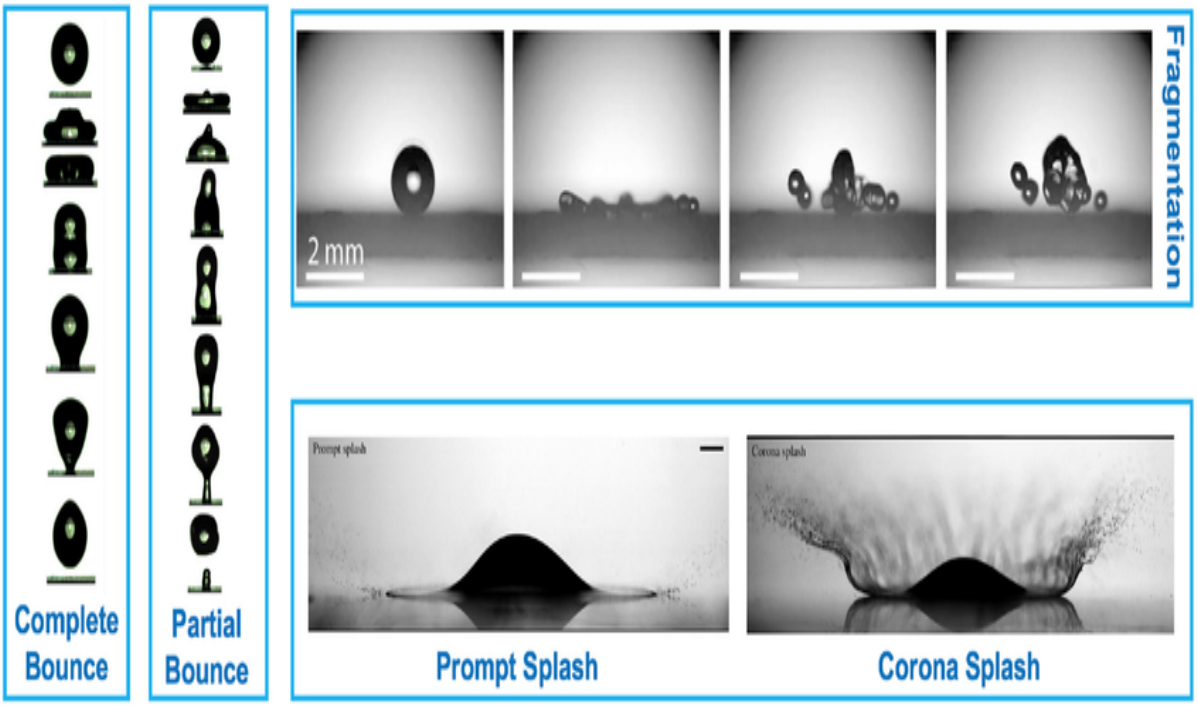


Figure 1 *Physical events during droplet impact on a rigid substrate.54,106,107 Reprinted from The Journal of Fluid Mechanics, 892, Burzynski, D. A., Roisman, I. V., and Bansmer, S. E, Weisensee, P. B., Tian, J., Miljkovic,N., King, W. P. 'Water droplet impact on elastic superhydrophobic surfaces', 30328, Copyright (2016), with permission of Springer Nature. Reprinted*

The effect of droplets on soft materials is a topic of great interest for modern technologies such as flexible printed electronics, improved functional materials, creation of functioning organs, tissue engineering, smart biomaterials, biosensor development, nanomaterial manufacturing, and defence against the COVID-19 epidemic, high resolution additive manufacturing, bio-printing, nano-printing, three-dimensional (3D) printing, and energy performance in biological medicine [22]. Consequently, a great deal of attention needs to be paid to the mechanics of droplet impact on soft materials. An overview of research on the physics of droplet effect on flexible materials is provided our course of study. A few uses of the droplet impact on soft materials are shown in the sections that follow. The physics of droplet impact on a substrate is next examined, along with the introduction of relevant non-dimensional factors. Following that, a detailed discussion of an overview of earlier research on the influence of droplets on flexible materials is provided.

In this section droplet impact on soft material in these advanced technologies is presented in details.

1.1.1. Coating and Printing

Among the many printing methods, droplet printing on soft viscoelastic materials has drawn a lot interest in the rapidly developing technologies of today, such as, this includes the creation of soft biomaterials, smart materials, flexible printed electronics, and improved functional materials. It is possible that the droplets contain biopolymers, biological liquids, and electronic conducting fluids. According to a recent study *odak et al.* [2020], enhanced flexible electronic materials can be produced by printing droplets comprising conducting solutions (silver inks) and polymers onto soft tapes. The "cavity collapse-driven single-micro-droplet ejection" method, which is seen in, uses a force balance between the impacting droplet's dynamic pressure and the groove's breakthrough pressure to impact the droplets into a super-hydrophobic groove. Furthermore, droplet impact on flexible materials has demonstrated a significant impact on 3D bio-printing for biomedical development.

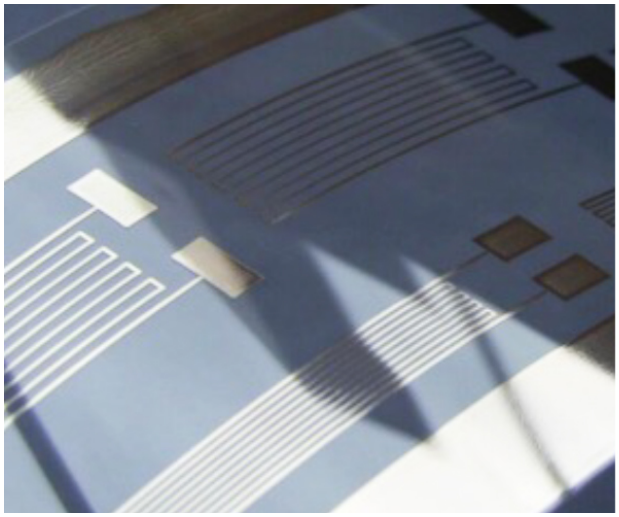


Figure 2:*Printing on a Flexible surface (Welsh Centre for Printing and Coating (WCPC), based within Swansea University (Wales, UK)*

In case of the impact of a biological droplet on a Teflon-coated surface using DMEM (Dulbecco's Modified Eagle Medium). Following the drying stage, the Teflon-coated substrate retained its hydrophobicity while the DMEM droplet turned hydrophilic. As a result, the surface develops a wettability gradient with the biological sample for use in studies using cell cultures [23]. Printing droplets is one of the many biological uses for three-dimensional bio-printing including proteins, living cells, and DNA molecules adhered to soft materials. In stem cell research, tissue engineering, 3D smart biomaterial production, biosensor manufacture, 3D functional organ fabrication, and gene expression analysis, three-dimensional bio-printing is a cutting-edge technology.

1.1.2. Biotechnology and Healthcare

Millions of lives were lost globally as a result of the COVID-19 pandemic, primarily due to the spread of SARS-CoV-2 droplets within communities [24].The typical It was discovered that the virus is propagated through aerosol-based SARS-CoV-2-laden respiratory droplets that are exhaled, coughed, and sneezed by infected people face masks were displayed in an effort to stop its social spread [25].Consequently, it is essential to comprehend the physical effects of droplet impact on soft face masks as well as the adherence and deposition of respiratory SARS-CoV-2-loaded impacting droplets onto soft super-hydrophobic face masks [26]. Furthermore, the COVID-19 pandemic has brought to light the Lack of thorough understanding regarding the way respiratory droplets interact with different types of skin and surfaces, including face masks that are soft and super-hydrophobic face masks used as personal protective equipment [27].

1.1.3. Flexible Printed Electronics

The technology used to create electronic devices based on the printing principle is known as printed electronics [28]. The printing machine uses electronic inks, which have the characteristics of being conductive, dielectric, semi-conductive, or magnetic, in contrast to standard printing methods. It is possible to print circuits on substrates other than silicon and glass, such as plastic, paper, and more flexible materials, as printed electronics is intimately associated with a variety of sectors, including organic electronics, plastic electronics, flexible electronics, and paper electronics [29]. The process by which organic and inorganic electronic components are placed on a flexible substrate to create a circuit is known as "classical flexible electronics"[30]. The rigid circuit board limits the electronics' ductility and flexibility even though it can shield the components from harm. Flexible electronics offers many potential applications in the fields of information, energy, medicine, and defence technology due to its intriguing properties like softness, ductility, and low-cost fabrication. These fields include the creation of smart sensors, actuators, flexible displays, organic light-emitting diodes (OLEDs), and more [31]. The most noticeable feature of flexible electronics is their flexibility in comparison to conventional rigid microelectronics; this flexibility allows them to be swiftly printed, stretchy, conformal, portable, and wearable [32].

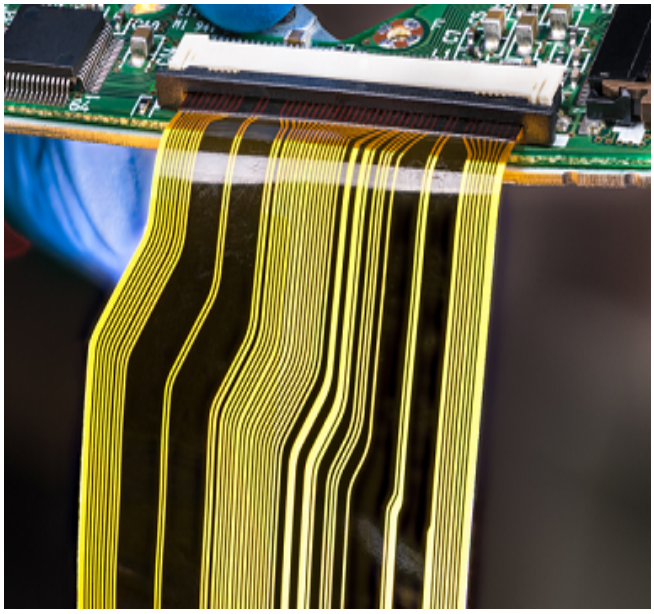


Figure 3: *Flexible Printed Electronics devices*

It is evident that flexible printed electronics (FPE) blends printed electronics and flexible electronics characteristics. This allows for the speedy production of flexible, functional electrical devices. Research on flexible printing has gained popularity as printing technology has advanced. Tapping mode printing, aerosol jet printing, roll-to-roll technology, inkjet printing, and micro-pen and brush printing [33] are just a few of the common printing technologies that have recently emerged.

1.1.4. Fabrication of Smart Biomaterials

The frontiers of contemporary medicine have been greatly expanded by the development of smart biomaterials. Because of their special properties that allow them to adapt to changes in their environment, these classes of biomaterials can be used as an "on-off" switch for a variety of applications at both nano-scale and macro-meter scales. For example, intelligent biomaterials can direct stem cells to improve tissue regeneration, which has a wide range of uses in tissue engineering. In order to encapsulate and release cells or medications in a controlled manner, they can also self-fold or self-unfold, creating an intelligent.

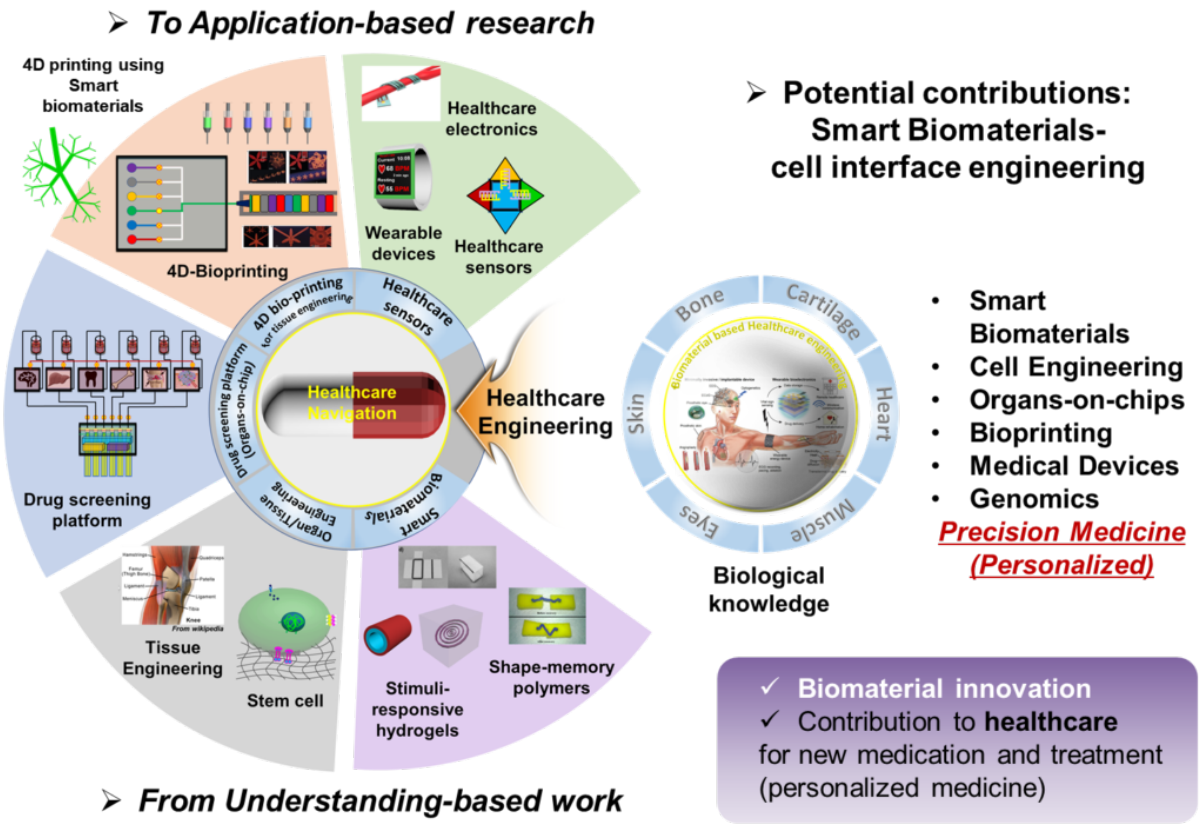


Figure 4:*Smart Biomaterials devices in schematic*

Inventive biomaterials are being discovered and developed by millions of researchers worldwide. These biomaterials may exhibit exceptional properties in a variety of applications, from therapeutic therapies to intricate diagnostics [34]. In particular, there is now a greater need for personal protective equipment, emergency medical care, diagnostic kits, medication, and vaccines in the wake of the COVID-19 outbreak, which has caused misery for individuals all over the world. A paradigm change from the usage of conventional biomaterials—which currently lack numerous functionalities—to the creation of more intelligent systems is required to address this growing demand . Incorporating stimuli responsive materials into the system could be a sensible approach

1.1.5. 3-D Bio-printing

Three-dimensional (3D) bio-printing is the use of methods similar to 3D printing to combine cells, growth factors, bio-inks, and biomaterials to create functional structures. These structures were originally used for tissue engineering applications, but there has been a recent surge in interest in other uses, including environmental remediation and bio-sensing [35]. In 3D bio-printing, materials known as bio-inks are typically deposited layer by layer to generate tissue-like structures that are subsequently used in a variety of medical and tissue engineering applications [36]. A wide variety of bio-printing methods and substances are

included in 3D bio-printing. Currently, tissue and organ models may be printed via bio-printing to aid in the study of medications and possible therapies [37]. It has been demonstrated that 3D bio-printed artificial organs, such livers and kidneys, lack vital components that impact the body, like functional blood arteries, urine-collecting tubules, and the development of billions of cells needed for these organs. The body cannot obtain the necessary nutrition and oxygen from deep inside itself without these components [38]. Since various cell types naturally make up every tissue in the body, there is variation in the capacity of various printing technologies to maintain the stability and survival of the cells throughout the production process. Several techniques are employed for the 3D bio-printing of cells, including direct cell extrusion, stereolithography, photolithography, and magnetic 3D bio-printing.

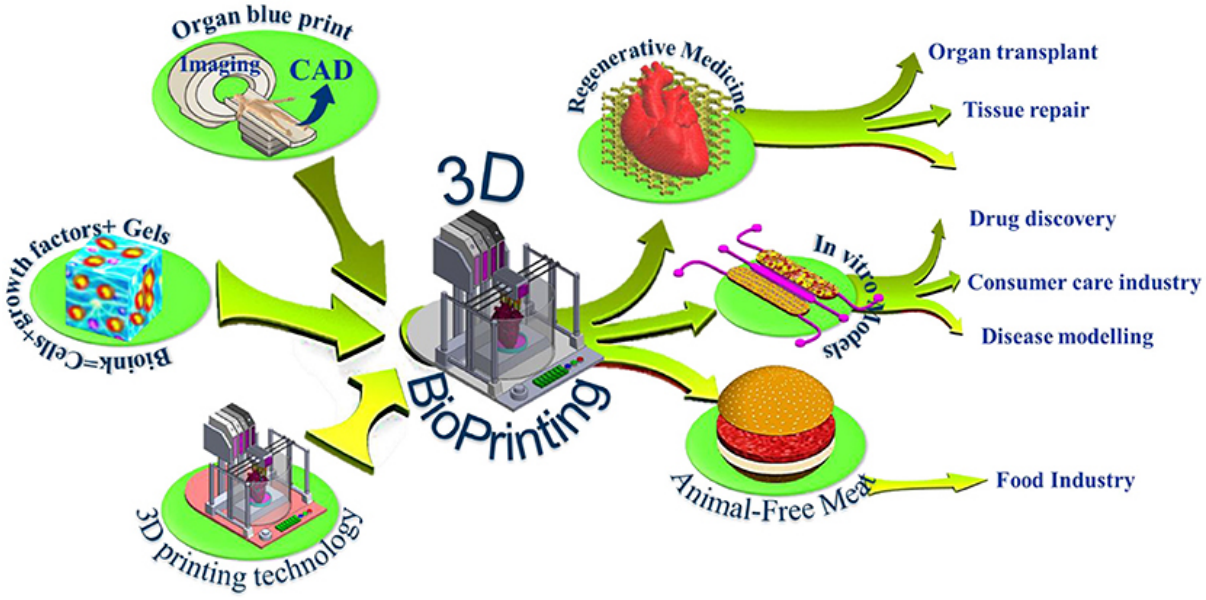


Figure 5:*3-D Bio-printing, Qasem Ramadan, Mohammed Zourab, College of Science and General Studies, Alfaisal University, Riyadh, Saudi Arabia*

1.1.6. Pesticides

The two main issues facing the world's rapidly growing population are food security and environmental preservation. The Food and Agriculture Organisation (FAO) defines a pesticide as any substance or combination of substances intended to prevent, eradicate, or control any irritation, including vectors of human or animal disease, undesirable plant or animal species. The US Environmental Protection Agency defines pesticides as substances meant to suppress weeds and pests (US-EPA, 2018). According to Carolyn *et al.* (2013), pesticide refers to a broad range of products, including herbicides, insecticides (which can include insect growth controllers, termiticides, and more), nematicides, piscicides, avicides, rodenticides, molluscicides, bactericides, antimicrobials, bug repellents, creature repellents,

fungicides, and disinfectants. Herbicides are the most well-known of them, accounting for over 80% of all pesticide applications [39]. Chemicals known as pesticides are applied not only to agricultural land but also to residential gardens, railway medians and other public spaces. Because of the expanding global population and the demand for increased food supply, it is anticipated that the use of pesticides for crop protection would rise.

1.1.7. Classification of Pesticides

All insecticides, fungicides, herbicides, rodenticides, garden chemicals, wood preservatives, and household disinfectants that can be used to kill certain pests are together referred to as "pesticides." Pesticides come in a variety of forms with distinct chemical and physical characteristics. Pesticides can be categorised primarily into three groups: those based on the

- The method of action [40].
- The targeted pest species, and,
- Chemical composition of the pesticides

1.1.7.1. Classification of Pesticides based on Mode of Action

Pesticides are divided into two categories under this kind of classification: non-systemic and systemic. Pesticides classified as non-systemic are those that do not significantly pierce plant tissues and are not, therefore, carried by the plant's vascular system. Conversely, systemic insecticides are those that efficiently enter plant tissues and are carried throughout the plant's vascular system to produce the intended result [41].

1.1.7.2. Classification of Pesticides based on Targeted Pest Species

The most common classification is probably based on the target pest. Herbicides target plants, whereas insecticides are chemicals that specifically target insects. The rest are avicides, virucides, bactericides, molluscicides, fungicides, acaricides, and miticides.

1.1.7.3. Classification of Pesticides based on Chemical Composition

Pesticides are classified based on their chemical composition and active components in this sort of classification. This type of classification is the most helpful for researchers looking into the relationship between pesticides and the environment, as it provides information on the physical and chemical characteristics of each pesticide, its effectiveness, application rates, and necessary precautions. This information is crucial for choosing the best application method. Pesticides can be broadly classified into seven groups based on their chemical

properties: azotic heterocyclic compounds, carbamates, pyrethroids, amides, anilins, organochlorines, and organophosphorus [42]. In the environment, these pesticides frequently build up and last because of their stable chemical structures. The majority of them are frequently employed as insecticides to manage a variety of insects. Organochlorine pesticides cause disruptions to the neurological system, which causes the insect to convulse, become paralysed, and eventually die.

Another class of extremely dangerous pesticides with a phosphate group is called an organophosphate; as of 1997, 48.6% of all pesticides were organophosphates [43]. Due to their application as weaponry during World War II, synthetic organophosphates became much more significant. Since then, a variety of industries and fields, including agriculture, manufacturing, cosmetics, and medicine, have used these insecticides [44]. These substances block the action of the acetylcholinesterase enzyme, which is responsible for hydrolysing acetylcholine in the neurological systems of several animals, including humans.

Organic pesticides called carbamates are generated from carbamic acid and reversibly deactivate the acetylcholinesterase enzyme. Unlike that of organophosphates, the cholinesterase inhibition of carbamates is species-specific and reversible [45]. Pyrethroids, which are synthetic versions of pyrethrins derived from the flowers of the pyrethrum plant (Chrysanthemum cinerariaefolium), were discovered in the 1980s to have insecticidal properties similar to those of the natural pyrethrum. Pyrethroids are known for their quick knockdown of insect pests, easy biodegradable. As a result, over the past 30 years, pyrethroid use has significantly increased.

In recent times, there has been a widespread use of amino herbicides, including butachlor, metolachlor, and acetochlor. Even worse, butachlor and metolachlor have been found to be mutagens. Nevertheless, they can linger in the environment for up to ten weeks. Pesticides are categorised based on the mode of formulation, activity spectrum, and toxicity level in addition to these classifications. Pesticides are divided into six classes based on how they are formulated: wettable powders, emulsifiable concentrates, baits, granules, dusts, and fumigants. Broad-spectrum and selective pesticides are the two categories into which active spectrum pesticides are divided.

The purpose of broad-spectrum pesticides is to eradicate a variety of nontarget organisms and pests. Conversely, insecticides that are selective are made to kill only those kinds of pests. Pesticides are divided into the following classes based on their potential to endanger human health: class Ia, which is extremely hazardous; class Ib, which is highly hazardous; class II, which is moderately hazardous; class III, which is slightly hazardous; and class IV, which is

composed of products unlikely to cause acute hazards under normal use. This toxicity level classification system was developed by the World Health Organisation (WHO).

1.2. Effect of Raindrops on Plant Surface

Raindrop impact on leaves is a frequent occurrence that has implications for many processes, such as the spread of diseases and propagules, erosion of leaf wax, gas exchange, absorption of water by the leaf, and canopy-mediated rainwater interception and storage. Raindrop impact is a phenomenon that natural surfaces frequently encounter. Raindrops can achieve maximum velocity of around 9–10 ms^{-1} and sizes of several millimetres. Owing to its speed and the water's high density, a raindrop can grow fairly large forces upon impacting a surface in relation to its size. While the engineering sciences, physics, and chemistry—especially in this case, the physical chemistry of surfaces is all very interested in drop impact [46]. A leaf normally comprises of a lamina and a petiole. Between the lamina and the stem, the petiole is a slender supporting structure that links and transfers nutrients. Typically, the lamina has a flat, blade-like form. The leaf continues to move in different directions in reaction to outside pressures because of the lamina's flatness: such as the wind, animal contact, and precipitation. The consequences of raindrop impact on plant surfaces are especially significant. For the dispersion of seeds or propagules, the impact energy of a drop may be significant. However, the most frequent (and hydrologically and ecologically significant) raindrop impact event on plant surfaces is when they strike leaves [47]. There are numerous related subjects. For instance, the hydrological cycle is affected by interactions between raindrops and leaves because leaves have the ability to collect and store water from rainfall before it reaches the soil. The leaves themselves are also affected by being exposed to rains in a variety of ways. Getting wet in the rain can have unfavourable effects. As an example, the effect of rains can directly impact the leaf surface by causing waxes to erode. When a water layer blocks stomatal openings after wetting, it might inhibit gas exchange and hence photosynthesis. Furthermore, infections can be transferred and ultimately deposited on leaves in a manner similar to how drop impact disperses propagules (*Kim et al.,* 2019; Bourouiba, 2021). Wetness encourages the growth of an epiphytic layer on leaves and the infection of plants with diseases, especially fungus/pathogen. Plant diseases can account for up to 60% of the world's yearly wheat loss, aggravating the situation of the billion undernourished people globally. Re-emerging rust strains have the potential to destroy one-third of all wheat crops in the near future. Plant pathogens consistently cost the United States of America more than $220 billion a year [48]. Even though plant morphologies vary widely, rainfall has been found to be a common antecedent to outbreaks of foliar diseases. In fact, moisture promotes the

disintegration of mucilage and the development of fluid on leaves that is loaded with pathogens.

Rainfalls spread foliar diseases caused by bacteria and spores that are trapped in sticky t mucilage.Splashing and inertial ejection are two possible outcomes that could effectively propel infections away and towards the next plant when they are suspended in these sessile water droplets. When it splashes, the raindrop strikes the leaf next to the tainted liquid residue and forcefully pushes it away from the leaf. Subsequently, the tainted liquid is stretched into a film that fragments into numerous droplets. The raindrop does not always come into contact with the liquid residue during inertial ejection. However, it bends the leaf so far that inertial forces split and eject the contaminated sessile drop when the leaf springs back. The researchers discovered that within ten minutes of water striking a plant's leaf surface, thousands of genes, hundreds of proteins, and several growth hormones are all impacted. According to recent research on the fluid dynamics of the spread of human disease, an infected host's pathogen footprint is influenced by thesize distribution of the droplets containing pathogens that it exhales.

For instance, during violent expirations, this is the situation like sneezes [49]. The pathogen load and expelled pathogen-bearing droplets' size can be determined their range of deposit. The transmission of pathogen depends on the Size of the droplet i.e., smaller droplet contains less pathogen as compared to larger droplets. For smaller droplet the mode of transmission of pathogen from an infected leaf plant to healthy leaf plant is less in comparison to larger droplet size.

Because of its statistical associations with rainfall, rain intensity—which is defined as the amount of rainwater per unit of time and area—has frequently been proposed as an epidemiological predictor Outbreaks of foliar diseases. In this instance, the primary a scenario that explains the connection between rainfall intensity and dispersal is the area where raindrops are shown to splash on film hypothesised to affect polluted fluid covering thin films diseased leaves. The impact of rainfall amount on trans-foliar pathogen port has been a significant undertaking. This review will discuss the drop impact itself, the physical processes it starts, how it directly affects the leaves, and how leaf characteristics affect the result. Among the Wettability is one of the key determinants of drop impact and is thought to be especially important. Thus, this presentation will begin with a synopsis of wettability in relation to recent discussions. Additionally, if and to what extent elements like "wettability,""roughness," and "contact angle" matter for drop impact will be covered.

In our present course of work mainly focuses on the deposition of pathogen containing droplet on a plant leaf.In our course of work we consider flexible surface as leaf and surface

is kept in cantilever design and we examine the behaviour of surface upon impact i.e., deflection, frequency of vibration etc.

1.2.1. Surface Wettability

The capacity of a water droplet to retain contact with a solid surface is known as surface wettability, and it is defined by the contact angles of the droplet on the surface. The water repellence of the surface is also indicated by it. For Understanding the wetting properties of a solid surface, or any two materials, is crucial to understanding their bonding and adhesion strength. While the cohesive forces in a liquid prevent it from spreading over a solid surface, the adhesive forces in the liquid aid in its spread across a solid surface. Therefore, it's critical to comprehend if a solid surface is hydrophobic or hydrophilic, as this can be determined utilising the contact angle measurement.

1.2.2. Types of Wettability

Non-reactive wetting: This type of wetting, also known as inert wetting, occurs when a liquid is spread out across a solid surface without causing any interaction or absorption at the interface.

Reactive wetting: Wetting occurs when there is a reaction or influence from the liquid on the solid medium during the liquid-solid medium contact process.

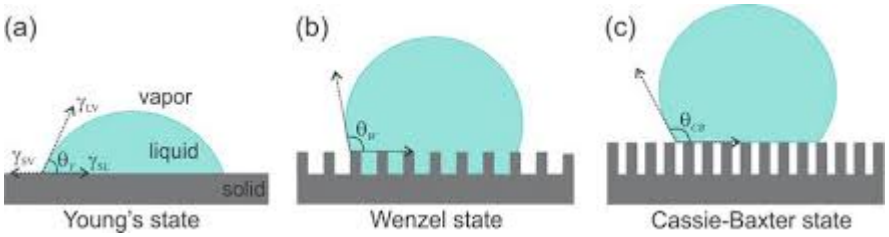


Figure 6*Schematic Representation of types of wettability,*

Interaction of Wetting on different Surfaces

It is crucial to understand the type of solid surface that the liquid interacts with since it affects the wettability of the liquid. There are two types of solid surfaces: high-energy and low-energy [50].

High energy solid surface: Materials with strong chemical bonds, such covalent and ionic bonding, such as metals, ceramics, glasses, etc., are solids. Larger forces are required to break the bonding and achieve complete wetting of the liquids on these surfaces when they interact with one another.

Low energy solid surface: These are solids whose molecules are bonded by hydrogen bonds, van der Waals forces, or other weaker molecular bonds, such as hydrocarbons or

fluorocarbons. The type of liquids used will determine whether these surfaces are completely or partially wet.

1.2.3. Measuring of Wettability

One qualitative method of determining the wettability of the liquids is the contact angle, which establishes whether the solid surface is conducive to wetting or not. The term "low contact angle" refers to a contact angle that is less than 90 degrees, indicating that the surface is suitable for wetting. It is referred to as a high contact angle when the angle of contact is less than 90 degrees, meaning that the surface is not suitable for wetting. This interaction on the solid surface of water can be referred to as the material's hydrophilic and hydrophobic characteristics.

Hydrophilic surface: A surface is referred to as hydrophilic if it draws water and allows droplets of water to spread out across it. With a low contact angle, the surface has excellent wettability. In this instance, there is a strong adhesive force between the liquid and solid.

Hydrophobic surface: When a surface repels water, it is referred to as hydrophobic since the water does not spread across it. With a high contact angle, the surface's wettability is regarded as poor. The dominant force in this liquid-solid interaction is the cohesive force.

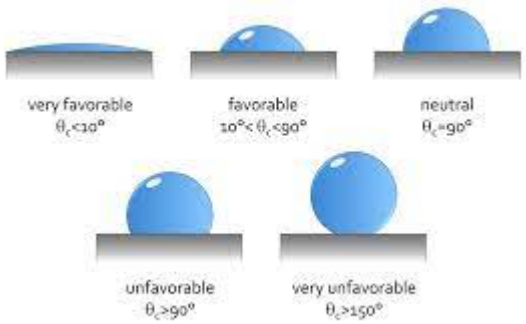


Figure 7:*Schematic representation of contact angles and wettability*

1.2.4 Contact Angle

The angle that separates the liquid-air interface's tangent at the three-phase line from the solid surface is known as the contact angle. According to the figure, it is measured in the droplet's inward direction. The contact angle of a droplet that is stationary on a solid substrate is referred to as a static contact angle. Wetting behaviour of static liquid droplet is described by static contact angle. Thomas Young presented a mathematical formula for calculating the static contact angle in with the aid of surface tension in 1805. Young's Equation is the name of it [51].

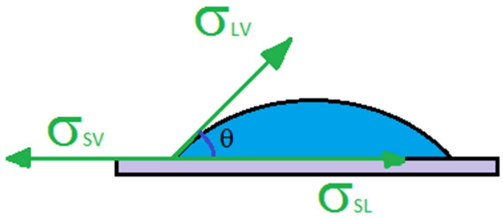


Figure 8:*Sessile Droplet on Solid Substrate*

σSV–σSL=σLVcosθ ..... (1)

Where σSV, σSL and σLV are solid-vapor, solid-liquid and liquid vapor surface tensions respectively. Contact angle hysteresis, which is the difference between the two contact angles at the droplet's sides if they are not equal, is a sign that the solid substrate is not horizontal. The static contact angle displays the relative molecular interactions in liquid, solid, and stages of vapour.

1.3. Literature Review

The important literature that has been studied regarding the impingement of base fluid droplets on soft super-hydrophobic surfaces is discussed in this part. However, a comparison of the behaviour of solely base fluids when they impact upon rigid super-hydrophobic surfaces should be made. We can nearly witness droplet impact on solid objects all around us. For instance, fog creation, steam cooling, or rain. But because of its significant uses in spray cooling, inkjet printing, and pesticide painting, scientists all over the world are enthusiastic about its potential to improve human existence. Soft materials are classified as elastic and flexible materials. In our course of work the focus is on flexible material. The impact of surface roughness and Weber Number (a dimensionless number in fluid mechanics which measures the relative importance of fluid's inertia compare to its surface tension), surface roughness and determine the spreading, recoiling, oscillating and splashing of the droplet. The work's conclusions includenormalised drop height, normalised drop radius, and change in configuration how theseeffects the behaviour of liquid droplet after impact and behaviour of flexible super-hydrophobic surface i.e., deflection, frequency of vibration, torque, damping ratio, Bending energy etc. The droplet flattens and its kinetic energy is transformed into surface energy as it strikes the surface and is redirected in a lateral direction. This kinetic-to-surface energy conversion mechanism is highly effective on low-friction surfaces, leading to very little energy dissipation due to the viscous effects. The reverse surface-to-kinetic energy conversion process starts when all of the kinetic energy has been transformed into the surface energy of the flattened droplet, causing the droplet to retract and lift off in a vertical direction. The entire contact time, or etc, between the initial collision and lift-off affects the mass,

momentum, and the transfer of energy between the solid and the droplet. Thus, controlling the duration of contact by means of the liquid-solid interface transport mechanisms are determined by the control of the internal flow physics. The droplet size controls the contact time of water impact on a stiff, planar super-hydrophobic surface. The droplet expands, achieves its largest diameter, retracts completely, and rises vertically off the surface upon impact [52]. The flexible super-hydrophobic substrate oscillates as a result of the force the droplet applies to it upon impact. The substrate's upward motion during oscillation controls the impacting droplet's contact time decrease, which speeds up the flattened droplet (~D_{max}) moving vertically against the force of gravity. The droplet separates prior to completing the entire surface-to-kinetic energy conversion process due to the additional upward force from the elastic substrate. The droplet maintains its spread, pancake-like form during early departure. Because of the springboard effect, which is inspired by the elastic-to-kinetic energy exchange of a vertically accelerated elastic membrane or spring that aids in a jumper's rebound, we refer to this early lift-off process as springboarding or the springboard effect. The balance between internal and external forces, such as electric and magnetic fields, governs how a droplet interacts with a substrate analogous interfacial physics [53]. Gravity, viscosity, and interfacial tensions are the governing physical forces

A droplet on a soft, flexible substrate is shown in Figure in its stationary state with interfacial pressures operating along the interfaces as a result of the droplet's impact deforming the soft substrate.

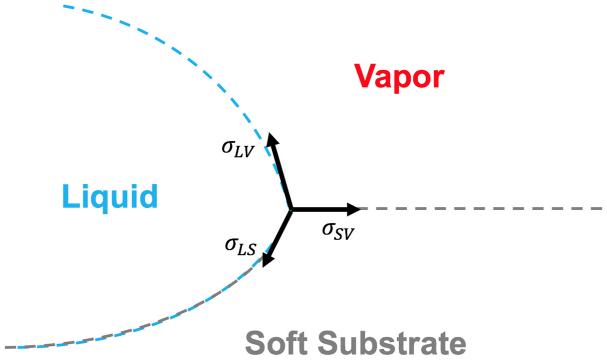


Figure 9: *Schematics of droplet onto a soft solid surface and the interfacial tensions along the interfaces. σ_{LV}: liquid-vapour interfacial tension; σ_{LS}: liquid-solid interfacial tension; σ_{LV}: solid vapour, Reprinted from Current Opinion in Colloid and Interface Science, 52, Liao, M., Liu, H.,Wang, X., Hu, X., Huang, Y., Liu, X., Brenan, K., Mecha, J.,Nirmalan, M., and Lu, J. R.*

The viscous dissipation is caused by droplet motion on a substrate being resisted by viscosity. Droplet stiffness is caused by interfacial stresses when it comes into contact with the content. The droplet puddling caused by gravity may not be significant since the droplet diameter is smaller than the capillary length. Physics of droplet impact may also be significantly

influenced by outside factors. Acoustic waves, electric and magnetic fields, dynamic pressure, substrate roughness, substrate chemistry, and substrate mechanical properties are the causes of the external forces.

Droplet impact physics is generally described by the Reynolds number (ratio of inertia to viscous effects) and the Weber number (ratio of inertia to capillary effects).Additional non-dimensional numbers might be introduced in the droplet impact physics due to the external forces (electric filed, magnetic field, vibration, wind and obstacles), substrate roughness, substrate chemistry and mechanical properties of the substrate. The droplet impact physics may introduce additional non-dimensional numbers as a result of external forces (such as vibration, magnetic fields, electric fields, and wind and impediments), substrate chemistry, substrate roughness, and substrate mechanical characteristics [54]. In the past few decades, research on droplet impact physics on soft, flexible materials has advanced significantly thanks to incredible high-speed imaging capabilities and computational fluid dynamics' capacity allowed for the quick physical occurrence to be made clear. Through experimental, computational, and theoretical efforts, a number of physical parameters relevant to the physics of droplet impact on smooth soft materials were examined. These parameters included force, drag, pressure, and shear stress, droplet form, air cushioning, and many more [55]. A substrate's mechanical characteristics, such as its roughness and chemistry, are important considerations in the physics of droplet impact on flexible substrates including stiffness and elasticity are vita. In interfacial science and technology, material deformation caused by droplet impact is important for many characteristics, including as adhesion, condensation, freezing growth, and evaporation. The physics of droplet impact on smooth and rough soft materials are covered in the sections that follow.

1.3.1. Droplet Impact on Soft Smooth Surface

According to reports, the substrate shear modulus and surface deformation are inversely correlated [56]. *Chen et al.* determined the physical interactions between the droplet and the soft substrate in order to experimentally study the impact physics of water droplets on soft viscoelastic hydrophobic substrates for a wide range of the Weber numbers.

The droplet spreads and deposits on the soft material at larger Weber numbers, while at smaller Weber numbers it bounces off the material.

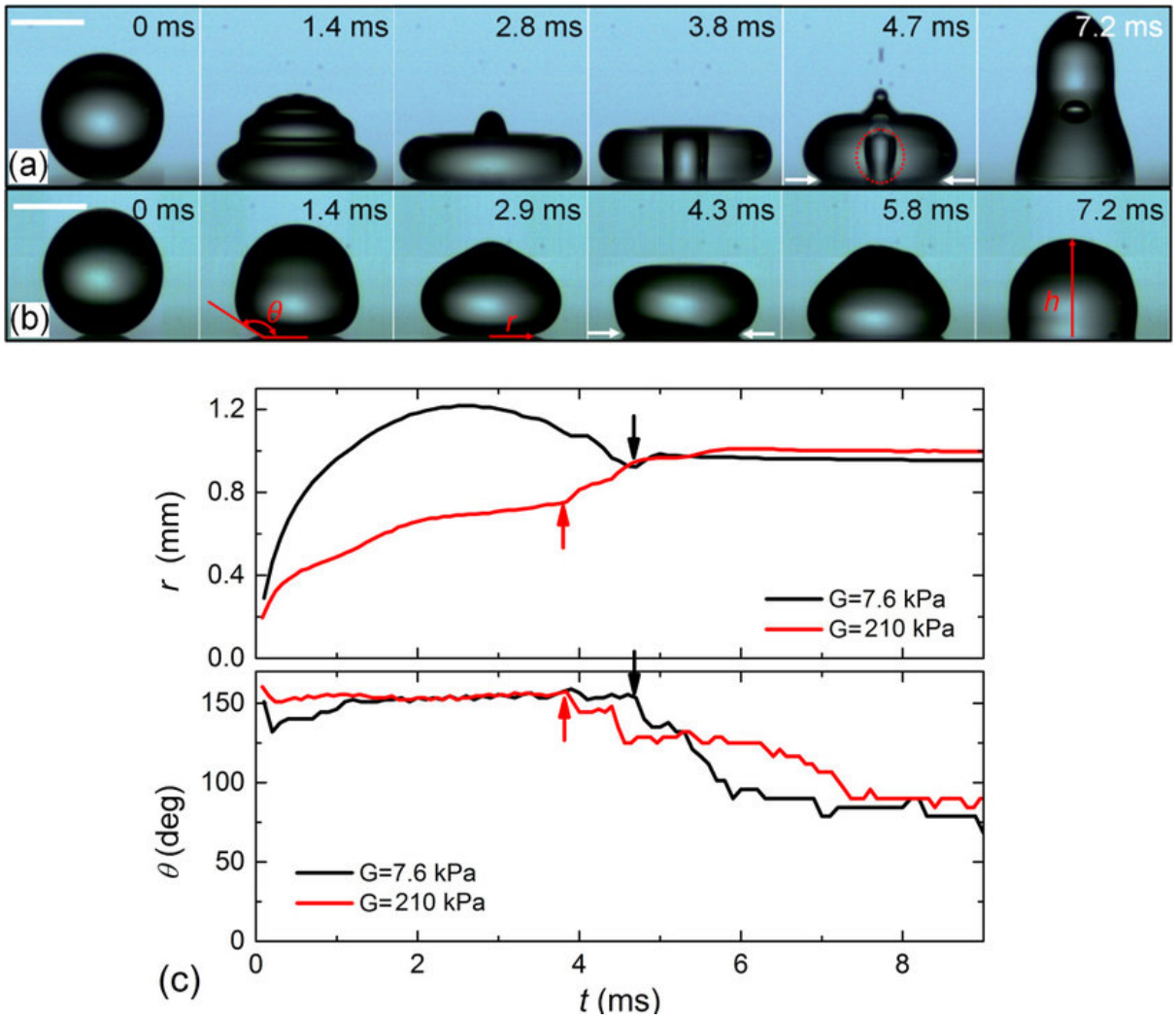


Figure 10:*Droplet impact on soft visco elastic surface (PDMS) Longquan Chen,* ElmarBonaccurso, Peigang Deng, and Haibo Zhang*

When a droplet is deposited on a soft substance, air bubbles become trapped inside it at a modest Weber number. A comparable mechanism for droplet impact on inflexible substrates was found.

Droplet does not bounce off of the soft viscoelastic materials with big Weber numbers. On the other hand, it was seen that the droplet partially bounced off of stiff objects. Similar to this, an elastic droplet bounces back off of a hard, super-hydrophobic substance.The dynamic of droplet dispersal after impacting a soft material is unaffected by the elasticity of the soft material [57].

Nonetheless, the wettability of the soft material controls the mechanical vibration of the droplet following impact on a flexible viscoelastic material.

Researchers *Langley et al*. looked into how soft substrate elasticity affected the development of an air layer and air bubbles beneath the droplet at the beginning of impact on the elastic

materials using an incredibly quick imaging method The photos of the air entrapment dynamics following an ethanol droplet impact on a glass substrate are shown in along with a comparison with an ethanol droplet impact on a soft (flexible) silicone substrate. The air layer forms beneath the droplet after impact, but its compressibility is delayed by the elasticity of the soft substance. The material's elasticity results in the formation of thicker air layers than those that formed underneath the droplet after impact with the stiff materials [58].

Chen and Bertola used high-speed imaging to examine the physics of a water droplet impact on a curved soft elastic material while taking into account variations in the curvature and elasticity of the material. Additionally, throughout a wide range of impact Weber values, their calculations and observations were compared. Research has demonstrated that a rise in the curvature of the elastic material causes more droplets to retreat from the soft material. The dynamic contact angle formed by a droplet impacting on an elastic curved material is determined by three factors: the impact Weber number, the material elasticity, and the curvature of the material[59].

Viscosity dissipation occurs as a result of soft material deformation following a droplet impact on an elastic, curved, or flat substrate.

The application of elastohydrodynamic lubrication, or soft lubrication, for a variety of systems, including stereolithography and biological adhesion, has received a lot of interest lately.

Experiments in this branch of technology have demonstrated that the elasticity of a soft material governs the kinetics of droplet impacts on it [60].

Similarly, it was observed that the contact line dynamics or the mechanical deformation of the soft material due to energy absorption influence the droplet impact physics.

1.3.2. Droplet Impact on Soft Rough Surface

Weisensee et al. demonstrated how the elasticity of the material influences the droplet impact mechanics on a soft, rough substance. Here it illustrates the droplet physics impact dynamics at very high impact velocities of 1.58 and 1.57m/s respectively into an elastic flexible superhydrophobic surface and a rigid superhydrophobic surface. Droplets break up and splash when they hit a rigid superhydrophobic surface, but they splash when they hit an elastic superhydrophobic surface, the droplet lifts off in a pancake-shaped pattern as the substrate vibrates [61]. Half of the time that a droplet is in touch with a rigid superhydrophobic substrate is the duration that a droplet is in contact with an elastic superhydrophobic substrate. The

impact of a water droplet on a smooth and patterned superhydrophobic substrate with different elasticity levels was investigated by *Alizadeh et al.* in relation to the role of material elasticity [62]. The elasticity of the material through the viscoelastic energy dissipation event determines the droplet's ability to spread upon and retreat from a soft substance.

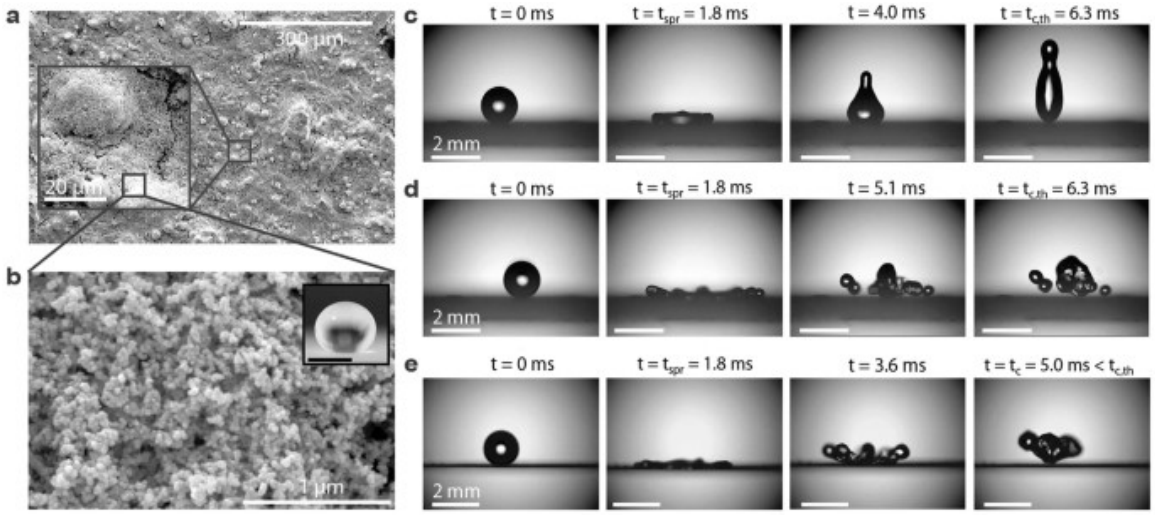


Figure 11*: Surface characterization and dynamic behaviour of water droplet impact on rigid and elastic superhydrophobic surfaces Patricia B. Weisensee, JunjiaoTian, NenadMiljkovic& William P. King*

It has been demonstrated that a soft material's decreased elasticity causes the droplet retraction from the soft substance to decrease. On a more elastic soft material, a droplet of water spreads less. There haven't been many studies done to try and understand how material roughness affects droplet impact on soft, flexible materials. Using high-speed photography, the mechanisms of droplet penetration and dispersion inside the pores of a rough, flexible material were examined. The outcomes were compared to their simulations [63] to this test was done to see how blood droplets would react to rough, flexible materials. Additionally, new attempts have been made to study the droplet response to an impact on a soft, flexible material. Recently, Banitabaei and Amirfazli investigated the impact speed and wettability of the spherical particles on droplet collisions with arrays of spherical particles.

It was demonstrated that the contact duration between a droplet and the superhydrophobic soft substrate is significantly shorter when droplets impact on an elastic superhydrophobic surface than when droplets strike on a rigid superhydrophobic substrate.

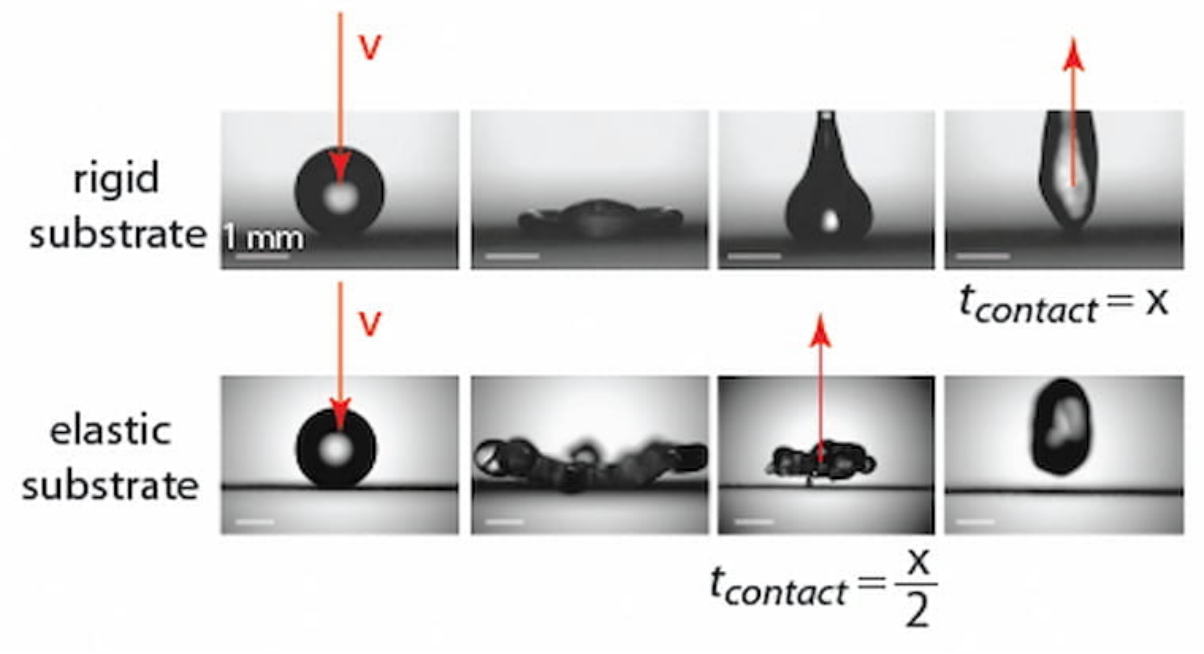


Figure 12: *High-speed visualization of water droplet impact on a rigid (top) and an elastic (bottom) superhydrophobic surface.107 P. B. Weisensee, J. Tian, N. Miljkovic, W. P. King, "Water droplet impact on elastic superhydrophobic surfaces", Sci. Rep. 6 (2016) 30328*

Furthermore, it was noted that by appropriately regulating the flexibility of the superhydrophobic material, micro- and nanopatterns on superhydrophobic soft surfaces can improve the droplet removal ability [64]. The reaction dynamics of elastic softsuperhydrophobic surfaces have not been extensively studied. Using the momentum conservation law, a recent work by Soto et al. showed how the deformation dynamics of a thin cantilever plate rely on the force caused by droplet contact [65]. Likewise, theoretical research conducted by *Gart et al.* demonstrated the elastic response of water droplet collision causes a cantilever plate. The dynamics of the elastic response include bending, damping, vibration, and deflection.

1.4. Gap Area

Many studies have been conducted related to the impact dynamics of rigidsuperhydrophobic surfaces after Droplet impact but very few studies are conducted on the impact behaviour of flexible superhydrophobic surface as well as the dynamics of the liquid droplet after impact. Not that there are less studies on the impact behaviour of flexible superhydrophobic surfaces after droplet impact but impact of liquid droplet in the three different configuration i.e., tip, middle and end position is the main aim of our experiment .Earlier droplet impact on the flexible superhydrophobic surface have been studied but in one configuration. This present thesis reflects these aspects.

1.5. Objective

Objectives of the present work is to

- Investigate the general impact behaviours of water droplets on superhydrophobic, flexible substrates
- Characterize the influence of droplet impact Weber number on the deflection of the substrate upon impact
- Study the effect of substrate inclination on the impact dynamics

2. MATERIALS AND METHODS

2.1. LIST OF EQUIPMENTS AND MATERIALS USED

2.1.1. EQUIPMENTS USED

1. High Accuracy Electric Weight Balance Machine (Sartorius, BSA 224S – CW, max 220g, accuracy 0.1mg)
2. Bath Sonicator – (Model – USB 3.5L H DTC, Serial No. – 369 APR 2017, Supply volt – 230V AC 50Hz)
3. Syringe pump
4. Medical syringe – Dispovan medical syringes
5. Blue needle- Dia0.670mm
6. Yellow needle-Dia0.266mm
7. Dispovan medical syringe needle (Purple needle-Dia0.508mm)
8. Vision research AMTEK Phantom highspeed camera (Model- VEO 310L)
9. Pro Series Auto Focus Macro extension tube set (12mm,20mm,36mm)
10. Nikon AF NIKKOR 50mm 1:14D camera lens
11. Manfrotto 055 Tripod for camera mounting.
12. GS VITEC LED Lamp (Model- MultiLED LT, Power supply- 24V 150W)
13. Optical Bench
14. Optical bench Rail
15. Pole
16. Pole holder
17. Optical Breadboard
18. NIKON AF-S NIKK8OR 300mm
19. Butterfly needle

- **High Accuracy Electric Weight Balance Machine(Sartorius, BSA 224S – CW, max 220g, accuracy 0.1mg)**

It is a device that measures weight or mass precisely and with the least amount of mistake is an accurate weighing scale or weighing machine.

Retail, industrial, transportation & logistics, and laboratory settings all utilise accurate weighing scales.

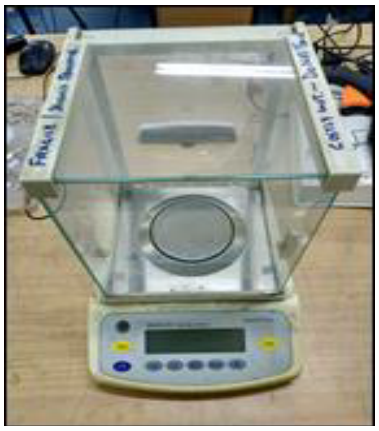


Figure 13:*High Accuracy Electronic Balance*

Bath Sonicator

The samples are degassed using sonicators. Additionally, ultrasonic baths ensure that no impurities from the preceding operation remain on glassware by providing a delicate yet effective cleaning action.These devices are used to clean lab glassware and plastics so that samples can be mixed and emulsified.



Figure 14*:Bath Sonicator*

- **Scientific Syringe Pump**

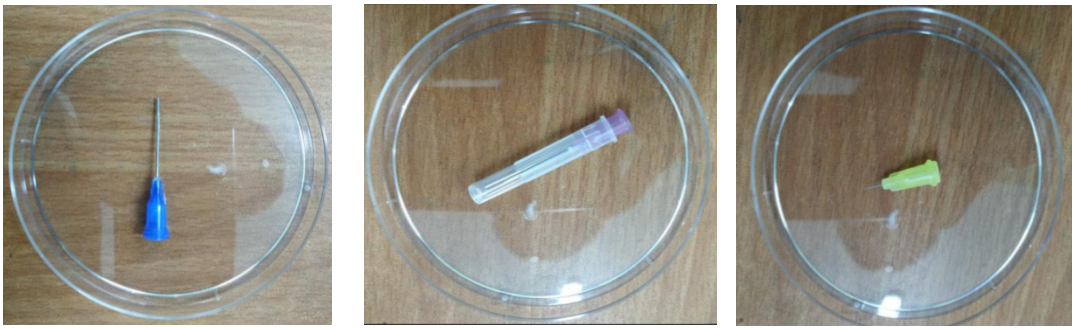
Syringe pumps, often referred to as syringe drivers, are motorised instruments that precisely regulate the flow of fluid out of a syringe by mechanically advancing or withdrawing the plunger. Stepper motors found in syringe pumps precisely move the platform that is connected to the plunger of a syringe. The syringe's body is kept stationary by the unit's body, allowing the motor to be the only source of movement.

Basic models can be used to infuse (and occasionally remove) liquids at a predetermined rate. The motor's speed can be changed to regulate the model.



Figure 15:*kd Scientific Syringe Pump Medical syringe – Dispovan medical syringes*

A single-use medical device for convenient and safe injection delivery is the Dispo Van syringe. It minimises injection pain while ensuring precise dosage delivery. For one-time use, the Dispo Van syringe is perfect since it offers convenience and safety.



(b

Figure 16:*Needles used for droplet impingement (a) Blue needle (Diameter: 0.670mm) (b) Purple needle (Diameter: 0.508mm) (c) Yellow needle (Diameter: 0.266mm)*

- **AMTEK Phantom highspeed camera**

The Phantom VEO camera series was created with almost any application in consideration. Phantom cameras are renowned for their outstanding imaging quality, which is achieved by their exclusive sensor and robust body design. These cameras are used on movie sets, in outdoor settings, and in science labs.The dependable Phantom VEO platform serves as the foundation for the VEO-E310L.



Figure 17*: AMTEK Phantom high-speed camera*

- **Pro Series Auto Focus Macro extension tube set**

Made to provide a lens the ability to focus closer than its typical minimum focusing distance.Enlarging your subject to make it look larger in your photos and in the viewfinderDesigned with every electrical component and mechanical interface needed to keep auto exposure and auto focus. Design that is lightweight to achieve the necessary magnification, tubes can be used singly or in any combination.



Figure 18: *Pro Series Auto Focus Macro extension tube set*

- **Nikon AF NIKKOR 50mm 1:14D camera lens :-**

One of the best kept secrets in low light photography is the Nikon 50mm f/1.4. Gathering light is a far more vital function of this lens than having a fast ISO speed. This f/1.4 lens on a D80 should do roughly the same in low light as an unusual f/2.8 zoom on a D3.



Figure 19: *Pro Series Auto Focus Macro extension tube set*

- **Manfrotto 055 Tripod for camera mounting**

The innovative 055 aluminium 3-section tripod, which is useful for a wide variety of photography and video applications, is part of the 055PRO3 set. It comes with a quick-release plate and the MHXPRO-3W X-PRO 3-Way Head so you can use the tripod with a range of gadgets. The 90Â° centre column mechanism, which is placed in the upper casting for compactness and can be rapidly extended as needed, makes it easy to transfer the tripod from vertical to horizontal position.



Figure 20:*Manfrotto 055 Tripod for camera mounting*

Gain greater creative control when taking pictures and videos. In order to save time and maintain your equipment in the right position, you can really change orientation while your camera is mounted. The 055XPRO3 tripod with head has extendable and adjustable legs.Levers on the QPL provide stronger locking of each leg piece as well, guaranteeing the utmost rigidity for your tripod. You have additional flexibility to shoot in a way that suits your own style thanks to intuitive and ergonomic leg angle selectors that enable each leg to be firmly and independently set to any of the preset angles. Accurate framing is made possible by the bubble level integrated at the top of the centre column. As it rotates freely, you can place it to allow you to observe while adjusting your tripod in the most convenient location. It will not, therefore, be blocked from view by any of your gear or interfere with your ability to operate your camera.

- **GS VITEC LED Lamp (Model- MultiLED LT, Power supply- 24V 150W)**

High speed cameras pair well with the powerful, flicker-free, continuous light source that is the GSVitec LT lamp. With its 24 high power LEDs, the GSVitec LT can provide 14,000 lumens of light. This lap unit has a long lifespan (more than 50,000 hours) .



Figure 21:*GS VITEC Flicker-free LED Lamp*

- **Optical Bench**

An optical bench is a surface that is primarily utilised to support systems utilised in optical constructions and investigations. Another way to describe it is as a bench that has all of the lenses and other devices clamped to it, maintaining the primary axis for perfect optical alignment. These benches' surfaces are designed to be extremely compact with minimal deflection, ensuring that optical component alignment remains constant throughout time.

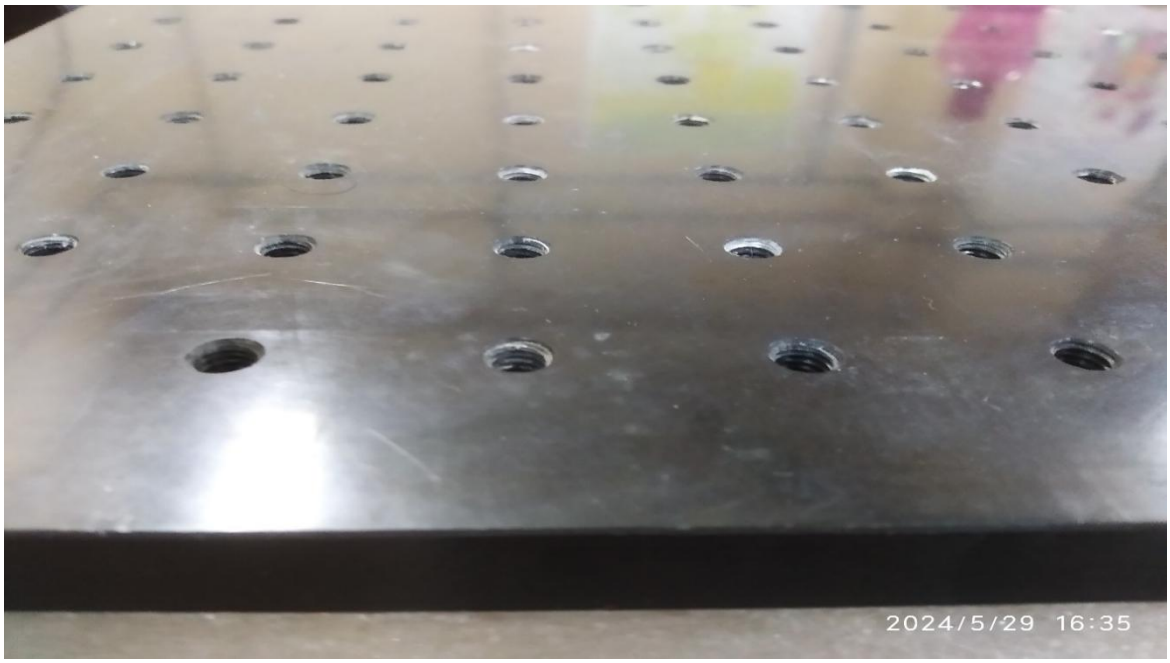


Figure 22: *Optical bench*

Minimal vibration of optical components is required by many optical systems. Consequently, optical benches are typically quite heavy. Their entire structure is designed to have inherent vibration isolation and dampening properties.Labs employ optical benches that are equipped with separate components including collimators, holders, measuring microscopes, and telescopes on a rail foundation. The devices used can change depending on what each experiment requires. They are organised and controlled because they are required to complete several test tasks. The components of the optical benches used for physics experiments include sliding seats, light sources, guide rails, picture screens, and other holders. Additional optical components, such as prisms, lenses, and polarisation sheets, are clamped onto the optical system in accordance with the requirements of the experiment.In addition, there is a positioning line on the movable seat that helps with optical element location.

- **Optical Bench Rail**

Beam steering and low-profile micro-optical bench systems can both be implemented with flat rail systems. These rail systems are perfect as a foundation for linear and asymmetrical structures because the bearing surfaces on the low-warpage aluminium alloy are precisely machined and coated with an abrasion-resistant black anodizing. The flat rail system is compatible with posts and holders.



Figure 23*: Optical Bench Rail*

The rails include M6 or ¼" bore hole patterns with slotted holes for attaching them to optical tables. The intricate design which includes a precision rail and carriers that are

interchangeable and have spring-loaded clamping, guarantees incredibly accurate component location within the structure.

- **Optical Bench Pole**

To install optical components, optical posts are necessary. The ends of the Ø1/2 in. (Ø12.7mm) and Ø1 in. (Ø25.4mm) optical posts have mounting holes #8-32 (M4) and 1/4-20 (M6), whereas the ends of the Ø1.5 in. (Ø38.1mm) mounting posts have tapped holes for 1/4-20 (M6).



Figure 24:*Optical Bench Pole*

These stainless steel optical mounting posts are available in a range of lengths, ranging from pedestal posts measuring as little as 1/2 in. (13mm) to optical posts measuring up to 14 inches.

- **Pole Holder**

Pole Holder is a black metal stand with locking screws. Every accessory that is affixed to a rod can fit within a holder.



Figure 25: *Pole Holder*

- **Optical Breadboard**

Optical breadboards offer a transportable surface including a grid of mounting holes for constructing independent optical assemblies or expanding the mounting space on an optical table. Performance parameters such as the rigidity and damping needed for a certain application are taken into consideration while choosing optical breadboards. For the construction of optical assemblies, small sub-systems, and small optical experiments, solid aluminium optical breadboard plates with a grid of 1/4-20 or M6 drilled holes offer an affordable, non-magnetic solid surface. While honeycomb breadboards employ a stainless-steel top skin working surface, these solid breadboards offer a matt black anodized surface that reduces undesired reflections. The breadboard edges have four counterbored through holes that make attachment to an optical table or isolator simple.



Figure 26*: Optical Breadboard*

- **Butterfly needle**

A butterfly needle, which comes in sizes 18 through 27, is a shorter needle with a narrower gauge. Butterfly needles are among the thinnest needles that phlebotomists can use since, according to gauge measurements, the higher the number, the narrower is the diameter. For blood draws, 21 or 23 gauge are typically utilised.Because of its "two wings," butterfly needles are often referred to as a winged transfusion set or a scalp vein.

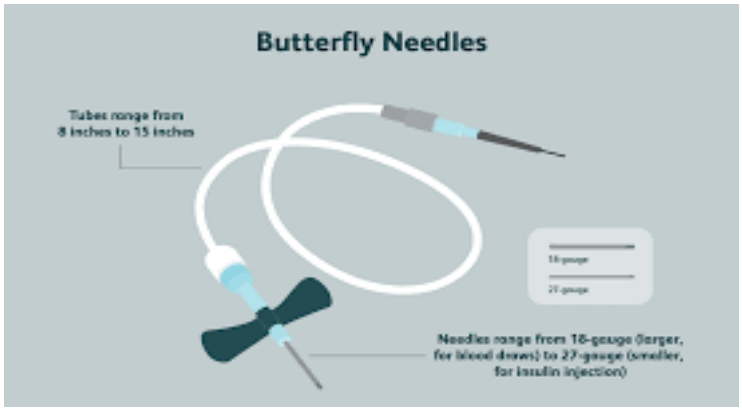


Figure 27: *Butterfly Needle*

2.1.2. MATERIALS USED

- Flexible substrate (Polyester thin film thickness overheaded projection) Length 5cm, Width =0.7cm, Thickness = 0.02cm
- Acetone (Fisher Scientific) CAS No.: 67 – 64 – 1, $(CH_3)_2CO$ = 58.08.
- Iso-Propyl Alcohol
- Distilled water
- GLACO

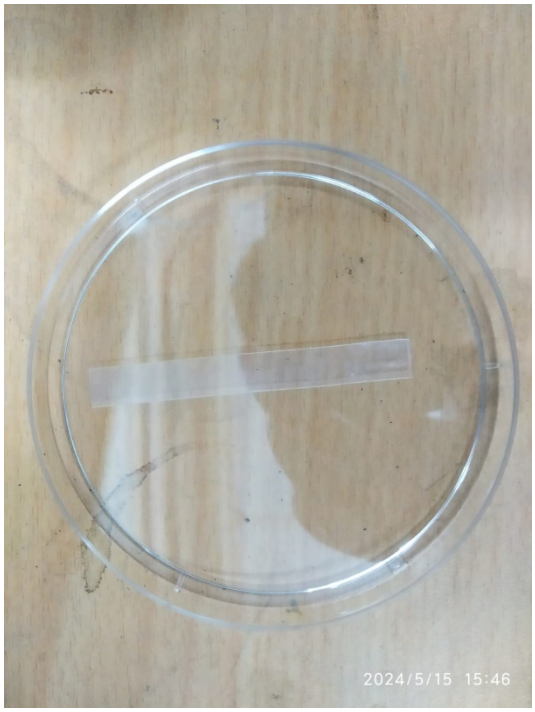


Figure 28:*Flexible Surface(polyesterthin film thickness over-headed projection)*

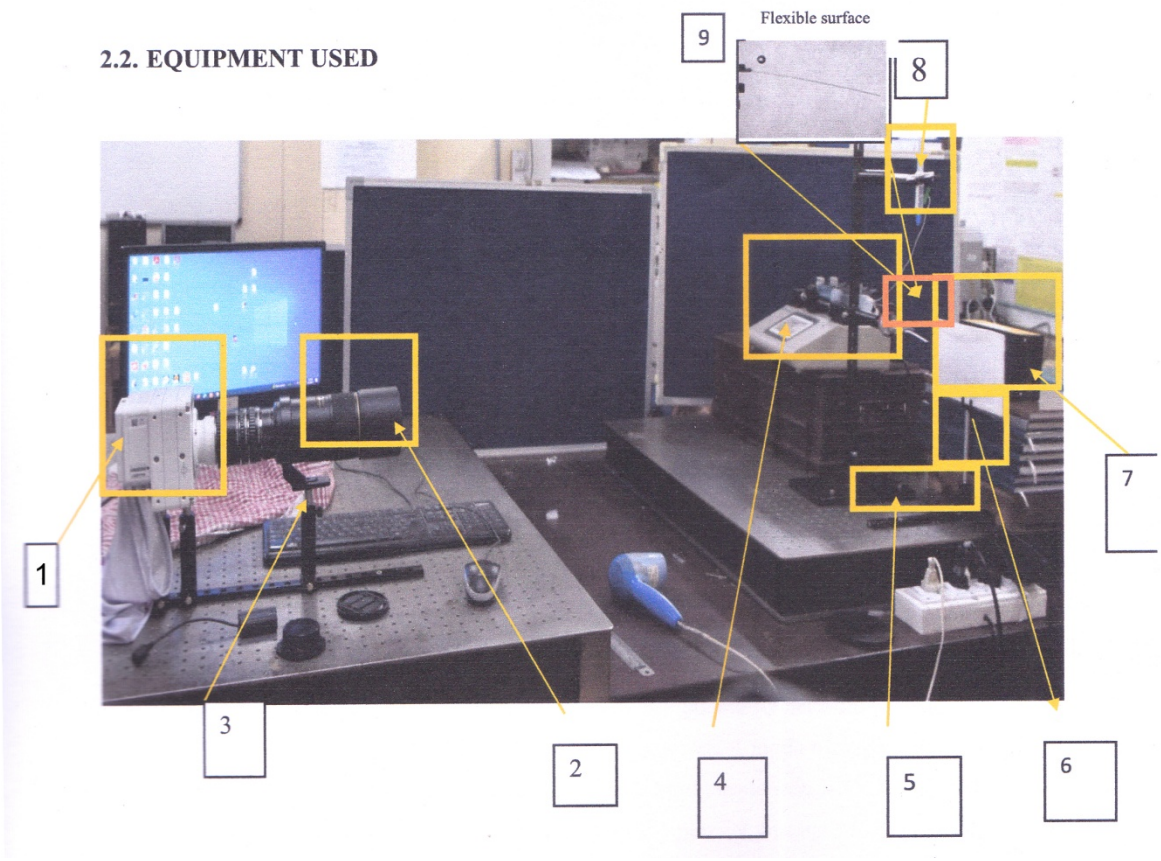


Figure 29*: Experimental Setup(1)Phantom VE0310 High speed camera,(2) Nikon AF Nikkor 300 mm,(3) Pole holder,(4) kd Scientific Syringe Pump,(5)Optical bench rail,(6)Pole,(7)GS Vitec Led Lamp,(8)Dispoven Medical syringe needle,(9)Flexible surface*

As shown above, experimental setup consists of a small optical breadboard which was placed above optical bench and a pole holder was fixed.Then the Optical bench rail was fixed in vertical position through pole holder.The Optical bench rail which was fixed in vertical position two pole and pole holder assembly was fixed with it. As mentioned two poles and pole holder assembly was used in case of one pole and pole holder assembly flexible substrate (polyester thin film thickness overheaded projection) was attached with holder through a red ball screw. Red Ball screw was mainly used to change the angle of inclination of the surface. In case of another pole and pole holder assembly a medical syringe was attached with it through a holder.Flexible substrate is a sheet of OHP with a transparent film placed on it and either an acrylic, polyester, or rubber-based adhesive layer coated on it. Additionally, an OHP sheet with a coating layer made of solid wax that works well with thermal fusible ink has been proposed. Later flexible substrate was coated with a thin film of Superhydrophobic layer over it.The needles of varied diameter were changed as per the progression of experiment.The syringe was connected with a

syringe pump through butterfly needle for dispensing droplet over flexible Superhydrophobic surface.The high speed camera was fixed with a pole which was then fit within a holder and the holder was fixed with an optical bench rail the whole assembly was placed over optical bench.In order to ensure the alignment of the camera the angle was measured with clinometer for confirmation.Pro focus auto extension tube was attached with the camera for clear view of the flexible superhydrophobic substrate. The Flexible superhydrophobic surface was placed in a cantilever design. Then the angle of the substrate was measured at 0 degree. We consider five angles of cantilever beam (0^o,-15 ^{o},15 ^{o},-35 ^{o},35 ^{o}). As the height was gradually increased pancake pattern for the droplets changed.The experiment was performed with water for three different needle diameters (0.670 mm,0.266 mm,0.508 mm).After that, needle was attached with dispo van syringe and then fixed with holder with the help of Double sided screw.A scale was clamped with the help of optical bench rail to measure the increasing height from the base.After that flexible superhydrophobic was placed in the holder at a position where droplet could be impinged over the surface.As mentioned earlier three different kinds of needle are used blue needle (Dia0.670 mm),yellow needle (Dia0.266 mm),purple needle(Dia0.508 mm). The butterfly needle was attached with the syringe and a plunger was used to dispense the droplet. The drop strikes the surface, and as it does so, its pancake diameter is measured. A high-speed camera recording at 3200 frames per second captures the entire occurrence. The high-speed camera was connected to computer having PCC software to record video and take pictures of the entire operation. An LED lamp was placed behind the surface i.e., in front of camera to take a clear view of the surface.In our experiment droplet impingement takes place at the three configurations i.e., tip,middle and base position.Before conducting the experiment, the flexible substrate is bath sonicated for 10 min in IPA(Iso propyl alcohol). Propan-2-ol, commonly known as isopropanol or 2-propanol, is an organic chemical that is colourless, combustible, and has a strong alcoholic smell. Isopropyl alcohol, or IPA, is a general-purpose cleaning solvent that works well on a range of substrates. At first 10 cm height was taken from the tip of the blue needle(0.670mm) to the tip position of the surface.The height was measured with the help of steel scale which was attached with the optical bench rail. The surface was placed at an angle of 0 degree the angle was measured with the help of clinometers then the droplet was impinged at the tip position.The length of the surface was 5 cm.Then in the same way maintaining a height of 10 cm droplet was impinged on the middle position (2.5 cm) .At last as mentioned maintaining the same height droplet was impinged at the base (near the holder).In our experiment impacting the droplet in three different

configuration was mainly done to observe the dynamic behaviour of droplet after impact as well as the behaviour of flexible superhydrophobic surface i.e., deflection,frequency of vibration etc.

Then in the next step we have to take the angle of the surface at 15 degree.The angle is measured with the help of a clinometers. We have to continue the same procedure as mentioned earlier by taking a height of 10 cm and maintaining the same height throughout the surface and Droplet was impinged on the three configuration i.e.,tip,middle ,base position.In the same way we have to take the remaining of the angles (-15^0,35^0,-35^0) and continue the same procedure. The main reason for taking five angles was that to observe the behaviour of the surface as well as droplet after impact and to determine the deposition of droplet for that we have taken contact time. Droplet impact can disperse propagules,pathogen can be transported and finally deposited on leaves. After taking a height of 10cm then we have to move to a height of 20 cm. Now take a height of 20 cm from the tip of the blue needle to that of the tip of the surface.In the same way maintaining height of 20 cm droplet is impinged at the three configurationsi.e.,tip, middle and base position. The angle of the surface is 0 degree.We have to repeat the same procedure by taking other angles(15^0,-15^0,35^0,-35^0).While changing angles we have to change the position of high speed camera and Led Lamp as per our requirements. Our aim for doing this is to observe the surface after impact as because sometimes droplet comes out of the surface of the computer screen after impact so we have to take care of that while conducting the experiment. We have to take atleast three trials for each position to reduce the chances of error.Now after taking a height of 20 cm we have to take a height of 30 cm. The five angles of the surface were taken and droplet was impinged on it at all the three position. Three different kinds of needle were taken as the droplet dispensed from the needle is of different diameters.The mass of the droplet was measured in precision weighing balance.

As mentioned above the whole procedure is for blue needle(Dia 0.670 mm) we have to continue the same procedure for yellow needle (Dia 0.266 mm) as well as purple needle (Dia 0.508 mm) by considering the same pattern.

3. RESULT AND DISCUSSIONS

3.1. Estimation of the Young's Modulus of Elasticity of the Substrate

In order to characterize the flexible surface, first its modulus of elasticity was determined from the classical theory of deflection of a cantilever beam under a uniformly distributed load (UDL). The relationship between stress (force per unit area) and strain (proportional deformation in an object) is described by Young's modulus.

The fundamental idea is that when a material is stretched or compressed, it experiences elastic deformation, which causes it to return to its original shape when the stress is released. In comparison to a rigid substance, a flexible material deforms more.

E =stress/strain

E is the Young's modulus of elasticity in N/m^2

As the surface is mounted horizontally in a cantilever configuration, its weight produces a UDL, which in turn produces a downward deflection of the substrate.

Theory of Cantilever with Uniformly Distributed Load

Consider a section *x–x*, at a distance *x* from free end B,

$$M_x = \frac{-w(x)^2}{2}$$

$$\therefore \quad EI\frac{d^2y}{dx^2} = M = \frac{-w(x)^2}{2} \qquad \ldots \text{(i)}$$

Integrating (i), we get

$$EI\frac{dy}{dx} = M = \frac{-w(x)^3}{6} + C_1 \qquad \ldots \text{(ii)}$$

Again integrating (ii), we get

$$EI\,(y) = \frac{-w(x)^4}{24} + C_1x + C_2 \qquad \ldots \text{(iii)}$$

Using end conditions,

at x = L, $\frac{dy}{dx} = \theta_A = 0$

$$\therefore \quad C_1 = \frac{wL^3}{6}$$

Also at x = L, $y = \delta_A = 0$

$$0 = \frac{-w(x)^4}{24} + \frac{wL^3}{6}L + C_2$$

$$C_2 = \frac{-wL^4}{8}$$

Hence, $EI\frac{dy}{dx} = \frac{-wx^3}{6} + \frac{wL^3}{6}$ … (iv)

$$EI\,(y) = \frac{-w(x)^4}{24} + \frac{wL^3}{6} \times x - \frac{wL^4}{6} \qquad \ldots \text{(v)}$$

Slope and deflection at free end,

i.e. x = 0

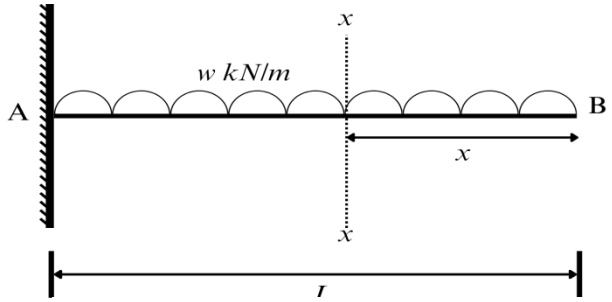


Figure 30: *Cantilever with uniformly distributed load*

$$\frac{dy}{dx} = \theta_B = \frac{1}{EI}\left(\frac{-w(0)^3}{6} + \frac{wL^3}{6}\right)$$

$$\therefore \quad \theta_B = \frac{wL^3}{6EI}$$

and, $$y = y_B = \frac{1}{EI}\left(\frac{-w(0)^4}{24} + \frac{wL^3}{6}(0) - \frac{wL^4}{8}\right)$$

$$\therefore \quad y_B = \frac{-wL^4}{8EI} \text{(Downward)}$$

We are taking negative as downward direction and positive as upward direction

Where,

I = Moment of Inertia; L = Length of the Surface; E = Young's Modulus of Elasticity;

Y_B = Deflection of the Surface; w = Uniformly Distributed Load

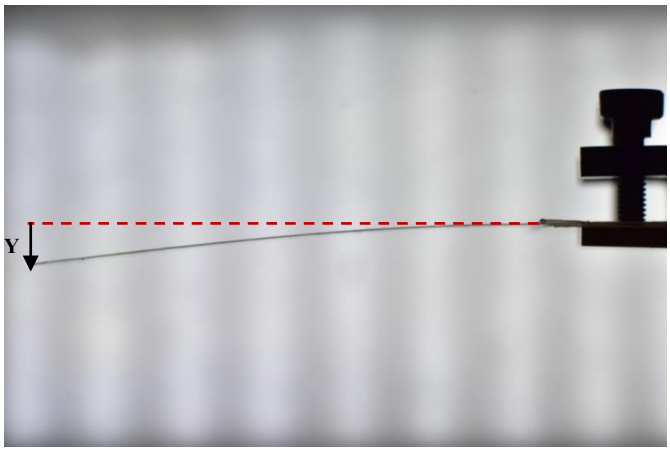


Figure 31: Flexible surface in cantilever position under its self-weight

Now, from the figure Let us consider the Length of the flexible surface as **a** and thickness as **b**

Consider positive value of direction

$$y_B = \frac{12ab\rho gL^4}{8\ Eab^3} = \frac{3\rho gL^4}{Eab^2}$$

Where,

E = Young's modulus of elasticity for coated surface, E = 0.53 MPa

E = Young's modulus of elasticity for uncoated (superhydrophobic) surface, E = 0.748 MPa

Table 1 - Weber Number ($\frac{\rho DV^2}{\sigma}$) and Diameter of Droplet dispensed fromdifferent Needle

droplet diameter 2.8624 mm			droplet diameter 2.228mm		droplet diameter 2.6622mm	
Inclination (degree)	Height(m)	Weber Number (*We*)	Height(m)	Weber Number (*We*)	Height(m)	Weber Number (*We*)
0	0.1	78.0004	0.1	60.713	0.1	72.55585
15	0.1	78.0004	0.1	60.713	0.1	72.55585
-15	0.1	78.0004	0.1	60.713	0.1	72.55585
35	0.1	78.0004	0.1	60.713	0.1	72.55585
-35	0.1	78.0004	0.1	60.713	0.1	72.55585
0	0.2	156.0008	0.2	121.426	0.2	145.1117
15	0.2	156.0008	0.2	121.426	0.2	145.1117
-15	0.2	156.0008	0.2	121.426	0.2	145.1117
35	0.2	156.0008	0.2	121.426	0.2	145.1117
-35	0.2	156.0008	0.2	121.426	0.2	145.1117
0	0.3	234.0012	0.3	182.139	0.3	217.6676
15	0.3	234.0012	0.3	182.139	0.3	217.6676
-15	0.3	234.0012	0.3	182.139	0.3	217.6676
35	0.3	234.0012	0.3	182.139	0.3	217.6676
-35	0.3	234.0012	0.3	182.139	0.3	217.6676

3.2.Substrate deflection upon droplet impact:

Upon impact with a flat, rigid superhydrophobic surface, a droplet unleashes its full kinetic energy, maximizing its spread. However, the story takes a different turn on a flexible superhydrophobic surface. Here, the energy gets divided. While a portion contributes to spreading the droplet, the remainder goes towards deflecting the flexible surface itself. Consequently, the maximum spread achieved on a flexible surface falls short of that achieved on a rigid surface. Interestingly, the opposite is true for contact time. The contact time between a droplet and a flexible substrate is higher compared to a rigid, flat substrate. This study investigates droplet impact on a flexible Glaco-coated PET sheet, used as a superhydrophobic flexible substrate. The sheet is hinged at one end, behaving like a cantilever beam. Its own weight acts as a uniformly distributed load throughout the sheet. The deformation due to uniformly distributed load is already given in mathematical form in my previous chapter.



Figure 32: *Time lapse snapshots of droplet impact phenomenon on 35 degree inclined super hydrophobic substrates with impacting weber number of 78.*

As we can see from the figure 33 as shown below, we primarily focus on two parameters, i.e., droplet impact at different inclination angles, and the behaviour of the surface after drop impact in terms of deflection. At 0^o inclination angle after droplet impact a significant part of the entire kinetic energy (acting kinetic energy) of the droplet is transferred to the flexible superhydrophobic surface, as a result of which, the surface attains a maximum deflection of 11.8489 mm. The entire kinetic energy of the droplet can be divided into four regimes, one of which accounts for the viscous dissipation (negligible for 0^o), followed by the part of the energy used in sliding of the droplet, and a part of this kinetic energy along-with a part of the substrate potential energy togetherly allowing the added deflection of the surface beyond self-weight. The remnant of the kinetic energy of the falling droplet is used by the droplet to bounce off the substrate and escape the experimental control volume. In the second case at an inclination of +15 (anticlockwise) after drop impact, the entire kinetic energy of the droplet is not transferred to the flexible superhydrophobic surface. The droplet slides down the surface to some extent due to its inclination angle, as a result viscous dissipation occurs showing a deflection of 10.8489 mm, which is clearly lesser than the deflection as in case of 0^o inclination angle. At -15^o (clockwise) Inclination angle, after drop impact, the viscous dissipation term in the acting kinetic energy cannot be ignored. This results in a deflection of 3.4371mm which is comparatively lower than that in case of $+15^o$(anticlockwise) as the substrate is placed in alignment of gravitational force. At $+35^o$ (anticlockwise), upon droplet impact, enhanced sliding of droplet takes place over the surface on an inclination of $+35^o$(anticlockwise) which, in turn, increases the viscous dissipation as well, causing a deflection of 9.76mm which is comparatively lower than that in case of $+15^o$(anticlockwise) when the substrate is placed at lower inclination. At -35^o (clockwise), when the droplet impacts the substrate, the droplet doesn't stay on the surface for a considerable amount of time to allow the potential of the acting kinetic energy to be transferred, and escapes the experimental regime after little sliding action, causing a minimal deflection of only 2.857mm.



Figure 33: *Droplet impact on flexible superhydrophobic substrate with different inclination angle at a fixed Weber number of 78*

As we can see from Figure 34, flexible superhydrophobic surface is fixed with the double sided screw holder and it is inclined at an angle of 0^o.Here two sides are shown, i.e., before and after drop impact. We have primarily focused on the two parameters, i.e., behaviour of the surface and droplet impact dynamics at different Weber numbers. In Figure 34, we can see that before impaction, the surface is slightly deviated from its original position due to self-weight, while when it contacts the surface, a deflection of 11.6489 mm occurs at a Weber number of 78. When the Weber number is increased to 156, the surface deflects by 12.8489 mm, while at a Weber number of 234, the surface is deflected by 14.8489mm. From these experimental studies, we can conclude that deflection of the surface is inherently dependent on the Weber number.



Figure 34: *Droplet impact on flexible superhydrophobic substrate with different Weber number at a fixed inclination angle of 0^o*

The impact behaviour of droplets is strongly influenced by the deflection of a surface at various inclination angles.For dispensing the water droplet, three needles, of diameters 0.670 mm, 0.266mm, and 0.508mm, were used. The droplets were released from different heights to produce momentum of different magnitudes. The variation of deflection vs angle of inclination is shown in figure 35. The data points in the plot are aligned with the data as shown in Table 1. The line represents the droplet release height from 100mm, 200mm, and 300mm respectively.

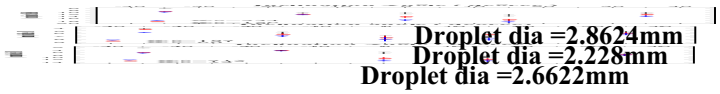


Figure 35: *Figures show how the substrate deflection changes with inclination for different weber number cases.*

3.3Variation of contact time with weber number and inclination

The maximum contact time is shown in the cases of Anticlockwise orientations (35 degree and 15 degree anti clockwise). This occurs as the droplet impacts on the free end of the substrate and it slides down the surface, enabling an enhanced contact time. When the substrate is set horizontally aligned (with any inclination whatsoever solely due to self-weight), the contact time is relatively lesser as the droplet slides less than the anticlockwise orientation cases. When the beam is inclined clockwise, the sliding droplets escape the substrate during spreading and sliding process, thereby ensuring the lowest contact times. Considering the phenomenon of splashing of the droplet on impact when the impacting weber number is high, satellite droplet formation takes place which reduces the mass of the droplet, reducing momentum as well, and the satellite droplets hold the main droplet during detachment thereby allowing for more contact time of thedroplet with the surface. Therefore, contact time, as found, is also a function of the Weber number, and increases.



Figure 36: *Figures show how the droplet substrate contact time changes with inclination for different weber number cases.*

4. CONCLUSION AND FUTURE SCOPE

4.1. Conclusion

Droplet impact behaviour on solid superhydrophobic surface and flexible superhydrophobic substrate is completely different. The maximum spreading of the droplet after impact and the droplet substrate contact time, both are distinguishable. In our study, we found that the increasing weber number gives us higher deflection of substrate and also higher value of droplet-substrate contact time. These deflections and droplet surface contact time phenomena also changes with substrate inclinations. As the inclination increases anti-clockwise, the droplet substrate contact time increases because droplet has higher tendency to stay on the surface, and this also reduces the deflection of the substrate because of viscous dissipation. The maximum deflection of the substrate is observed when the substrate inclination angle is near to zero with horizontal, because the impacting droplet dissipates maximum energy in this orientation.

4.2. Future Scope

The mechanics of droplet impact over soft elastic (flexible) materials has been the subject of numerous researches, considering both smooth and rough surfaces with or without bending. The physics of droplet impact dynamics into soft elastic substrates was also explained by a number of physical nondimensional characteristics, such as Weber number and Reynolds number. The majority of research on the dynamics of droplet impact into flexible, soft surfaces uses Newtonian liquids like ethanol, silicone oil, and water.However there are few opportunities and challenges remaining in the field.

- More variation of droplet diameters with different kinds of nanoparticles with different kinds of surfactant can be studied in order to investigate the dynamic behaviour of droplet impingement on flexible surface which has potential applications in the study of heat transfer mechanisms in advanced cooling, system.
- Droplet impingement on different kinds of flexible surface can be studied.

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Water droplet impact on elastic superhydrophobic surfaces

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