Supplementary Information for

How a raindrop gets shattered on biological surfaces

Seungho Kim, Zixuan Wu, Ehsan Esmaili, Jason J. Dombroskie, and Sunghwan Jung*

E-mail: sunnyjsh@cornell.edu

This PDF file includes:
Supplementary text
Figs. S1 to S10
Captions for Movies S1 to S7
References for SI reference citations

Other supplementary materials for this manuscript include the following:
Movies S1 to S7
A. Velocity profile of an impacting drop

1. Experiments. When a liquid drop impacts a small target surface, it creates a spreading liquid sheet in the air (so-called a drop-impact version of Savart sheet) (1–3). We presume that such a spreading liquid sheet could be similar to our spreading drop on a superhydrophobic surface due to negligible viscous stress on the superhydrophobic surface. To further validate our assumption, we directly measured the velocity profile of the impacting drop on a superhydrophobic surface by virtue of its optical transparency. We first covered the surface with glass particles of 20 μm in radius, r_p, and 2,500 kg/m^3 in density, ρ_p, respectively. Then, a water drop was released on the particle-laden surface, and the motion of particles was captured with a high-speed camera at a frame rate of 10,000 Hz with a pixel resolution of 1,024 × 672. The corresponding experimental setup is illustrated in fig. S1a. The Stokes number, St, defined as a ratio of the relaxation time of a particle t_r = (2/9)ρ_p r_p^2 μ / ρ_L U_0 (4) to the spreading time of an impacting drop t_d = (16/3) R U^{-1} (4) is typically less than 0.1, which implies that seeding particles follow the fluid motion. Particles (fig. S1b) were traced using our image processing algorithm. The footprints of traced particles was shown in fig. S1c. Now, we can measure/characterize the velocity profile of the spreading drop. Figure S1d showed the spreading motion of particles.

2. Theoretical model and validations. For the liquid sheet, the following self-similar solution is suggested to describe its velocity profile (1): u = r/(t + b). Here, b is a time constant, which is proportional to a collision time scale. Since the collision time scale is much smaller than the spreading time scale of an impacting drop, the above equation can be further reduced to

\[ u = \frac{r}{t}, \]  

which was previously validated for a spreading drop in the air (1). Since viscous forces could be negligible in the kinematics of an impacting drop on a superhydrophobic surface (5), we employ eq. (1) to estimate the velocity profile for our system. Scattered data in fig. S1e are well collapsed onto a single line in fig. S1e, which indicates that this drop-impact version of Savart sheet model, eq. (1), works well with our experiments. Here, the slope of the best-fitting line is also close to 1.

B. Thickness profile of an impacting drop

1. X-ray experiment. We used a X-ray phase contrast imaging technique at the Argonne National Lab. A polychromatic beam with the first harmonic energy near 13 keV and a 100 μm-thick LuAG:Ce scintillator was used to visualize the motion of the impacting drop. The image sequences were recorded by a high-speed camera (Fastcam SA-Z) with a resolution of 1024×1024 pixels at a frame rate of 20,000 s^{-1}. This X-ray imaging technique allows us to see not only complicated liquid morphology consisting of fingers and splash droplets, but also the detailed thickness profile of the impacting drop, as shown in fig. S2a. We found that at a later stage the thickness of outer rim (last panel in fig. S2a) is larger than that of the central region of the spreading drop. Such a drop shape cannot be measurable via conventional optical methods. Therefore, our experiments using a X-ray were an important step to measure the drop thickness and verify the thickness model below. Here, we plotted the film thickness at different times in fig. S2b and fig. S2c.

2. Theoretical model and validation. Because of negligible viscous stress in a spreading drop on a superhydrophobic surface (SI Appendix A), we used the thickness profile, h(r,t), for the drop-impact version of Savart sheet (1) as

\[ h(r,t) = a_n \left( \frac{Ut}{r^2} \right)^n, \]  

where n and a_n are an integer and a unknown coefficient, respectively. This expression covers the following two previous models: h(r,t) \sim R^2 Ut/r^3 [25], and R^2/(Ut) [24]. These are two n = 3, and n = 1 of the general model in eq. (2), respectively. Here, we also introduced a thickness profile corresponding to n = 0 in eq. (2) to describe the thickness profile of the spreading drop at the last stage (fig. S2a and fig. S2b, c). At this last stage, h(t) \sim R^2/(Ut^2) is expected when the drop reaches its maximum radius. These three thickness equations can be valid in different times. Vernay et al. (2015) recently reported the critical time, t_c, to separate valid time ranges for the first two models (2). Following a similar approach, we express three different thickness profiles as:

\[ h(r,t) = \begin{cases} a_3 D^3 U \frac{1}{r^2} & \text{for } t < t_{c_1} \\ a_1 \frac{D^3}{r^3} \frac{1}{r} & \text{for } t_{c_1} < t < t_{c_2} \\ a_0 \frac{D}{r^2} \frac{1}{r} & \text{for } t > t_{c_2}. \end{cases} \]  

Here, t_{c_1} can be determined by equating the first and second models, t_{c_1} = \sqrt{\pi a_1 / (6a_3)} r / U \ (2), and t_{c_2} is obtained in the same manner, t_{c_2} = [6a_0/(πa_3)]r / U. Based on the above thickness model, the thickness profiles in fig. S2b and fig. S2c are collapsed onto a single line depending on its relevant time frame, as shown in fig. S2d-f. Here, a_3, a_1, and a_0 are found to be 0.06, 0.17, and 0.25, respectively. The first two values of a_3 and a_1 are reasonably in good agreement with the previous reported values (a_3 = 0.061 (2) and a_1 = 0.159 (3)).
C. Hole nucleation mechanism

For $U > U_c$, a spreading drop is ruptured by forming multiple holes soon after approaching its maximum spreading radius. The hole is always nucleated on top of a bump as the shock-like wave moves around the bump, as shown in fig. 4a.

The schematic inside the first image of fig. S3a shows our experimental apparatus to visualize the instantaneous amplitude of shock-like waves on a superhydrophobic surface. We first prepared a slightly curved polycarbonated film and a micro-patterned surface (Type-III), which are coated with a superhydrophobic spray (NeverWet, Rust-Oleum). Then, a water drop is released on the superhydrophobic surfaces, where the temporal growth and spatial undulation of the top interface of the spreading drop were captured by a high-speed camera.

Figure S3a, b show a shock-like wave formed on the top interface of a spreading drop, which radially propagates backwards. Then, both the average film thickness and the wave amplitude decrease with time. Also, the wave propagates back toward the drop center (see the movement of the black and white arrows in 2.9 ms and 3.9 ms in a, and 3.6 ms and 4.6 ms in b). The wavelength of the wave, $\lambda$, is measured to be close to an average spacing of microbumps, $s$.

Hole formation on fewer micron-sized bumps rather than all the bumps is because of the intrinsic thickness undulation of an impacting drop, and the rapid velocity of the hole expansion. First, an impacting drop is known to induce weak azimuthal thickness modulations (2). Such azimuthal thickness undulations generate a few local minima in the spreading drop, which is impacting drop, and the rapid velocity of the hole expansion. First, an impacting drop is known to induce weak azimuthal thickness undulations based on our experimental observations (SI Appendix C). Then, we impose a dynamic boundary condition on the top surface using the unsteady Bernoulli equation.

D. Dispersion relation of shock waves

For simplicity, we considered the two-dimensional wave in a local coordinate system $(r', z')$, as shown in fig. S4a. Here, $u$ and $h$ are the average velocity and the average film-thickness of a spreading drop, respectively. We first assumed that the thickness profile of microstructures, $\eta$, follows a simple sinusoidal function, as illustrated in fig. S4a:

$$\eta = e \cos(kr').$$

Here, $e$ and $k$ correspond to the amplitude and the wavenumber of the microstructure: $k = 2\pi/s$ where $s$ is the wavelength of the microstructure. Since viscous forces can be negligible as shown in SI Appendix A&B, the perturbed velocity, $\tilde{u}'$, can be expressed as the gradient of a potential function: $\tilde{u}' = \nabla \phi$. Then, we presume the functional form of $\phi$ satisfying the continuity equation, $\nabla^2 \phi = 0$ in this film domain.

$$\phi = e u \sin(kt' - wt')e^{k(z' - h)},$$

where $w$ and $t'$ are the frequency and the elapsed time measured after the wave formation, respectively. We assume that the wavenumber of the shock-like wave equals to the wavenumber of the bottom micro-structure based on our experimental observations (SI Appendix C). Then, we impose a dynamic boundary condition on the top surface using the unsteady Bernoulli equation, $\rho (\partial \phi / \partial t') + p u |\nabla \phi| + p = \text{constant}$. Here, the second term on the left-hand side in this equation is the first-order inertia term in Bernoulli equation; neglecting the zeroth-order term, $(1/2)\rho u^2$, and the second-order terms, $\rho (|\nabla \phi|^2)$. We also use the Young-Laplace equation to express the pressure inside the spreading drop, $p$, in terms of $\eta$. Now, the dynamic boundary condition at the top interface becomes:

$$\frac{\partial \phi}{\partial z'} + \rho u \frac{\partial \phi}{\partial r'} = \gamma k \frac{\partial^2 \eta}{\partial r'^2} \text{ at } z' = h.$$  

The typical length scales of $r'$ and $t'$ are on the order of 100 $\mu$m and 0.1 ms, respectively. Since $r' \ll r \sim 1$ mm & $t' \ll t \sim 1$ ms, the leading-order velocity, $u$, and the leading-order film thickness, $h$, can be approximated to be constant in this small local area. The approximation is especially effective for $U \gg U_c$, where a hole is immediately nucleated after the wave formation. It allows us to solve eq. (6), explicitly. By plugging $\phi$ of eq. (5) into the left-hand side of eq. (6), and by integrating $\eta$ with respect to $r'$ twice, we can get the following thickness profile of the wave:

$$\eta = e \frac{\rho u^2}{\gamma k} \left( \frac{w}{k t} - 1 \right) \cos(kt' - wt'),$$

with boundary conditions ($\partial \eta / \partial r' = 0$ and $\eta = 0$ when $r' \rightarrow \infty$). To get the frequency, $w$, we apply a kinematic boundary condition at the top liquid-gas interface.

$$\frac{\partial \phi}{\partial z'} = \frac{\partial \eta}{\partial t'} + u \frac{\partial \eta}{\partial r'} \text{ at } z' = h.$$  

By plugging $\phi$ (eq. (5)) and $\eta$ (eq. (7)) into the left-hand and the right-hand side in eq. (8), respectively, one can obtain the following dispersion relation.

$$w = uk \pm \sqrt{\frac{\gamma k^3}{\rho}}.$$
which finally gives the amplitude of the perturbation, $|\eta|$, by plugging eq. (9) into eq. (7).

$$|\eta| = \alpha \epsilon u \sqrt{\frac{\rho}{\gamma k}}. \quad [10]$$

Here, an additional coefficient, $\alpha$, describes the three-dimensional effect of the wave that can lower the wave amplitude by allowing a liquid to flow out of the plane. Hence, $\alpha$ is expected to be less than 1. The scattered raw data in fig. S4b are collapsed onto a single line in fig. S4c. Here, the $x$-axis is based on the amplitude model in eq. (10). Here, the slope of the best-fitted line, $\alpha$, is measured to be 0.45. Eq. (10) implies that $|\eta|$ is large around the outer edge of the drop due to a high velocity, $u \approx r/t$. Thus, for a given time, the film near the outer edge of the spreading drop is prone to make a hole earlier according to the hole threshold relation, $h(t) - |\eta| \approx \epsilon$. Experiments (third image of fig. 2c and fig. 2d) showed this trend.

### E. Independence of a critical impact velocity on the size of impacting drops

To characterize the dependence of the critical impact velocity on the drop size, we released water drops on an artificial superhydrophobic surface (type-I) and varied the drop size and impact velocity, as shown in fig. S5. It is found that the impact velocity of the drop on the superhydrophobic surface is independent to the drop size, which is consistent with our theoretical prediction of eq. (4) in the main text.

### F. Decrease in contact time via wave-like drop fragmentation

1. **Decrease in the contact radius and the contact time via the formation of a hole.** For $U \approx U_c$, a hole is popped up on a spreading drop, thereby leading to the formation of a new 3-phase contact line inside the spreading drop (fourth image of fig. S6a). The outer part of the 3-phase contact line of the hole quickly disappears by coalescing with the original contact line of the spreading drop (fifth image of fig. S6a). Therefore, after the hole formation, the contact distance of the spreading drop, $d$, is redefined to follow the stepwise decrease in $d$ (gray dashed line in fig. S6b), and correspondingly the decrease in $t_{\text{contact}}$ ($t_{\text{contact}}/\tau < 1$ in fig. S6c).

2. **Theoretical limits of contact time.** For $U \approx U_c$, the contact time, $t_{\text{contact}}$, can be estimated as the hole-nucleation time, $t_{\text{hole}}$, since a hole is nucleated right before an impacting drop bounces off. Then, the contact time is approximated as the theoretical capillary contact time, $\tau = 2.3\sqrt{dR/\gamma}$. Therefore, $t_{\text{contact}}/\tau \approx 1$ near the threshold impact velocity.

For $U \gg U_c$, $t_{\text{contact}}$ can be also estimated as $t_{\text{hole}}$ for the different reason; a number of nucleated holes appear simultaneously within a few milliseconds as shown in fig. 2c. Hence, the contact time, $t_{\text{contact}}$, can be approximated from Eq. (2) as

$$t_{\text{contact}}/\tau \approx 0.6\sqrt{\frac{U}{\gamma}} \left[1 + a\sqrt{\frac{\rho}{\gamma k}}\right]^{1/2} \epsilon^{-1/2} U^{-1}. \quad [11]$$

On the leading order, the non-dimensional contact time, $t_{\text{contact}}/\tau$, does not depend on the drop radius, $R$, which is consistent with fig. 5c.

In summary, we evaluated that $t_{\text{contact}}/\tau$ approaches to 1 for $U \approx U_c$ as the maximum value, and the minimum value is estimated to be 0.13 for $U \gg U_c$ at given experimental conditions. Experimentally, a range of $t_{\text{contact}}/\tau$ (see fig. 5c) remains between the two asymptotic limits, 0.13 $< t_{\text{contact}}/\tau < 1$, which confirms the validation of our asymptotic limits.

3. **Dependence of contact time on the micro-bump spacing.** To characterize the contact time, $t_{\text{contact}}$, with different microbump spacings, $s$, we used micro-patterned surfaces using a soft lithography technique. Figure S7 shows that the number of holes emerging on a spreading drop, $N_{\text{hole}}$, slightly increases with decreasing the bump spacing, $s$. This is because more dense bumps (smaller $s$) stochastically nucleate/create more holes. As more holes are nucleated with smaller $s$, the contact time is reduced as shown in the last time stamps of fig. S7a-c.

### G. Hole nucleation behaviors by chemical impurities on solid surfaces

Marangoni effect due to a local change in surface tension is known to nucleate holes on a thin liquid film (6, 7). In order for the Marangoni stress to be in effect, chemical impurities shedded from biological/artificial surfaces must travel to the upper air-liquid interface of a spreading drop to lower the surface tension locally. Here, we calculate the Pécelt number defined as a ratio of advection to diffusion, $Pe = U h / D$, where the fluid velocity, $U$, is about 1 m/s, and the thickness of the spreading drop, $h$, is about 10 μm. The diffusion coefficient, $D$, is taken to be $10^{-9}$ m$^2$/s as a typical diffusion coefficient of alcohol molecules through water. In our experiments, $Pe$ is on the order of $10^7$, which implies that advection is dominant over diffusion. In other words, a local fluid volume with lower surface tension will be advected to the rim of the spreading drop. Thus, the surface tension is lowered at the rim region close to the contact line not on the central spreading film.

To further characterize the Marangoni effect experimentally, we performed drop tests on micro-patterned surfaces with alcohol-coated particles as shown in fig. S8. For the particles, we used stainles steel spheres (Atlantic Equipment Engineers, Type 304), whose the density is 7.9 g/cm$^3$ and the diameter is approximately 40 μm. Then, we submerged the particles in an isopropyl alcohol bath, and waited until the alcohol is fully evaporated. The alcohol-coated particles were deposited on a micro-patterned surface with microbumps of 300 μm and 40 μm in spacing and height, respectively. If the Marangoni effect...
triggers the rupture of the spreading drop, it is expected that the critical impact velocity becomes smaller or the number of nucleated hole increases for the surfaces with alcohol-coated particles. However, we found that the critical impact velocity remains to be the same ($U_c \approx 2 \text{ m/s}$) compared to micro-patterned surfaces without impurities, and the number of nucleated holes gets smaller with the surfaces with alcohol-coated particles, as shown in fig. S8. Therefore, Marangoni effects due to chemical impurities on biological/artificial surfaces are negligible for the rupture of spreading drop, as shown in the above paragraph.

H. Dispersal of a pathogenic spore by shock-induced drop fragmentation

When a wheat leaf is infected, a pustule of pathogenic spores is breaking through the epidermis of the wheat leaf (first images in S9\textit{a} and S9\textit{b}), which forms superhydrophobic microbumps on the leaf (8). To see the effect of a superhydrophobic leaf surface onto a drop splash, we used the infected wheat leaf prepared the same as in Kim et al. (8). Figure S9 shows that an impacting drop on the infected leaf undergoes the same behaviors as shown earlier: formation of shock waves (second images in \textit{a} and \textit{b}), the rupture of the spreading drop (third image in \textit{a}), and the drop fragmentation (fourth image in \textit{a}). It is noted that the drop fragmentation generates many smaller satellite droplets, which can carry pathogenic spores along with them (third image in fig. S9\textit{b}). Therefore, this indicates another type of pathogenic spore dispersal mechanism beside the air-vortex-induced dispersal (8).

I. Methods of characterising morphological properties of substrates

We measured the morphological property of microbumps of various test samples. Fig. S10\textit{a} illustrates the shape of microbumps used in our study, and fig. S10\textit{b}, \textit{c} show the top and side views of a cracker butterfly (\textit{Hamadryas}) in which $s$ and $\epsilon$ are defined. For artificial surfaces, we characterized the surface morphology from microscopic images. We measured the height and spacing of microbumps in the upper region within 20% of the maximum height from side-view images. The distributions of $s$ and $\epsilon$ on type-I artificial surfaces are plotted in fig. S10\textit{d}, \textit{e}. For theoretical models to predict $t_{\text{hole}}$ and $U_c$, we used the averaged values of $s$ and $\epsilon$ as listed in table I. For micro-patterned surfaces (type-III and type-IV) using a soft lithography technique, $s$ and $\epsilon$ are simply constants determined by a photo-mask we used.
Fig. S1. a. Schematic of showing our experimental apparatus. b. Particles (blue dots) are placed on the substrate to measure the local velocity of a drop impacting a superhydrophobic surface (type-II). c. Particle trajectories (white dots) are visualized by overlapping multiple images. d. Temporal evolution of the radial position of particles. e. The radial velocity of particles is plotted $r/t$ as proposed in the theoretical model (1).
Fig. S2. a. Image sequences of the interface profile of an impacting drop on a superhydrophobic surface (type-II) using a X-ray phase contrast imaging technique, where $[R, U]=[1.5$ mm, 2.0 ms$^{-1}$]. Thickness profile of an impacting drop of 1.5 mm in radius on a superhydrophobic surface at $U=2.0$ ms$^{-1}$ (b), and $U=2.8$ ms$^{-1}$ (c). $h(r, t)$ is plotted according to the thickness model of eq. (3) for $t < t_{c_1}$ (d), for $t_{c_1} < t < t_{c_2}$ (e), and for $t > t_{c_2}$ (f), where the slopes correspond to $a_3 (=0.06)$, $\pi a_1 b (=0.09)$, and $a_0 (=0.25)$, respectively.
Fig. S3. Lateral view of an impacting drop of 2.0 mm in radius on slightly curved superhydrophobic surfaces. The substrates used in a, b correspond to type-I and type III, where impacting velocities are 2.8 m/s and 3.5 m/s, respectively. The schematic in a shows an experimental apparatus to measure the amplitude of shock-like waves and observe the hole formation. Here, the drop impacts on a slightly curved surface, where the white dashed line indicates the plateau of the curved surface.
Fig. S4. a. Schematic of the interfacial behaviors of a spreading drop on a superhydrophobic surface, where the thickness profile of microstructure is simplified to be represented by a sinusoidal function, \( \eta_s = \epsilon \cos(kr') \) with the wavenumber, \( k \), being \( 2\pi/s \). b. Instantaneous amplitude of the shock-like wave, \( |\eta| \), versus the radial position of a microbump, \( r_b \), for the type-I artificial surface. c. \( |\eta| \) plotted against eq. (10).
Fig. S5. Impact velocity vs. the radius of impacting drop to show the critical impact velocity, $U_c$, depending on the drop size. Here, an artificial superhydrophobic surface was used in this parametric study.
Fig. S6. a. Sequential images of drop impact on a superhydrophobic surface (type-I) for \([R, U] = [2.0 \text{ mm}, 2.1 \text{ m/s}]\), where the upper and lower arrows represent the contact distance of a spreading drop, \(d\), of the upper and lower sides of the spreading drop, respectively. b. Temporal evolution of \(d\). c. Dimensionless contact radius, \(d/R\), versus dimensionless time, \(t/\tau\).
Fig. S7. Image sequences of an impacting drop on micro-patterned surfaces, where \([ R, U ] = [2 \text{ mm}, 3.4 \text{ m/s}]\): a. \( s = 400 \mu\text{m} \). b. \( s = 600 \mu\text{m} \). c. \( s = 800 \mu\text{m} \). d. The number of holes, \( N_{\text{hole}} \), versus impact velocity, \( U \). e. A ratio of the number of holes to the number of bumps underneath, \( N_{\text{hole}}/N_{\text{bump}} \), versus impact velocities, \( U \). Here, \( N_{\text{bump}} \) denotes the number of bumps under the drop at the maximum spreading radius.
Fig. S8. a. A drop of 2 mm in radius impacts a micro-patterned surface at $U' = 2.4 \text{ m/s}$. Here, a regular array of quadrilateral microbumps is fabricated through a soft lithography process, where the spacing and height of microbumps are 300 and 40 $\mu\text{m}$, respectively. b. The drop with the same conditions impacts the micro-patterned surface, where alcohol-coated particles are deposited on the surface (see black particles in the inset of the first panel).
Fig. S9. a. Drop impact on an infected wheat leaf, where \([R, U]=[1.6 \text{ mm, } 2.8 \text{ m/s}]\). b. The solid, dashed, and dotted insets represent the solid, dashed, and dotted boxes in a. Shock waves formed by pustules induce the rupture of an impacting drop, and then lead to the formation of smaller satellite droplets, which can carry pathogenic spores along with them.
**Fig. S10.**

**a.** Biological surfaces for drop impact experiments (upper panels) and their microscopic images obtained using a focus stacking technique. From the left, the images correspond to northern gannet (*M. bassanus*), dragonfly (*Anax*), cecropia moth (*H. cecropia*), zebra swallowtail butterfly (*P. marcellus*), cracker butterfly (*Hamadryas*), and katsura leaf (*C. japonicum*), respectively. **b, c.** Top and side views of a cracker butterfly wing (*Hamadryas*) in Fig. 1b. Here, the spacing, \( s \) and height, \( \epsilon \) of microbumps are defined. **d, e.** Distributions of \( s \) and \( \epsilon \) are plotted for artificial surfaces (type-I).
Movie S1. Impact of a water drop of 1.7 mm in radius on biological surfaces listed in fig. 1.

Movie S2. Impact of a water drop of 1.7 mm in radius on other biological surfaces: swallowtail butterfly, cecropia moth, and dragonfly.

Movie S3. Impact of a water drop of 1.7 mm in radius on a tiger moth wing.

Movie S4. Impact of a water drop of 1.7 mm in radius on type-I artificial surfaces listed in fig. 2.

Movie S5. Impact of a water drop of 1.7 mm in radius on type-III artificial surfaces listed in fig. 2.

Movie S6. Impact of a water drop of 1.2 mm in radius on an artificial surface (type-I) at a critical impact velocity (≈ 2 m/s). A spreading drop on the surface is ruptured just before rebouncing, where the hole nucleates on the smooth interface of the spreading drop, implying the total dissipation of shock waves.

Movie S7. Impact of a water drop and an isopropyl alcohol drop of 1.4 mm in radius on glass surfaces, where a thin needle is situated slightly above the glass surface to generate shock-like waves on a spreading drop.

References

1. Wang Y, Bourouiba L (2017) Drop impact on small surfaces: thickness and velocity profiles of the expanding sheet in the air. *Journal of Fluid Mechanics* 814:510–534.

2. Vernay C, Ramos L, Ligoure C (2015) Free radially expanding liquid sheet in air: time-and space-resolved measurement of the thickness field. *Journal of Fluid Mechanics* 764:428–444.

3. Villermaux E, Bossa B (2011) Drop fragmentation on impact. *Journal of Fluid Mechanics* 668:412–435.

4. Pasandideh-Fard M, Qiao Y, Chandra S, Mostaghimi J (1996) Capillary effects during droplet impact on a solid surface. *Physics of fluids* 8(3):650–659.

5. Richard D, Quéré D (2000) Bouncing water drops. *EPL (Europhysics Letters)* 50(6):769–775.

6. Néel B, Villermaux E (2018) The spontaneous puncture of thick liquid films. *Journal of Fluid Mechanics* 838:192–221.

7. Kim S, Kim J, Kim HY (2019) Dewetting of liquid film via vapour-mediated marangoni effect. *Journal of Fluid Mechanics* 872:100–114.

8. Kim S, Park H, Gruszewski HA, Schnale DG, Jung S (2019) Vortex-induced dispersal of a plant pathogen by raindrop impact. *Proceedings of the National Academy of Sciences* 116(11):4917–4922.