ABSTRACT: The present article highlights an approach to generating contrasting patterns from drying colloidal droplets in a liquid bridge configuration, different from well-known coffee rings. Reduction of the confinement distance (the gap between the solid surfaces) leads to systematized nanoparticle agglomeration yielding spoke-like patterns similar to those found on scallop shells instead of circumferential edge deposition. Alteration of the confinement distance modulates the curvature that entails variations in the evaporation flux across the liquid—vapor interface. Consequently, flow inside different liquid bridges (LBs) varies significantly for different confinement distance. Small confinement result in stick-slip motion of squeezed liquid bridges. On the contrary, the stretched LBs exhibit pinned contact lines. The confinement distance determines the characteristic length scales of the thin film formed near the contact line, and its theoretical estimations are validated against the experimental observations using reflection interferometry, further exhibiting good agreement (in order of magnitude). We decipher a proposition that a drying liquid thin film (height \( \sim O(10^{-3}) \) m) present during dewetting near the three-phase contact line is responsible for the aligned deposition of particles. The coupled interplay of contact line dynamics, evaporation induced advection, and dewetting of the thin film at a three-phase interface contributes to the differences in deposition patterns.

1. INTRODUCTION

The formation of patterned drying precipitates from evaporating colloidal drops is a complex non-equilibrium process, where the multiscale heat and mass transfer of the droplet are governed by the coupled interplay between solvent evaporation and advection—diffusion of particles. Several factors, such as the surrounding atmosphere (temperature, humidity), substrate properties (wettability, substrate temperature), and nature of particle (for example, particle size and shape), can be tailored to regulate the outcome of the deposition patterns, which finds potential applications in ink-jet printing, fabrication of functional coatings, and development of miniaturized electronic devices. The seminal article by Deeg et al. reported that evaporation of a sessile droplet containing particles typically leads to a ring-like deposit, commonly referred to as “coffee-ring”. In this case, the droplet contact line (CL) remains pinned to the substrate, and non-uniform evaporation flux along the liquid—vapor interface generates radially outward capillary flow that advects the particles toward the pinned edge, thereby resulting such deposits. Variations in deposition patterns, for instance, multiple rings instead of a single one, central deposits, hexagonal cells, and even uniform deposits, were also observed by fellow researchers. Further, depinning of the CL and Marangoni stresses have been found to determine the precipitation patterns. The contribution of thermal Marangoni advection induced by the latent heat of evaporation or activated due to substrate heating on the deposition dynamics is well documented. Recent reports have shown that inducing differential vapor gradients around droplet surroundings leads to a reconfiguration of CL that modifies the residual precipitates. Therefore, simple yet intriguing patterns can be obtained by manipulating CL, controlling the evaporative flux across the droplet interface, and modulating the associated fluid flow within the evaporating drop.

Researchers from different backgrounds have investigated the evaporation dynamics of a sessile drop and the subsequent emergent patterns due to solvent depletion. However, very little attention is paid to drying droplets in the capillary liquid bridge configuration, particularly in the case of colloidal dispersions. In many biological and industrial processes, this type of confined drying of droplets is observed and offer an advantage in controlling the solvent evaporation flux so that engineered deposition patterns can be realized. One of the earliest reports by Lin and Granick on colloidal deposits for restricted geometry (sphere-on-plate) demonstrated the formation of concentric rings. Similar observations (concentric rings with...
gradients) were also confirmed by Xu et al.\textsuperscript{17} when they explored the drying of liquid bridges under sphere-on-plate geometry. Considering sphere-on-plate configuration, Mondal and Basavaraj\textsuperscript{18} concluded that the concentration of the particles influences deposition patterns of suspensions containing ellipsoidal particles. The sphere-on-plate geometry is not exactly symmetric as one end (top) of the liquid bridge is attached to a curved surface, whereas the other end (bottom) is with a flat surface. This configuration inherently induces contact angle (CA) variations at both ends. This may contribute to the differences in evaporation flux across the meniscus of the droplet due to the geometrical restrictions. These effects can be mitigated if one chooses a parallel plate configuration.

Only a handful of research groups have attempted to study the evaporation of colloidal drops confined by parallel plates. Experiments performed with concentrated colloids (very high volume fractions) exhibit distinct deposit patterns formed due to interfacial instability\textsuperscript{19} or the buckling phenomenon.\textsuperscript{20} Mahanta and Khandekar\textsuperscript{21} compared the evaporation characteristics of liquid bridges (pure solvent and nanoparticle (CuO)-based media) between the heated surfaces and concluded that the presence of particles enhances the overall rate of evaporation owing to higher diffusional conductivity. Of late, the article by Mondal and Basavaraj\textsuperscript{22} demonstrated the role of the confinement distance (distance between the solid surfaces) and particle concentration on the deposits. According to them, the continuous stick–slip motion of the CL resulted in symmetric spiral deposits independent of the shape of the particles. Very recently, Upadhyay and Bhardwaj\textsuperscript{23} examined the colloidal liquid bridge by altering the wettability of solid surfaces and the size of particles along with the composition of the colloids. Their observations include the formation of multiple rings governed by the stick–slip motion of CL. Additionally, they reported notable asymmetric deposits composed of larger particles, with the majority of the particles present at the bottom surfaces as their transport is influenced by gravitational forces rather than the hydrodynamic forces. Likewise, Deegan et al.\textsuperscript{24} presented the deposition patterns of the evaporated droplet for a wide range of surfaces, solvents, and solutes. The evaporation phenomena of droplet and extreme modes of contact angle on a strongly hydrophobic substrates were discussed briefly by Staub et al.\textsuperscript{25} The comparison of theoretical predictions with the experimental results on variation of a thin droplet in a shallow well and the effect of non-uniform evaporation of the fluid were presented by Ambrosio et al.\textsuperscript{26} Tomo et al.\textsuperscript{27} reported the variation of ultrathin films in nanotubes with the addition of molecular interactions and balance of pressure variations in the formation of the meniscus in the ultrathin films. Also, there are several applications of the liquid bridges like many medical problems involving respiratory diseases, and the health of the body joints depends on liquid bridges.\textsuperscript{28} Liquid bridges are now commonly used in growth of cell cultures, evaporation in porous media like soil, etc.

From the discussion of the literature survey, it is understood that evaporation of the colloidal liquid bridge can result in varying deposition patterns that differ from the conventional “coffee ring”. This opens up an opportunity to tailor the precipitate patterns that may be of greater interest to several industrial and biological processes. Moreover, one must comprehensively understand the fundamental insights into the CL dynamics during evaporation and the physical deposition mechanisms of particles that yield a specific pattern. Following this aim, we study the evaporation of colloidal liquid bridges (LB) in a parallel plate configuration. In this contribution, we experimentally demonstrate how the commonly observed “coffee ring” can be turned into differently orientated patterns (similar to spokes) by modifying only the confinement distance for the same particle concentration. To the best of our knowledge, no article has reported this kind of pattern in the case of colloidal liquid bridges. The drying kinetics of the colloidal LB systems and the role of specific parameters in controlling those patterns are discussed thoroughly. It has been shown that the evaporation flux across the surface of LB is strongly dependent on the confinement distance and the curvature of the surface of LB. The evaporation flux across the surface of the LB is a deciding parameter in the depinning of CL for lower confinement distance leading to thin-film instabilities and unique pattern formation. The thin-film theory explains the mechanism that led to the differences in deposition patterns, and further interferometric measurements were carried out that confirm the theoretical proposition.

2. MATERIALS AND METHODS

2.1. Materials. The colloids were prepared by suspending neutrally buoyant, monodispersed, charge stabilized, fluorescent polystyrene particles (purchased from Thermo Fisher Scientific) to de-ionized (DI) water. The suspensions were sonicated for about 30 min, resulting in a
homogeneous distribution of particles in the liquid. Post sonication, the suspensions were stored in centrifuge tubes (Tarsons Product Ltd.). The particles do not form sediments or agglomerates for at least 2 weeks from preparation (refer to the zeta potential data of the particles in the Supporting Information for stability). Three different colloids with varying concentrations (φ = 0.02%, 0.1%, 1% v/v) were prepared for a monodisperse particle size of 860 ± 20 and 100 ± 20 nm having 1% volume fraction. The substrate used in the present study was glass slides of dimensions 25 × 25 × 1 (length × breadth × height) mm². The standard glass slides with a planar area of 75 × 25 mm² (procured from Blue Starc) were meticulously sliced with a glass cutter to obtain the required dimension. The square slides were designed to minimize the edge effects so that a drop placed at the center of that slide is almost equidistant from both the spatial dimensions. These square slides were sonicated in a bath of propan-2-ol (isopropanol) for 10 min and further rinsed with Kimwipes (Kimberly Clark International). All the suspensions were stored in centrifuge tubes (Tarsons Product Ltd.).

2.2. Experimental Setup. A colloidal droplet of 0.3 ± 0.1 μL was minutely placed on to the central part of the square slide (bottom) using a micropipette (purchased from Thermo Scientific Finnpipette, range: 0.2–2 μL), and later the top slide was positioned accordingly with the help of an actuator, so that the drop was allowed to dry in a liquid bridge (LB) configuration. The evaporation dynamics of the sandwiched droplet were recorded at 30 fps from the side view using a digital camera (Nikon D5600) fitted with a zoom lens assembly (Navitar) in the presence of a controllable LED light source (5 W, procured from Holmarc), as shown in Figure 1a. A diffuser was placed between the light source and the LB for homogeneous light distribution. An optical microscope (Olympus) fitted with a CCD camera (Nikon D7200) simultaneously visualized the contact line (CL) dynamics of the LB from the top. The dried precipitates were volumetrically illuminated using a mercury source with a filter, and the emission signal (612 nm) was captured (at 10× to 50× magnification) by the same microscopic arrangement described earlier. Image analysis was carried out with open source software FIJI (ImageJ). Also, the deposition patterns were also scrutinized by SEM to observe the particle aggregation and analyzed with the help of an optical profilometer (Talysurf Hobson) to estimate the thickness of the dried colloids.

Microparticle image velocimetry (μ-PIV) is done to quantitatively assess the flow inside the liquid bridge. The liquid bridge is illuminated volumetrically by a laser beam (Nd: Yag laser NanoPIV, Litron Laser) from the bottom (refer to Figure 7a). The images are captured from the bottom in the plane of observation near the base of the LB. An Imager Intense CMOS camera (LaVision) fitted to a Flowmaster MITAS microscope [field of view: 1000 × 600 μm², depth of field: 28 μm] is used for capturing images. Images are acquired at the plane 50 μm above the base of the LB at 0.5 fps using the single-frame-single pulse technique. It has been ensured that 3–4 pixels of particle shift are maintained between the subsequent frames, which is deemed optimal for computation.

Evaporation dynamics (dewetting phenomena of the liquid layer) of the colloidal LB at variable confinement distance and their temporal deposition patterns were examined with the help of reflection interference microscopy. Microscopic alignment and the arrangement of associated components are shown in Figure 1b. A pulse-laser source of 640 nm wavelength (Cavitar, Finland) of the light source is positioned on a beam splitter that transmits and reflects the light beam. The reflected light beam passes through the microscopic objective (4× and 20×) and reflects from the bottom glass plate positioned at the focal length of the microscope. The developed phase difference of the light beam at the leading of the LB repels from the glass surface and passes through the objective, beam splitter, zoom lens (Navitar), and dichoric mirror, as seen in Figure 1b. The change in phase difference induces the interference fringe patterns that are captured using a high-speed camera (Photon SA-5, LaVision). The detailed procedure of postprocessing the images obtained from these experimental observations is included in the Supporting Information.

3. RESULTS AND DISCUSSIONS

3.1. Formation of the Liquid Bridge and Its Lifetime. A sessile aqueous drop of dispersed particles after evaporation of solvent leave deposits of particles. In most of these dried precipitates, the particles accumulate at the three-phase contact line (CL), forming well-known “coffee-ring” patterns. However, contrasting patterns emerge when a colloidal drop is allowed to evaporate in a liquid bridge (LB) configuration, confined between two impermeable solid surfaces. Before proceeding to the analysis of deposit patterns, we will discuss some of the
As the evaporation continued, the drop lost more and more correspondent to individual drops; refer to Figure S1 in the Supporting Information for temporal reduction of the diameter of the liquid bridge (at the neck region) for different confinement distances. Further, those two drops underwent evaporation until the final precipitates formed on the top and bottom glass slides.

The period during which the drop remains in its LB configuration while undergoing evaporation before its separation into individual drops is referred to as \( t_{lb} \). The evaporation timescale of the individual droplets from their evolution to completion of drying is given a symbol \( t_{wd} \). The addition of these three-time scales yields the lifetime of the evaporating capillary bridge. When placed on a glass slide, the sessile drop contact diameter (CD) and droplet height are designated as \( D_s \) and \( h_s \) respectively (refer to Figure 2a). The distance between two parallel slides, referred to as “confinement distance”, is indicated by \( \Delta H \). The CD and \( CA \) in LB configuration are indicated by \( D_{lb} \) and \( \theta_{lb} \). The end-to-end distance of the square glass slide is represented by \( D_{ss} \). Subsequently, in the first image of Figure 2b–f, the dashed green line indicates the bottom edge of the top glass slide. The top droplet in the first image of Figure 2b–f is the fictitious reflection of the actual sessile droplet placed at the bottom surface. The overall sequence of images from left to right represents droplet placement, initiation of the liquid bridge, stretching to the confinement distance, and curvatures before detachment. However, the final image in Figure 2b–f shows the individual drops after the separation of the LB. The contact angle (CA) of the sessile colloidal drop was observed to be \( 33^\circ \pm 5^\circ \), and the respective initial contact diameter (\( D_{co} \)) was measured to be \( \approx 1.8 \text{ mm} \). A variable “\( \alpha \)” denotes the non-dimensional confinement distance, as \( \Delta H \) is normalized with respect to \( D_{co} \). The higher the \( \alpha \), the larger is the gap between the two surfaces.

3.2. Patterns of the Colloidal Liquid Bridge. Figure 3a illustrates the final deposition patterns that emerged from colloidal liquid bridges. The confinement distances of those systems were altered (\( \alpha = 0.11 \) to 0.31), keeping the same volume fraction (\( \varphi = 1 \% \text{ v/v} \)) and particle size (860 nm). We further classify the confinement distance regimes into low (\( \alpha < 0.2 \)), intermediate (0.2 \( \leq \alpha \leq 0.3 \)), and high (\( \alpha > 0.3 \)). The
analysis of deposition patterns of bottom surfaces reveals an outermost “coffee ring” that is present in all the cases (refer to Figure 3a).

This ring forms due to capillary flow when the sessile drop is placed initially on the glass surface (bottom one) as the droplet maintains its spherical cap configuration and remains pinned to the bottom surface. In this article, the deposition patterns refer to the corresponding central deposits unless otherwise specified. For higher $\alpha$ ($\alpha > 0.3$) [volume fraction ($\varphi = 1\%$ v/v) and particle size (860 nm)], the LB remains pinned at both top and bottom surfaces (Figure 3a). This behavior allows the particles to accumulate at the CL of LB, thereby resulting in a central coffee ring. In the case of intermediate and low confinement distances, the LB goes through a “stick–slip” motion as it continuously depletes solvent (water) to the surroundings. However, there are considerable differences among the patterns of intermediate and lower cases (Figure 3a). While the intermediate LBs ($\alpha = 0.22, 0.25$) exhibit multiple coffee rings, further reduction of confinement distance ($\alpha = 0.11, 0.14$) leads to the evolution of spoke-like deposition patterns instead of coffee rings. For $\alpha = 0.17$, spokes are observed; however, they are not continuous like in the other two cases ($\alpha = 0.11, 0.14$).

These types are ordered particle alignment, analogous to spokes, are unprecedented, and have not been reported till now to the best of the authors’ knowledge, particularly from the drying of colloidal LBs. We identify these spoke-like patterns as “scallop shell” patterns due to their peculiar similarity with the patterns observed on the outer shells of the scallops (Figure 3b). However, it is noteworthy to mention that an article by Mondal et al. has reported spiral deposition patterns for a similar configuration of liquid bridges on glass slides with aqueous colloidal dispersions. The liquid used by Mondal et al. is an aqueous hematite dispersion to which nitric acid is added; in contrast, we have used polystyrene particles suspended in DI water. The change in the solution might have led to the spiral patterns as compared to the spoke-like patterns in the present article. The corresponding precipitates at the top surfaces are replicas of the bottom surface deposits; however, the outermost ring is absent (Figure 3a). This is expected as the initial deposition of a colloidal sessile drop on the bottom surface leads to the outermost ring due to capillary flow-induced particle aggregation at the initial CL, while the deposition at the top surface begins only after the LB is formed. The deposition patterns at the top surface also reveal similar sequences (from “coffee ring” to “scallop shell”) as the confinement distance is diminished ($\alpha = 0.31$ to 0.14).

To understand what led to the differences in patterns, we systematically investigate the evaporative behaviors of these systems. A sessile colloidal drop forms a single coffee ring by virtue of its loss of solvent around the three-dimensional surrounding space while the particles aggregate at its pinned CL. By sandwiching the droplet between two parallel solid surfaces, a part of its evaporation flux component is suppressed (that allows vertical mass transport from the sessile drop), while allowing its mass transfer to happen sideways, more so in the radial direction (refer to Figure 2b). To estimate the role of evaporation suppression in the pattern formation, we carried out additional experiments where we placed the top glass slide to the nearest possible vicinity of the apex of sessile drop (however, not in contact with the sessile drop), and the sessile drop remains unperturbed in the presence of the top surface. In this case, a very thin air gap existed between the droplet apex and top surface, and the height of this air layer was measured to be $\sim O(10^{-6})$ m. The initial droplet height ($h_0$) was found to be sufficiently large ($O(10^{-3})$ m) than this air layer, higher by at least two orders of magnitude. The objective was to compare the performances of the sessile drop and LB by maintaining very similar magnitudes of confinement distance ($\Delta H_{\text{scale}} = 258 \mu m$ and $\Delta H_{\text{LB}} = 250 \mu m$, in terms of $\alpha$: $\alpha_{\text{scale}} = 0.43$, $\alpha_{\text{LB}} = 0.14$) and to examine the role of confinement in their evaporation characteristics. After complete evaporation, the coffee ring pattern appears for the sessile case (Figure 3b), while the LB resulted in a scallop shell pattern (Figure 3a, $\alpha_{\text{LB}} = 0.14$), as noted previously. This gives us an impression that the distribution of evaporation flux across the curvature of the drop, which governs the mass transport through the liquid–vapor interface, may play a domineering role in modifying its evaporation dynamics and in the formation of variant residual...
precipitates rather than the vertically imposed spatial constriction.

3.3. Evaporation Dynamics of the Colloidal Liquid Bridge. The salient features of evaporation of the colloidal LB are presented in Figure 4. The temporal variation of the non-dimensional CDs ($D_{flb}$) at the bottom surface is obtained by normalizing the instantaneous CDs ($D_{lb}(t_{lb})$) of LB with respect to the corresponding initial CDs ($D_{ibo}$) (as shown in Figure 4a), where $D_{ibo}$ indicates the initial contact diameter of the drop after it attains a stable LB configuration (refer to Figure 2a). For low confinement distance ($\alpha = 0.11$), the maximum reduction in CD is noticed during the evaporation time period. With an increasing gap, the decrement in CD is relatively low, and at the highest confinement distance ($\alpha = 0.34$), hardly any change in CD is observed as the CL appears to be almost static. However, the evaporation behaviors of the squeezed LBs are entirely different from the higher $\alpha$ cases. In these cases, the mass transfer mechanism is governed by the stick—slip motion leading to a significant reduction in CD. One can notice a slight enhancement of CD (Figure 4a) during the penultimate stages (just before the rupture of LB, $t \sim 0.95 t_{lb}$) of dewetting. This is attributed to the complex interplay among the dynamic change in evaporation flux across the surface tension, and the gravitational forces that are responsible for splitting the LB into individual drops. The time-dependent variations of CDs corresponding to top surfaces show analogous behaviors to the bottom surfaces.

Figure 4b compares the transient variations of CAs (top and bottom of the left curvature of corresponding LBs) of different confinement distances. The instantaneous CAs ($\theta(t_{lb})$) of LBs at top and bottom surfaces are normalized against the initial CA ($\theta_{ibo}$) of the sessile drop to obtain the non-dimensional CAs ($\theta^*$). In the sessile configuration, $\theta_{ibo}$ (33°) represents the mean initial CA of the colloidal drop. With time, $\theta^*$ exhibits a declining trend up to a critical time threshold, beyond which the slope (the rate of change of CA with time) becomes steeper (by 6–10 times) (Figure 4b). This threshold (indicated by the black dashed line, Figure 4b) is noted to be $\sim \text{0.85–0.9} \ t_{lb}$, taking all the cases into account. As opposed to a pinned LB ($\alpha = 0.31$) whose CA gradually decreases with time, in the case of the LBs showing considerable dewetting, the CAs show a non-monotonic trend. Between successive slipping movements, the LB adjusts to a new position, thereby contributing to the temporal alteration of CAs. With increasing the gap between the surfaces, the magnitude of the initial CAs decreases. This is because, for a given volume of liquid, the reconfiguration of colloidal droplets for LBs with higher confinement distance leads to reduced initial CDs with lower slopes of the liquid meniscus at the three-phase contact point. The differences between the CAs corresponding to the top and bottom surfaces for a given confinement distance are estimated to be around a maximum of 7°. With increasing the confinement distance, this deviation becomes minimum.

Further, we analyze the timescales and dewetting velocity as a function of the confinement distance (Figure 5). The detailed interpretation of these individual timespans is already explained previously (refer to Figure 2). The $t_{lb}$ is estimated to be $\sim \text{90–120} \ s$, depending on adjustments required to achieve desired confinement distance. With increasing confinement distance, the $t_{lb}$ decreases significantly. Analysis reveals that three times enhancement in $\alpha$ results in $\sim \text{75%} \$ reduction of $t_{lb}$ (Figure 5a), while $t_{lb}$ becomes larger. This is expected as more stretched confinement cases. The dewetting ($v_{dew}$) velocity is calculated by measuring the average displacement of CL over the entire timescale ($t_{lb}$) during which the drop remained in an LB configuration. The estimated $v_{dew}$ demonstrates a non-monotonic decrement as it decreases by one order (from $O(10^{-7})$ m/s to $O(10^{-8})$ m/s) with increasing the confinement distance (Figure 5b). This is consistent with the characteristics portrayed in Figure 4a as a maximum reduction in CD was observed for the case having the highest dewetting velocity. A higher dewetting velocity can be related to the stick—slip motion of the LB drop, while low $v_{dew}$ indicates almost stationary CL.

Also, we compare the experimentally observed $v_{dew}$ with the theoretical one (Figure 5b). To find out the theoretical velocity, we first evaluated the evaporation flux by using the following expression:23

$$J_{flb} = \frac{2D(1 - RH)\dot{e}_{sat}}{D_{ibo} \ln(D_{ib0}/D_{ibo})}$$

Figure 5. (a) Comparison of two timescales ($t_{lb}$ and $t_{flb}$) against different confinement distance ($\alpha = 0.11 \text{ to } 0.34$). The blue circle corresponds to $t_{lb}$, and the green triangle represents $t_{flb}$. (b) Dewetting velocity (estimated from experimental observations) as a function of confinement distance.
In the eq 1, $D$, $RH$, $c_{sat}$, and $D_{sat}$ represent mass diffusivity ($2.5 \times 10^{-5}$ m$^2$/s) of liquid vapor in air, relative humidity (45%), saturated water vapor concentration (0.0232 kg/m$^3$) at the vapor–liquid interface, and the length scale far away from the squeezed drop (we consider the distance between two extreme ends of the glass slide, equal to 25 mm, refer to Figure 2), respectively. The estimated $j_M$ comes to about $1.35 \times 10^{-4}$ kg/m$^2$s. The theoretical dewetting velocity ($v_{vap}^{th}$) calculated as per ($v_{vap}^{th} \sim j_M/R\rho$) is found to be $O(10^{-6})$ m/s. This shows that theoretical dewetting velocity agrees with experimental values of lower confinement distances; however, it fails to accurately predict the velocity scales of LBs having higher confinements ($\alpha > 0.3$). Since this expression is derived from the steady-state equation, this cannot capture the transient variation of evaporation flux. Moreover, this does not consider the curvature effects and role of confinement distances. Although eq 1 has limitations, its derived velocity scale still reasonably estimates the experimental ones for low confinement distances.

3.4. Evaporation Induced Flow inside the Liquid Bridge. Differential evaporation across the liquid–vapor interface of a sessile droplet induces a flow inside the droplet, commonly known as evaporation-driven flow (EDF).\textsuperscript{6,32}

Analogous to sessile droplets, evaporation occurs differentially over the surface due to the surface curvature of the LB.\textsuperscript{25} The evaporation flux is maximum near the glass surface and minimum at the center of the LB as in the present study; for all cases, the meniscus is concave.\textsuperscript{23} The LB surfaces have varying curvatures depending upon the value of $\alpha$ (also, the curvature changes dynamically with evaporation); evaporation flux is dependent on the curvature of the surface and can influence the flow inside the LB. It is thus crucial to understand the variation of the concentration field of water vapor across the surface of LB of different curvatures (i.e., different values of $\alpha$) to understand its influence on flow inside the LB. Evaporation from the surface of the LB can be considered quasi-steady, and the diffusion equation ($V^2c = 0$) is the governing equation of the concentration field. The two-dimensional diffusion equation for the gas phase is solved using ANSYS FLUENT software (2021, R2). The curvature profile of the LB (for the fluid domain, as shown in Figure 6a) for different values of $\alpha$ is imported from the experimental data (images obtained from the shadowgraph).

The following are the boundary conditions used:

1) Concentration at the surface of the LB curvature $= C_s$ (saturation concentration of water vapor at 25 °C and 40% RH).

2) The concentration flux of water vapor normal to the glass slide (glass plate boundary) $\frac{dc}{dn} = 0$ where $n$ is the direction normal to the glass plate.

The concentration field relaxes to the relative humidity at the far-field. The far-field is considered to be at a distance of 20 mm from the liquid bridge. The mesh consists of $\sim 37,500$ elements (with individual size 0.00001 mm) and 200 divisions near the LB curvature (refer to Figure 6a). The mesh is tested for grid independence, and the results do not change by varying the element size by one order. The SIMPLE algorithm with second-order discretization is used for solving the governing equation.\textsuperscript{33}

The concentration contours represent the solution for the governing equation in Figure 6b,c. The solution is similarly calculated for different values of $\alpha$ ($=0.14, 0.2, \text{and } 0.31$). The objective is to consider at least one confinement distance from different regimes (low, intermediate, and high) and compare their performances. We non-dimensionalize the data for concise representation in a flowing manner:

i) Non-dimensional concentration flux (CF) $\cdot (M)$

Figure 6. (a) Steady-state solution for the concentration field of water vapor. The gas-phase domain with the meshes and boundaries. (b) Concentration contours of the water vapor near the LB. (c) Concentration contours of the water vapor in the entire domain. Plots of (d) non-dimensional concentration flux across the surface of the LB for different values of $\alpha$ and (e) ratios of concentration flux near the base to the concentration flux near the neck region for different values of $\alpha$. 

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α = − ΔH

For given α, the curvature of LB is minimum, the CF is maximum,
and the curvature of LB is maximum, the CF is minimum.

$Y = \frac{y \text{ coordinate on the LB curvature}}{(\Delta h)_{\alpha=0.31}}$

$R = \frac{\text{water Vapor concentration flux at the base of LB}}{\text{water Vapor concentration flux at the neck region of LB}}$

It is apparent from Figure 6d that the area under the curve increases with the increase in the value of α. This corresponds to increased total evaporation with an increase in ΔH. However, interestingly, the value of R (i.e., the relative concentration flux from the base of the LB to the neck region) also increases substantially (up to ~40% increase in R for the change in the value of α from 0.14 to 0.31 as shown in Figure 6e). Due to the larger gradient of concentration across the surface of LB for α =
0.31 compared to $\alpha = 0.14$, we expect the EDF (which would be driven radially outward) to be stronger for the case $\alpha = 0.31$. This can be experimentally verified by observing the flow inside LB for the cases $\alpha = 0.14$ and $\alpha = 0.31$.

The gradient of evaporation ($R$) for case $\alpha = 0.14$ is significantly less, inducing low evaporation-driven flow velocity ($\sim U_C \sim O(10^{-7})$ m/s). The low radially outward flow velocity fails to compensate for the efflux of evaporation from the CL, leading to early depinning of the drop. Later, the flow inside the LB is driven by the depinning force exerted by the CL (dominant force) compared to the radially outward EDF. The depinning of CL for the case $\alpha = 0.14$ directs the flow away from the depinning contact line with a velocity scale of $U_C \sim 1$ µm/s (refer to Figure 7b and Video S1).

However, for case $\alpha = 0.31$, the flow is directed radially outward toward the pinned edge with $U_C \sim O(10^{-7} - 10^{-6})$ m/s (refer to Figure 7c and Video S2). As explained earlier in this section, the strength of EDF is directly dependent on the differential evaporation flux of the curvature. The higher gradient of evaporation ($R$) across the surface of the LB for case $\alpha = 0.31$ drives the flow toward the edge of the LB (similar to the capillary flow in a sessile droplet). As a result, the particles move toward the rim, permanently pinning the CL.

3.5. Mechanism of Particle Deposition: Role of the Thin Film. From the above discussions, it is clear that evaporation characteristics are indeed different when the confinement distance of the LB is altered. However, this is not sufficient to explain the differences in deposition patterns. The coffee ring patterns emerge as the droplet CL remains pinned, and the particles jam into the three-phase CL due to the capillary flow. Further, the agglomerated particles retard the dewetting of CL, thereby forming a ring-like structure. However, we need to understand the rationale for particle deposition like spokes (ordered and aligned) instead of the coffee rings. To elucidate this departure from conventional coffee ring patterns, we resort to the dynamics of the liquid thin film near the three-phase contact line where the particles deposit onto the surface. First of all, we anticipate that a liquid thin film of height “$h$” (that exists till the final moment of drying during dewetting of CL) is responsible for the deposition of particles in an aligned manner, and in the case of the LB droplet (Figure 8a).

We also suggest that the height of the confinement distance ($\Delta H$) is proportionally related to the height of this thin film. This means that cases with higher $\alpha$ will have higher $h$, and more squeezed LB will have lower $h$. Now there are three possibilities when we compare the TF length scale ($h$) with the length scale of the particle ($D_p - $ diameter of the particle): (i) $h > O(D_p)$ [TF height has higher order than particle size], (ii) $h \sim O(D_p)$ [TF height and particle size are of equivalent order], and (iii) $h < O(D_p)$ [TF height is of a lower order than particle size]. We speculate that ordered spoke-like patterns are possible only when $h \sim O(D_p)$ or $h < O(D_p)$. A higher value of $h$ suggests the augmented propensity of multilayer particle agglomeration rather than monolayer ordered arrangement.

To check the validity of our proposition, we further investigate the patterns of colloidal LB having a smaller particle size of 100 nm (Figure 8b) with a volume fraction of 1%, maintaining a confinement distance of $\alpha = 0.11$. Ordered alignment similar to spokes was observed, although the deposition seems to be pretty dense compared to the $\alpha = 0.11$ case of 860 nm particle size (Figure 3a). This is understandable as the number density of particles is considerably higher for smaller particle sizes for the given particle concentration. This gives an idea about the length scale of this TF, and it is expected that $h \leq O(10^{-5})$ m (considering our assumptions are true, i.e., $h \leq O(D_p)$). The analysis is further supplemented by comparing
the characteristic length scale obtained from theoretical relations
with the experimental ones. As the thickness of the TF becomes
smaller than 1 \( \mu \)m (\( h < 1 \mu \)m), intermolecular and capillary
forces may dominate the fate of the thin
film. Following this
reason, mentioned by Vrij,34 we can
find out the theoretical
characteristic length scale from the following expression

\[
\lambda_{TF} = \frac{4 \pi \sigma_{sl}}{h A^{1/2}}
\]

where \( (\lambda_{TF})_{th} \) indicates the theoretical characteristic length, \( h \)
denotes the height (10\(^{-7}\) m) of liquid TF, \( \sigma_{sl} \) represents the
surface tension (62.8 mN/m) of colloidal dispersions at the
solid–liquid interface, and \( A \) is referred to as the Hamaker
constant (10\(^{-19}\) J). The experimental data (symbols) is found to
be in good agreement with the theoretical predictions (shaded
yellow region) as both of them are of the same order irrespective
of particle sizes and con
finement distances (Figure 8c).

Now the question remains whether particle concentration has
any effect in the dried colloidal patterns for a given confinement
distance (\( \alpha = 0.14 \)) and given particle size (860 nm). As
observed from Figure 8d, reducing the volume fraction by two
orders to 0.02% results in scattered distribution of particles.
However, in the case of intermediate particle concentration
(0.1% v/v), disjointed spikes appear with intermittent rings.
Therefore, it can be inferred that deposition patterns are
dependent on the particle concentration of the colloidal media,
and obtaining the desired pattern can be exercised by tuning the
volume fraction of the particulates. Another way to distinguish
these patterns is by comparing the velocity scale of dewetting
(Figure 8b). The low dewetting velocity (of the order of a few
nm/s, in the case of \( \alpha = 0.31, 0.34 \)) is a signature of pinned CL,
thereby leading to coffee ring deposits (refer to Figure S2a in the
Supporting Information). Even when the CL slips and sticks to a
new location, the existence of multiple coffee rings signifies that
the timescale between two successive slips is sufficiently higher
than the particle residence timescale, thereby allowing particle
aggregation at the CL. However, if the velocity of dewetting is
relatively higher (for \( \alpha = 0.11, 14 \)), or for instance, a colloidal
droplet goes through quasi-continuous dewetting, less particles
have the opportunity to settle within this TF, instead of being
accumulated at the CL. This may plausibly lead to an ordered
alignment (refer to Figure S2b in the Supporting Information)
rather than the conventional coffee ring. Further, we confirm the
sequential deposition of the nanoparticles for particle sizes of
860 and 100 nm from the SEM images (Figures S3a,b).

Monolayer deposits are observed in the case of 860 nm LBs,
whereas the 100 nm case shows the possibility of two-three
layers of deposition, confirmed by the profilometry data (Figure
S3c in the Supporting Information).

3.6. Experimental Validation with Reflection Interfer-
ence Microscopy. Further, we carried out reflection interference microscopy to validate our proposed theory of
liquid thin film. Figures 9 and 10 demonstrate the rapid
alteration of the thin-film formation and dewetting process
during the formation of the liquid bridge and the receding of the

Figure 10. Transient variations of TFs for different confinement distances: \( \alpha = 0.17 \) (a), \( \alpha = 0.2 \) (b), \( \alpha = 0.25 \) (c). Quantitative analysis of the
}
liquid layer during the evaporation process at the varying time scales. During this formation of LB, the exchange of the liquid layer to the top contact surface results in the reduction of the pinned surface region of the droplet in the bottom surface plate. The rapid alteration in the pinned surface region leaves a liquid layer around the LB. Therefore, the variation in interference patterns of this remnant liquid is captured using reflection interference microscopy using a high-speed camera at 250 frames per second, as shown in Figure 9a-c (left column). When the top glass plate comes into contact with the sessile drop for the first time, high densely spaced fringe patterns were observed from the concentrated liquid layer near the CL (Figure 9a).

As the time elapses, the liquid layer’s reduction with widespread fringe patterns and rupture of the thin-film layer nearer to the liquid bridge is evident. Figure 9c exhibits the evaporation sequence of the thin film that ruptures from the edge of the newly pinned LB at the bottom surface and gradually moves toward the previously pinned edge corresponding to the CL of the sessile drop. Due to the drying of this liquid layer, one can observe a scattered deposition of the nanoparticles between the outer ring and central pattern, as was evident from the patterns presented in Figure 3a. The temporal variation in the thickness of this liquid layer and its two-dimensional distribution is determined by the variation in interference fringe patterns through employing the fast-frequency guided algorithms (refer to the Supporting Information). The thin-film thickness variation for the time sequence is observed from the right column of Figure 9a-c.

The two-dimensional distribution of the liquid layer exhibits the pattern of higher film thickness at the outer edges and lower film thickness adjacent to the edge of the LB, and as the liquid layer evaporates, a significant reduction in its thickness is noticed. Transient analysis reveals that the average reduction of the height of this layer is \( \sim 8 \) to 3 \( \mu \text{m} \) (Figure 9d) across the selected plane, indicated by the red line in Figure 10a. The local variation of the contact angle (CA), presented in Figure 9e, demonstrates several interesting features. The contact angle measured in this analysis is different from the three-phase contact angle. As shown in Figure 9e, the CA varies spatially, whereas the three-phase CA is measured at a singular point. Here, the change in CA of the liquid layer during the evaporation is accessed through the thickness of the liquid film in the radial direction (refer to eq 4 of the Supporting Information). For the initial time instance, the CA is relatively higher (\( \sim 4^\circ \)) at the outer-edge periphery and follows the same trend depicted by the thickness of the film. The CA remains spatially invariant for a large region and attains a lower value (\( \sim 1^\circ \)). Further solvent depletion in the liquid layer results in almost constant CA (less than 1\(^\circ\)), consistent with Figure 9e.

Now let us rewind the discussion of liquid TF that we have estimated to be present during the dewetting of CL, contributing to the particle deposition. Figure 10a-c illustrates the dewetting dynamics of the TFs of respective LBS at different confinement distances. The interference patterns were captured at 60 fps by employing a 20× magnification objective lens focusing at one of the leading edges of LB. The evolution of the receding TF for the LB of \( \alpha = 0.17 \) is presented in Figure 10a. With the progression of time (i.e., \( t_\text{b} = 57 \) s), the CL is observed to slip, leaving a trace of thin film between subsequent pinning events. This TF can be distinguished by observing widely spaced fringe patterns consisting of circular loops, whereas the leading edge has closely spaced fringes. The extent of the spread of the TF is noted at the time intervals of 155 and 157 s, including the progress of additional circular loops in the fringe patterns. The development of circular loops, to a larger extent, leads to the initiation of the dewetting process in the liquid layer.

Subsequently, the TF illustrated in Figure 10b reveals the identical interference patterns for \( \alpha = 0.2 \). The augmented evaporation rate with an increase in confinement distance of the LB is evident from the time intervals of Figure 10a,b, where the complete dewetting of the liquid layer occurred at \( t_\text{b} = 96 \) s for \( \alpha = 0.2 \) compared to \( t_\text{b} = 157 \) s of \( \alpha = 0.17 \). In the case of \( \alpha = 0.25 \), the receding of the leading edge is not observed from the interferometric images (Figure 10c). The transient data indicates that the reduction in densely spaced fringe patterns till the droplet remains in an LB configuration. We do not observe any dewetting of TF for higher confinement distances by the interferometric measurement, as the CL remains pinned. Several times, we have attempted to measure the TF dynamics for low confinement distances (\( \alpha < 0.17 \)), however, we were unable to resolve the images due to infrastructural limitations of the present setup.

The plausible particle deposition mechanism can be explained by the thin film’s receding dynamics adjacent to the CL. In the case of \( \alpha = 0.17 \), the development of multiple circular loops leads to multiple dewetting regions in the liquid layer due to the slower evaporation rate of LB (Figure 10a). Figure 10d,e exhibits the transient variation of the height of the TF and the CA for the selected region (the respective planes indicated by the red line). For lower values of \( \alpha \), the elongated spread in the TF with lower film-thickness measurements was considered. The increment in confinement distances (\( \alpha \)) of the respective LBS resulted in the enhanced average height of the corresponding TFs that reduces as the drying progresses. In particular, the TF thickness, estimated at the final instance (\( t_\text{b} = 144 \) s), is \( \sim 1 \) to 1.5 \( \mu \text{m} \) for the LB having \( \alpha = 0.17 \). Therefore, by extrapolating the trend of Figure 10d, it can be inferred that for more squeezed LBS (lower \( \alpha \)), the height of the corresponding TFs is expected to be at least lower than \( O(10^{-6}) \) m. This conforms to the observations based on our theoretical proposition, where \( h \) is of submicron length scale, and we have employed the same in eq 2 to estimate the dominant capillary length scale. The comparison of CA (Figure 10e) shows similar behaviors as reflected in Figure 9e, where the spatial variation of CA increases toward radially inward (toward the center of LB) direction for a given confinement distance, although the magnitude remains a bit higher (\( \sim 8^\circ \)).

4. CONCLUSIONS

In this article, for the very first time, we demonstrate that tailoring the confinement distance of a colloidal liquid bridge (LB) can transform the post-evaporation patterns from a conventional coffee ring to the patterns found on scallop shells. Altering the gap between solid surfaces modifies the curvature of the LBS, thereby giving rise to significant variations in the evaporation flux across the liquid–vapor interface. The non-uniform nature of solvent depletion contributes to developing a concentration gradient across the curvature of LB that exhibits higher differences in concentration magnitudes for increased confinement distance. This, in turn, controls the respective flow field distributions within the LBS that hint toward the stick–slip motion of LBS at lower confinement distances. However, pinned behaviors are noticed in the case of more stretched LBS. LBS corresponding to higher confinement distances remain pinned at the solid surfaces (both top and bottom), and with time their curvature changes significantly, finally resulting in a single coffee
ring. For a colloidal drop sandwiched at intermediate confinement distances, the LB exhibits dewetting of the contact line (CL) that is evident in the form of the multiple coffee rings. When squeezed to a considerable extent, the LB undergoes faster dewetting for a significant portion of its evaporation lifetime and yields ordered deposition of particles analogous to a scallop shell. During the dewetting, submicron drying liquid film near three-phase CL has been found to govern the particle deposition in an aligned fashion. The experimental observations from interferometric measurements corroborate the theoretical propositions regarding this liquid layer. Interestingly, the gap between the solid surfaces strongly influences the thickness of the thin film. The differences in drying patterns from colloidal LBs are attributed to the compound effect of pinning/depinning of the CL coupled with evaporation-induced flow inside the LBs and the deposition of particles via drying thin film. Further, the theoretically estimated dominant capillary length scale is similar to the experimental observations, irrespective of particle size and confinement distance. The particle volume fraction is one key parameter that controls the final precipitates. This approach of generating distinct patterns by tuning the confinement distance of colloidal LBs can be employed in various potential applications such as printing, coating, and similar areas requiring selective particle self-assembly.

**ASSOCIATED CONTENT**

* Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.langmuir.2c00196.

- SEM images of nanoparticles; schematic depicting the particle deposition mechanism; zeta potential measurements; data analysis from interference measurements; determination of solid–liquid surface tension of water on the glass surface, variations in the neck region of the LB for different confinement distances (PDF)
- Video S1: Flow visualization near the bottom surface of the LB for $\alpha = 0.14$ (AVI)
- Video S2: Flow visualization near the bottom surface of the LB for $\alpha = 0.31$ (AVI)

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**Notes**

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**REFERENCES**

(1) Sun, J.; Bao, B.; He, M.; Zhou, H.; Song, Y. Recent Advances in Controlling the Depositing Morphologies of Inkjet Droplets. ACS Appl. Mater. Interfaces 2015, 7, 28086–28099.

(2) Hammond, P. T. Form and Function in Multilayer Assembly: New Applications at the Nanoscale. Adv. Mater. 2004, 16, 1271–1293.

(3) Cao, Q.; Rogers, J. A. Ultrathin Films of Single-walled Carbon Nanotubes for Electronics and Sensors: A Review of Fundamental and Applied Aspects. Adv. Mater. 2009, 21, 29–53.

(4) Wu, L.; Dong, Z.; Li, F.; Zhou, H.; Song, Y. Emerging Progress of Inkjet Technology in Printing Optical Materials. Adv. Opt. Mater. 2016, 4, 1915–1932.

(5) Martel, R. Sorting Carbon Nanotubes for Electronics. ACS Nano 2008, 2, 2195–2199.

(6) Deegan, R. D.; Bakajin, O.; Dupont, T. F.; Huber, G.; Nagel, S. R.; Witten, T. A. Capillary Flow as the Cause of Ring Stains from Dried Liquid Drops. Nature 1997, 398, 827–829.

(7) Yunker, P. J.; Still, T.; Lohr, M. A.; Yodh, A. G. Suppression of the Coffee-Ring Effect by Shape-Dependent Capillary Interactions. Nature 2011, 476, 308–311.

(8) Xie, Q.; Harting, J. From Dot to Ring: The Role of Friction in the Deposition Pattern of a Drying Colloidal Suspension Droplet. Langmuir 2018, 34, 5303–5311.

(9) Bhardwaj, R.; Fang, X.; Attinger, D. Pattern Formation during the Evaporation of a Colloidal Nanoliter Drop: A Numerical and Experimental Study. New J. Phys. 2009, 11, 75020.

(10) Hu, H.; Larson, R. G. Marangoni Effect Reverses Coffee-Ring Depositions. J. Phys. Chem. B 2006, 110, 7090–7094.

(11) Pasa, M.; Harmand, S.; Sefiane, K.; Bigereille, M.; Deltombe, R. Effect of Substrate Temperature on Pattern Formation of Nanoparticles from Volatile Drops. Langmuir 2015, 31, 3354–3367.

(12) Hegde, O.; Chattopadhyay, A.; Basu, S. Universal Spatio-Topological Control of Crystallization in Sessile Droplets Using Non-Intrusive Vapor Mediation. Phys. Fluids 2021, 33, 12101.

(13) Kabi, P.; Pal, R.; Basu, S. Moses Effect: Splitting a Sessile Droplet Using a Vapor-Mediated Marangoni Effect Leading to Designer Surface Patterns. Langmuir 2020, 36, 1279–1287.

(14) Montanero, J. M.; Ponce-Torres, A. Review on the Dynamics of Isothermal Liquid Bridges. Appl. Mech. Rev. 2020, 72, 010803.
(15) Kumar, S. Liquid Transfer in Printing Processes: Liquid Bridges with Moving Contact Lines. Annu. Rev. Fluid Mech. 2015, 47, 67–94.
(16) Lin, Z.; Granick, S. Patterns Formed by Droplet Evaporation from a Restricted Geometry. J. Am. Chem. Soc. 2005, 127, 2816–2817.
(17) Xu, J.; Xia, J.; Hong, S. W.; Lin, Z.; Qiu, F.; Yang, Y. Self-Assembly of Gradient Concentric Rings via Solvent Evaporation from a Capillary Bridge. Phys. Rev. Lett. 2006, 96, 66104.
(18) Mondal, R.; Basavaraj, M. G. Influence of the Drying Configuration on the Patterning of Ellipsoids—Concentric Rings and Concentric Cracks. Phys. Chem. Chem. Phys. 2019, 21, 20045–20054.
(19) Leng, J. Drying of a Colloidal Suspension in Confined Geometry. Phys. Rev. E 2010, 82, 21405.
(20) Boulogne, F.; Giorgiutti-Dauphiné, F.; Pauchard, L. The Buckling and Invagination Process during Consolidation of Colloidal Droplets. Soft Matter 2013, 9, 750–757.
(21) Mahanta, T. R.; Khandekar, S. Evaporation Characteristics of a Confined Nanofluid Bridge between Two Heated Parallel Plates. J. Flow Visualization Image Process. 2018, 25, 297.
(22) Mondal, R.; Basavaraj, M. G. Patterning of Colloids into Spirals via Confined Drying. Soft Matter 2020, 16, 3753–3761.
(23) Upadhyay, G.; Bhardwaj, R. Colloidal Deposits via Capillary Bridge Evaporation and Particle Sorting Thereof. Langmuir 2021, 37, 12071–12088.
(24) Deegan, R. D.; Bakajin, O.; Dupont, T. F.; Huber, G.; Nagel, S. R.; Witten, T. A. Contact Line Deposits in an Evaporating Drop. Phys. Rev. E 2000, 62, 756.
(25) Staubner, J. M.; Wilson, S. K.; Duffy, B. R.; Sefiane, K. Evaporation of Droplets on Strongly Hydrophobic Substrates. Langmuir 2015, 31, 3653–3660.
(26) D’ambrosio, H.-M.; Colosimo, T.; Duffy, B. R.; Wilson, S. K.; Yang, L.; Bain, C. D.; Walker, D. E. Evaporation of a Thin Droplet in a Shallow Well: Theory and Experiment. J. Fluid Mech. 2021, 927.
(27) Tomo, Y.; Askounis, A.; Ikuta, T.; Takata, Y.; Sefiane, K.; Takahashi, K. Superstable Ultrathin Water Film Confined in a Hydrophilized Carbon Nanotube. Nano Lett. 2018, 18, 1869–1874.
(28) Alencar, A. M.; Majumdar, A.; Hantos, Z.; Buldyrev, S. V.; Stanley, H. E.; Suki, B. Crackles and Instabilities during Lung Inflation. Phys. A 2005, 357, 18–26.
(29) Siddon, C. E.; Smith, Q. T.; McNeel, K.; Ozman, D.; Goldman, K. J. Protocol for Estimating Age of Weathervane Scallops Patinopecten Caurinus in Alaska; Alaska Department of Fish and Game, Division of Sport Fish, Research and Technical Services, 2017.
(30) Bansal, L.; Chakraborty, S.; Basu, S. Confinement-Induced Alterations in the Evaporation Dynamics of Sessile Droplets. Soft Matter 2017, 13, 969–977.
(31) Bhardwaj, R.; Fang, X.; Somasundaran, P.; Attinger, D. Self-Assembly of Colloidal Particles from Evaporating Droplets: Role of DLVO Interactions and Proposition of a Phase Diagram. Langmuir 2010, 26, 7833–7842.
(32) Larson, R. G. Transport and Deposition Patterns in Drying Sessile Droplets. AIChE J. 2014, 60, 1538–1571.
(33) Khawaja, H.; Moatamedi, M. Semi-Implicit Method for Pressure-Linked Equations (SIMPLE)—Solution in MATLAB®. 2018.
(34) Vrij, A. Possible Mechanism for the Spontaneous Rupture of Thin, Free Liquid Films. Discuss. Faraday Soc. 1966, 42, 23–33.