

Magnetically actuable Janus microplate arrays for droplet rectified transport, capture, and on-demand splitting

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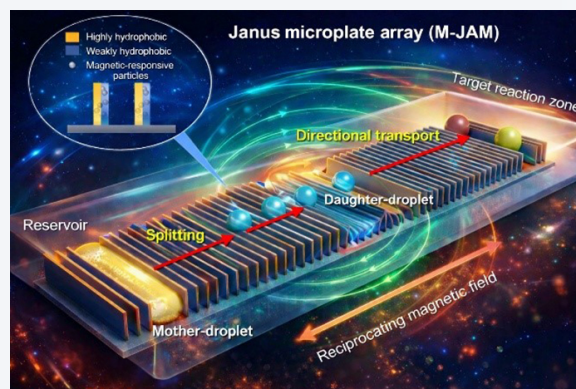
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ABSTRACT: Open-surface droplet manipulation is essential for digital microfluidics, point-of-care diagnostics, and programmable microreactors; however, achieving robust, programmable, and multifunctional control remains challenging due to the absence of physical confinement and intrinsic directional bias. To address this, we introduce a magnetically actuable Janus arrayed-microplate (M-JAM) platform that synergizes structural deformation with engineered wettability asymmetry to enable deterministic droplet operations by asymmetric capillary adhesion. The platform comprises an array of parallel microplates, each with a strongly hydrophobic side opposite a weakly hydrophobic side. This asymmetric design enables three core functions: rectified droplet transport, vertical capture/release via adhesion modulation, and on-demand splitting with tunable daughter-droplet volumes dictated by a scaling law. As a functional demonstration, M-JAM orchestrates a multi-step enzymatic glucose assay using only a reciprocating magnetic field, showcasing its capability as an integrated platform for microreactions and biochemical sensing. By coupling magnetic actuation with built-in surface heterogeneity, M-JAM provides a versatile, reconfigurable system for high-precision droplet-based automation and integrated bioanalytical applications.



KEYWORDS: Janus wettability, droplet rectification, on-demand droplet splitting, digital microfluidics, point-of-care diagnostics

1 Introduction

The deterministic manipulation of droplets on open solid surfaces is essential for emerging technologies such as digital microfluidics [1–4], programmable chemical synthesis [5–7], biosensing [8–11], and adaptive reaction platforms [12–14]. Compared with enclosed microchannels [15, 16], open-surface droplet systems offer intrinsic advantages including low hydraulic resistance, minimal clogging, and facile access for reagent delivery and real-time observation [17–20]. However, the absence of physical confinement renders

droplet motion on open systems highly sensitive to contact-line pinning [21, 22] and external disturbances [21], presenting a key challenge to achieving robust, programmable, and collective operations (e.g., transport, capture, and splitting) in interfacial science and microfluidics.

Various actuation strategies have been explored to address these challenges, including wettability gradients [23], asymmetric micro/nanostructures [24], and external fields such as electric [25], optical [26], acoustic [27], or magnetic stimuli [28]. Among these, magnetic actuation is especially promising for its remote, rapid, and reversible control without direct contact or Joule heating [29–31]. However, existing magnetic-driven droplet systems, which rely on particles [32], deformable substrates [33], or responsive microstructures [34–37], typically possess uniform surface wettability. Consequently, droplet motion remains governed by the external field, is inherently reversible, and lacks intrinsic directional bias, thus hindering robust unidirectional transport, gravity-

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resistant motion, and deterministic multi-step operations such as capture and splitting. Parallel efforts in open-surface chemical reactions [38] and digital liquid handling on structured or functionalized surfaces, including transport-assisted mixing [39], reagent delivery, and reaction triggering [40], also often rely on passive capillary or external propulsion, lacking intrinsic directional selectivity and structural programmability for integrated, multifunctional droplet processing.

Although Janus wettability concepts are well established in interfacial sciences [41–43], and have been introduced into magnetically actuated microplate architectures for switchable wettability and selective droplet manipulation [44], the use of asymmetric wettability for encoding deterministic droplet transport directionality and programmable multifunctional droplet operations remains largely unexplored. Existing droplet manipulation systems on magnetically actuated microplate architectures limit multifunctionality and directional controllability. Here, we introduce a magnetically actuable Janus arrayed-microplate (M-JAM) platform for programmable droplet manipulation, comprising parallel microplates with asymmetric hydrophobicity on opposing sides. Under a moving magnetic field, these microplates undergo collective bending, generating a programmable wave-like motion that enables directional droplet transport, vertical capture/release, and controllable splitting. By coupling structural deformation with built-in wettability asymmetry, the present platform achieves deterministic rectified droplet manipulation under a simple reciprocating magnetic field, without requiring complex electrode arrays or pumping systems. This synergistic design provides a scalable and versatile strategy for multifunctional open-surface droplet control.

2 Experimental

2.1 Preparation of the M-JAM

The M-JAM was fabricated using a hybrid process combining three-dimensional (3D) printing (mold dimensions as shown in Fig. S1 in the Electronic Supplementary Material (ESM)) and mold casting. The raw materials comprised polydimethylsiloxane (PDMS) prepolymer (Sylgard 184A), PDMS curing agent (Sylgard 184B), iron(III) oxide tetroxide (purity $\geq 97\%$, Shanghai McLean Biochemical Technology Co., Ltd.), and silicone thinner (Smooth-Oh). Figure S2 in the ESM illustrates the M-JAM fabrication process comprising four steps: I) printing a mold with high aspect ratio grooves using a 3D printer (Anycubic Photon D2), followed by a series of treatments (Fig. S3 in the ESM) including 1 h ultraviolet (UV) exposure, 5 min plasma treatment, and 24 h fluorination at 90 °C in a sealed environment (1H,1H,2H,2H-perfluorodecyltriethoxysilane, Shanghai McLean Biochemical Technology Co., Ltd.). II) Polydimethylsiloxane was mixed with curing agent and silicone oil thinner at a 10:1:8 (w/w) ratio, then blended with carbonyl iron powder at a 70% mass ratio. After thorough mixing and degassing, the mixture was poured into the mold. III) The sample was cured in a 90 °C oven for 3 h. The distribution of Fe_3O_4 within the micropores was permanently fixed. IV) A silica suspension was sprayed onto one side of the microplate. The wettability asymmetry was achieved through a selective spraying process under a magnetically induced bent geometry. During spraying, the exposed side directly received the spray coating and formed a dense hydrophobic layer, while the shielded side underwent weaker deposition. Finally, M-JAM was

obtained. The silica suspension preparation procedure was as follows: 1.5 mL of ethyl orthosilicate (TEOS, purchased from Xilong Science) was added to a mixture of 50 mL of anhydrous ethanol and 5 mL of ammonia solution ($\text{NH}_3\cdot\text{H}_2\text{O}$, 25%–28%, purchased from Aladdin Reagents). The solution was transferred to a beaker and stirred for 8 h at room temperature. Subsequently, 2 mM of 3-aminopropyltriethoxysilane (APTES, purchased from Aladdin Reagents) was added to 5 mL of anhydrous ethanol. After being stirred for 2 min, the mixture was transferred to the aforementioned beaker. The solution was heated in a water bath at 50 °C while being stirred for 2 h. Then, a specific volume of 1H,1H,2H,2H-perfluorodecyltriethoxysilane (15% by volume relative to ethyl orthosilicate) was added, followed by stirring at room temperature for 4.5 h [45–47].

2.2 Construction of a magnetic field for manipulating M-JAM

The device utilized linear guides as its operating track and incorporated a slider assembly with integrated magnets. Driven by an electric motor, it moved the magnets at a preset speed, using the magnetic force to drive the M-JAM for droplet transport (Fig. S4 in the ESM). The slide module was procured from Chengdu Fuyou Technology Co., Ltd.

2.3 Calibration of glucose concentration

The principle for detecting glucose concentration primarily relied on the colorimetric reaction between KI and hydrogen peroxide (H_2O_2), where H_2O_2 was generated through an enzyme-catalyzed reaction involving glucose oxidase (GOx) and horseradish peroxidase (HRP). Experimental procedure: using PBS buffer as the solvent, prepare solutions containing 100 U/mL GOx and 25 U/mL HRP. The two enzymes were mixed at a 1:1 ratio to obtain the enzyme mixture. PBS glucose solutions with concentrations ranging from 0 to 200 μM were prepared. First, 1 mL of the enzyme mixture was mixed with 1 mL of 0.5 mol/L KI solution. Then, 1 mL of glucose solution was added. After reacting for 10 min, the color change was observed. The reacted solution was transferred into a centrifuge tube and placed in a photography chamber. Photographs of the standard glucose concentration color-gradient centrifuge tubes were captured under white light using a mobile phone. The images were imported into Adobe Photoshop (PS), and the RGB values were measured. According to the Lambert–Beer law, convert the blue channel value from the RGB data (B) to logarithmic color intensity (I_B) using the formula: $I_B = \lg(B_0/B)$, where B_0 is the color value of the blank control and B is the color value of the sample being tested [48, 49].

2.4 Characterization

The surface morphologies of both the strongly and weakly hydrophobic sides of the M-JAM were characterized using scanning electron microscopy (SEM, TESCAN MIRA LMS). The static water contact angles (CAs) were measured on the M-JAM surfaces using an optical contact angle goniometer (Model 250, Ramé-hart, USA) with water droplets at ambient temperature. Atomic force microscopy (AFM, Bruker Dimension Icon, Germany) was employed to evaluate the surface roughness of both sides of the M-JAM. Furthermore, the tensile properties of the prepared materials were determined using a universal mechanical testing machine (Model ZQ-990B, ZHIQU). Optical images and videos were captured using a smartphone (VIVO S16 Pro).

3 Results and discussion

Here, we report a versatile platform for programmable droplet manipulation based on M-JAM. This system enables integrated droplet transport, capture, and splitting on an open surface (Fig. 1(a)). It consists of an array of parallel, magnetically responsive

microplates, each asymmetrically functionalized with a strongly hydrophobic side and a weakly hydrophobic opposite side. Under a moving or reciprocating external magnetic field, the microplates undergo cyclic bending and recovery, dynamical reshaping the droplet's local contact angle, contact-line pinning, and interfacial curvature. The coupling between field-induced deformation and

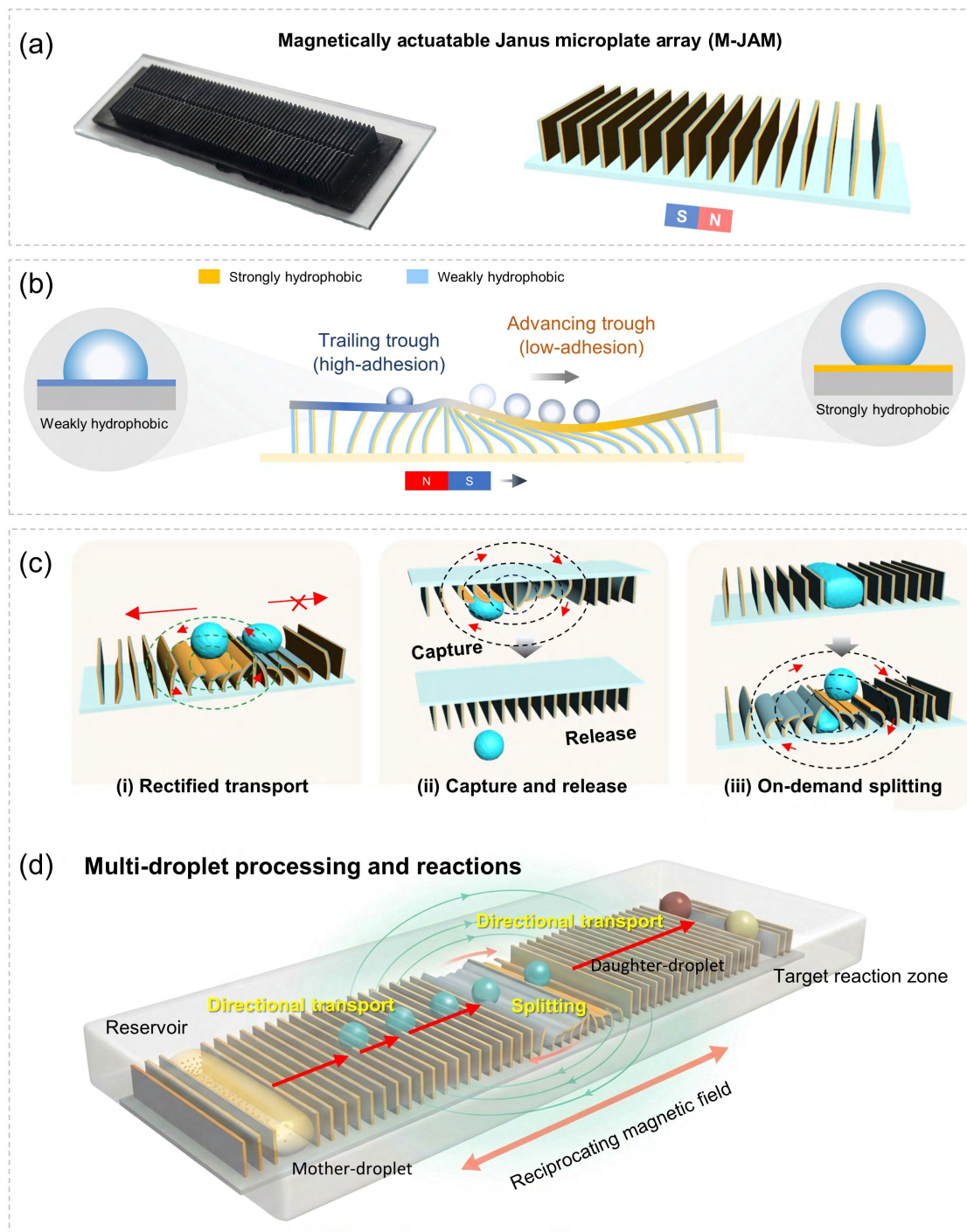


Figure 1 Features and multifunctional capabilities of magnetically actuable Janus arrayed microplates (M-JAM). (a) Schematic and optical image of the M-JAM platform, consisting of parallel magnetic microplates with asymmetric wettability. (b) Working principle: under a reciprocating magnetic field, cyclic bending of the Janus wettability microplates creates a directional adhesion landscape. This asymmetry generates a traveling wave that propels droplets along the low-adhesion advancing trough while pinning them against backward motion at the high-adhesion trailing trough. (c) Core droplet-manipulation functions: (i) rectified unidirectional transport, (ii) controlled vertical capture and release via adhesion modulation, and (iii) on-demand splitting with tunable volume ratios. (d) Integrated multi-droplet processing and cascade reactions on a reconfigurable open platform.

Janus wettability creates a direction-selective capillary adhesion landscape, yielding a traveling wave with macroscopic wettability contrast: Droplets are propelled along the low-adhesion (hydrophobicity-enhanced) advancing trough, while backward motion is suppressed by strong pinning on the high-adhesion (hydrophobicity-weakened) trailing trough (Fig. 1(b)). The synergistic combination of dynamical structural deformation and asymmetric surface wettability fundamentally distinguishes M-JAM from conventional magnetic-actuated systems, providing precise and multifunctional droplet control. Specifically, the coupling between field-induced deformation and Janus wettability generates a rectification effect, thus enabling robust unidirectional transport even against gravity or inclines (Fig. 1(c)(i)). Beyond transport, M-JAM allows controllable droplet capture and release via deformation-programmed adhesion modulation, i.e., arresting droplets on a high-adhesion “gripper” trough, and releasing them upon crest translation that locally reduces adhesion (Fig. 1(c)(ii)). Moreover, M-JAM allows programmable droplet splitting with tunable volume ratios via magnetic actuation speed, offering a versatile strategy for digital liquid handling (Fig. 1(c)(iii)). By integrating these operations, M-JAM supports multi-droplet processing and cascade reactions on a reconfigurable open surface, serving as an adaptable microreaction platform for microfluidics and interfacial engineering (Fig. 1(d)).

3.1 Fabrication and characterization of M-JAM

The M-JAM was fabricated by a multi-step process (Fig. 2(a)). First, a mixture of Fe_3O_4 , PDMS, and curing agent was cast into a 3D-printed mold to produce an array of microplates on a substrate (Fig. 2(a)(i)). These microplates were then bent and overlapped under a strong magnetic field to approximate a continuous plane. Subsequently, a silica (SiO_2) suspension containing fluoroalkyl silane was selectively sprayed onto the array (Fig. S2 in the ESM). Owing to the bending geometry, a greater amount of the suspension was deposited on the exposed outer side of the microplates (Fig. 2(a)(iii)), leading to an asymmetric SiO_2/F coating. This process established distinct Janus wettability on each microplate, with the exposed side being strongly hydrophobic and the shaded side weakly hydrophobic.

The surface morphology of the M-JAM was characterized by SEM. The weakly hydrophobic side shows a sparse distribution of silica particles (Fig. 2(b)), while the strongly hydrophobic side is fully covered by a dense silica layer (Fig. 2(c)). Energy-dispersive X-ray spectroscopy (EDS) mapping of fluorine (F) further revealed a distinct contrast: Only a faint F signal (related to the hydrophobicity-enhancing fluoroalkyl silane) was detected on the weakly hydrophobic side (Fig. 2(d)), in contrast to pronounced F enrichment on the strongly hydrophobic side (Fig. 2(e)). Quantitative analysis of the corresponding areas (Fig. 2(f)) confirmed the presence of a substantial fluorine signal (10.65%) on the strongly hydrophobic side, whereas the weakly hydrophobic side exhibited a near-absence of fluorine signal (Figs. S5 and S6 in the ESM). AFM measurements revealed clear differences in surface roughness (Fig. 2(g)). The strongly hydrophobic side displayed pronounced topography, with height variations from -677.1 to 427.8 nm (Fig. 2(g)(i)), while the weakly hydrophobic side was markedly smoother, varying between -65.9 to 52.3 nm (Fig. 2(g)(ii)). Given the intrinsic hydrophobicity of the silica/fluoroalkyl silane and the established role of coarse surface textures in enhancing hydrophobicity [50], these structural and

chemical differences produced a pronounced wettability contrast across each microplate.

The surface wettability was systematically characterized by measuring water CA, sliding angle (SA), and adhesion force. When the microplates were deformed to expose the strongly hydrophobic side (termed the hydrophobicity-enhanced state), droplets exhibited a high CA of $\sim 155^\circ$ and low SAs of $\sim 12.3^\circ$ (left tilt, toward the bending direction) and $\sim 15.7^\circ$ (right tilt, opposite the bending direction), indicating pronounced hydrophobicity and weak adhesion (Fig. 2(h)(i)). In the non-deformed state with upright microplates, the surface maintained a CA of $\sim 136^\circ$ and similarly low SAs of $\sim 15.5^\circ$ (left tilt) and 16.0° (right tilt), confirming consistently low adhesion (Fig. 2(h)(iii)). In contrast, deformation that exposed the weakly hydrophobic side (the hydrophobicity-weakened state) resulted in a CA of $\sim 129.5^\circ$ and an SA of 180° (no spontaneous sliding), demonstrating strong adhesion (Fig. 2(h)(ii)). Moreover, the M-JAM exhibits excellent uniformity and maintains great stability in large-area distribution (Fig. S7 in the ESM). Quantitative analysis of sliding angles across these three states (non-deformed, hydrophobicity-enhanced, and hydrophobicity-weakened) exhibits a clear correlation with adhesion strength (Fig. 2(i)). Although the CA varies among states, all values are significantly higher than that of the untreated microplate array (Fig. S8 in the ESM), confirming the effective wettability enhancement imparted by the SiO_2 /fluoroalkyl silane (Fig. 2(j)). The coexistence of these three magnetically actuated states, defined by a distinct combination of structural deformation and interfacial heterogeneity, establishes a platform for achieving unidirectional droplet transport, programmable manipulation, and advanced droplet-based microreactor functions.

3.2 Magnetic actuation behavior of M-JAM

When placed above a rectangular magnet, the microplate array is instantly magnetized. Microplates at the center of the magnetic field remain nearly upright, while those surrounding them bend toward the center, forming a graded deflection profile that decays with distance from the central axis (Fig. 3(a)). Such coordinated deformation generates a well-defined, wave-like structure across the array, exhibiting a trough-crest-trough morphology (Fig. 3(b) waveform). It is noted that this field-guided wave structure emerges and moves regardless of whether the microplates are coated with SiO_2 /fluoroalkyl silane. Under a static magnetic field, the crest stays centered with symmetric troughs on both sides. When the field moves, the whole waveform shifts accordingly, with the crest lagging slightly behind the magnet's center position but consistently following its trajectory. During this motion, an advancing trough forms and expands noticeably, while the trailing trough shrinks and may nearly disappear (Fig. 3(c)). Crucially, owing to the Janus design of each microplate, the moving crest and its adjacent troughs exhibit asymmetric hydrophobicity: One side presents enhanced hydrophobicity, while the opposite side remains weakened in hydrophobicity (Fig. 3(d)). This built-in asymmetry enables direction-selective droplet transport: Droplets are propelled forward when the advancing trough is hydrophobic and the trailing trough is less so, and is otherwise suppressed.

This deformability behavior of M-JAM, can be quantified by wave-crest length (L) and height (h), which depend on material composition (Fe_3O_4 content, PDMS-to-curing-agent ratio, silicone-oil adding), structural geometry (e.g., microplate height and width) and magnetic-field strength. Under optimized conditions (with a

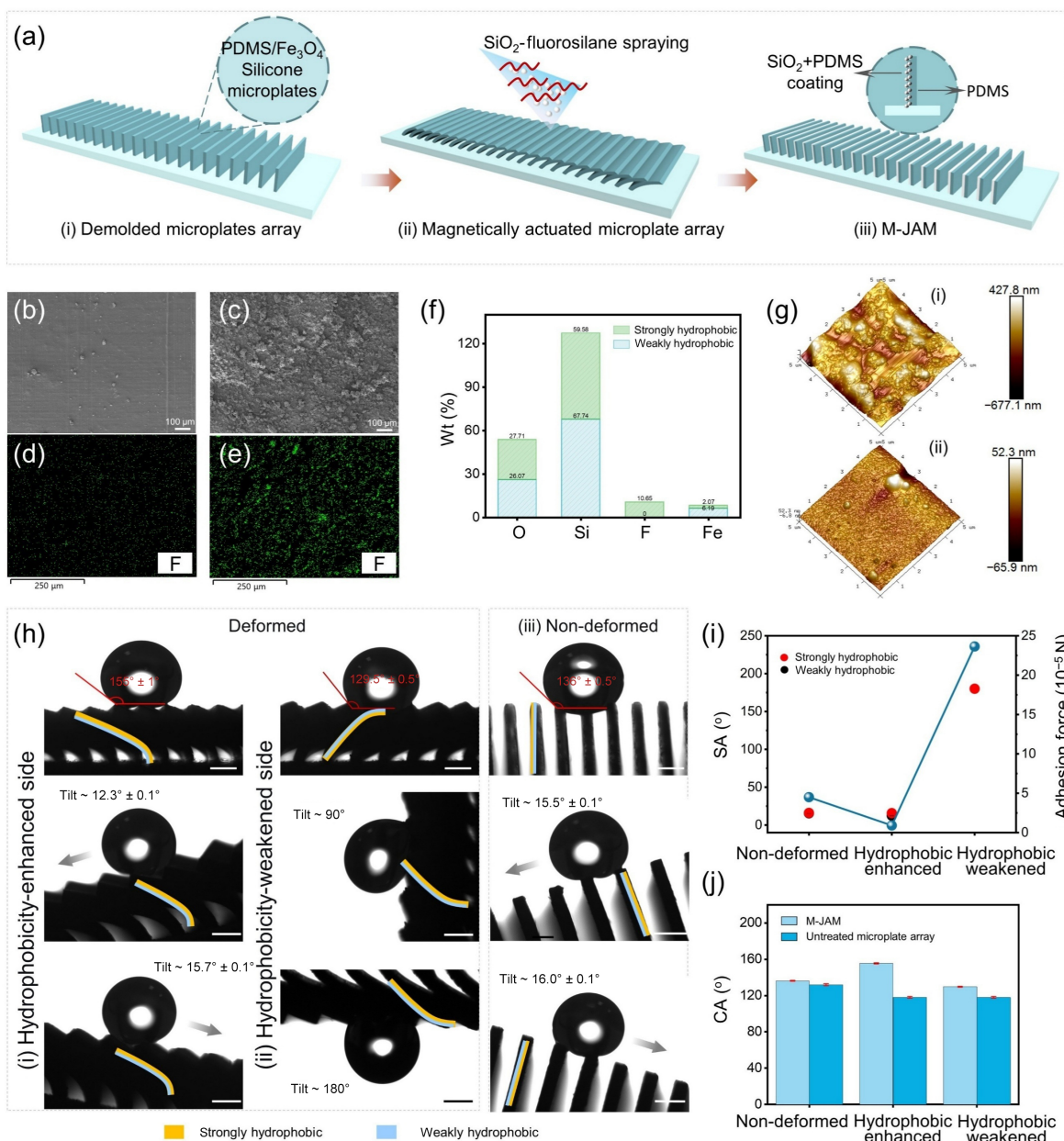


Figure 2 Fabrication and Characterization of M-JAM. (a) Schematic illustration of the multi-step fabrication: (i) demolded Fe_3O_4 /PDMS based microplates array, (ii) magnetic bending to form a continuous surface, and (iii) selective spraying of a SiO_2 /fluoroalkyl silane to create asymmetric Janus wettability. SEM images showing surface morphology: (b) sparse particle coverage on the weakly hydrophobic side and (c) dense silica/fluoroalkyl silane coating on the strongly hydrophobic side. EDS mapping of fluorine distribution: (d) minimal signal on the weakly hydrophobic side and (e) pronounced enrichment on the strongly hydrophobic side. (f) Quantitative elemental analysis confirming significant F content on the strongly hydrophobic side. (g) AFM topography revealing distinct roughness: pronounced textures on the strongly hydrophobic side (top), and smoother features on the weakly hydrophobic side (bottom). (h) Water CA and SA measurements under different deformation-induced states: (i) hydrophobicity-enhanced, (ii) hydrophobicity-weakened, and (iii) non-deformed. (i) Summary of sliding angles and adhesive force between droplet with M-JAM of different states. Among them, the blue polyline represents the adhesive force profile. The adhesive forces corresponding to the non-deformed, hydrophobicity-enhanced, and hydrophobicity-weakened states are 4.5, 0.91 and 23.64 (unit: 10^{-5} N), respectively. (j) Contact angles across states, confirming adhesion modulation and enhanced wettability compared to an untreated microplates array.

microplate height of 4 mm, Fe_3O_4 content fixed at 70 wt.%, a PDMS: curing-agent ratio of 10:1, and inclusion of silicone oil, a well-developed, large-scale wave crest ($L > 5$ mm, $h > 1.5$ mm) is achieved (Figs. S9 and S10 in the ESM). In addition, an appropriate magnetic-field strength is required, with a maximum field strength of 175 mT used in this work (Fig. S11 in the ESM). This robust waveform can serve as a reliable carrier for the directional transport of various droplets.

3.3 Droplet manipulation for multifunctional applications

3.3.1 Rectified droplet transport

Droplet transport on the magnetically actuable microplate array is achieved by traveling wave crests, which propel droplets along the direction of the moving magnetic field [35, 37]. This field-guided motion is fundamentally enhanced by the Janus asymmetry of the wave crest: Its advancing side forms a hydrophobicity-enhanced

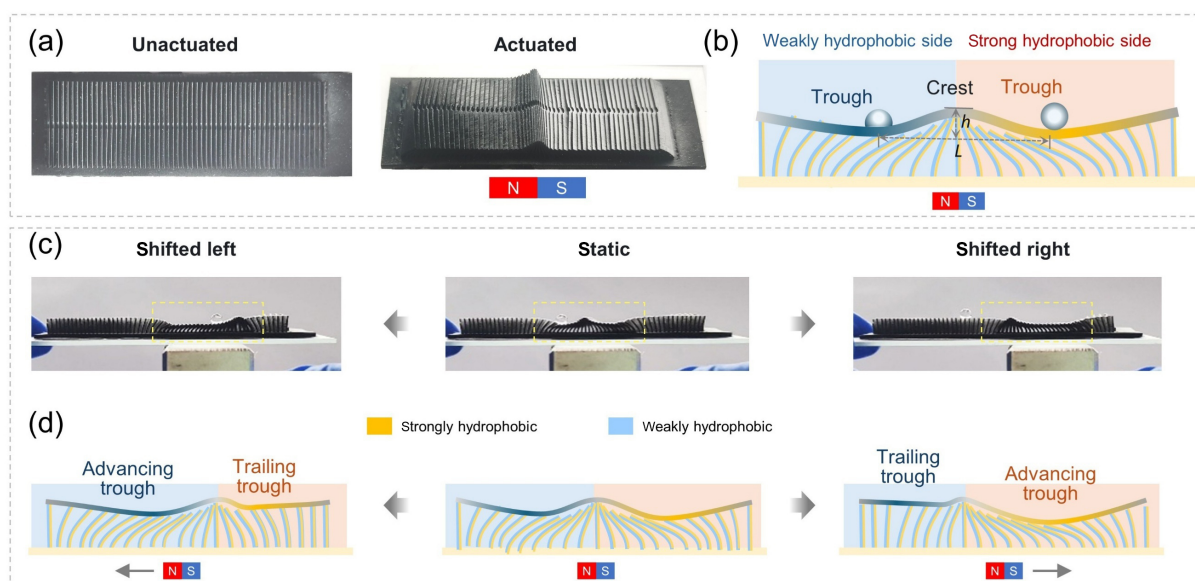


Figure 3 Magnetic actuation behavior of M-JAM. (a) Optical image of the M-JAM in the unactuated (flat) state and actuated (bent) state when placed above a stationary magnet. (b) Schematic of the wave-like trough-crest-trough profile formed across the array upon magnetic actuation. (c) Translational movement and reshaping of the waveform as the external magnet shifts laterally; the crest slightly lags behind the magnet's center. (d) Wettability asymmetry in the moving wave: bent microplates expose either the strongly (yellow) or weakly (blue) hydrophobic side, creating direction-dependent adhesion.

region (the magnet moves toward hydrophobic side of microplates), while the trailing side becomes a hydrophobicity-weakened region (left panel of Fig. 4(a)). This built-in asymmetry enables directional transport, and reversing the field direction does not yield effective propulsion (right panel of Fig. 4(a)).

When a droplet resides on the hydrophobicity-weakened (high-adhesion) region, it experiences a strong pinning force, f_i . Although the moving crest exerts a forward driving force (F_{D1}), the condition $F_{D1} < f_i$ holds, leaving the droplet pinned (Fig. 4(b)). In contrast, on the hydrophobicity-enhanced (low-adhesion) region, the droplet encounters minimal friction (f_b , see Fig. 2(i)). Here, the driving force (F_{D2}) exceeds the pinning force ($F_{D2} > f_b$), allowing the droplet to be propelled along the groove path. As the magnetic field shifts, the crest propagates continuously, sustaining unidirectional droplet transport. This directional motion is maintained even under a reciprocating magnetic field (Fig. S12 in the ESM) and is effective for droplets across a range of volumes (Fig. S13 in the ESM).

The transport dynamics were further investigated. Figure 4(c) presents the real-time interaction of a droplet with the traveling wave crest. At low magnetic field speed (< 150 mm/s), the droplet rolls forward intermittently, propelled forward briefly upon contact with each crest front before halting until the next crest arrives, resulting in discontinuous motion. At a field speed of 150 mm/s, the motion transitions to continuous propulsion, with the droplet's velocity (~ 163 mm/s) closely matching the field speed (Fig. 4(d)). When the field speed increases further (> 150 mm/s), the droplet can no longer follow synchronously. Its motion becomes inertia-dominated and decouples from the crest, falling into the “non-transport” regime (white region in Fig. 4(d)). Furthermore, droplets can be transported against gravity on inclined M-JAM, with reliable transport achievable up to a tilt angle of $\sim 20^\circ$ (Fig. 4(e)).

Unlike conventional magnetically actuated arrays, which often require deactivating and reactivating the field between transport cycles to avoid unwanted droplet displacement, the M-JAM platform can selectively propel droplets on its hydrophobicity-enhanced (low-adhesion) side or pin them on the hydrophobicity-

weakened (high-adhesion) side using only a reciprocating magnetic field. This direction rectification enables sequential processing of multiple droplets without external resetting, making the platform suitable for programmable droplet-based reactions. As a demonstration, a multi-step chemical reaction was performed (Fig. 4(f)). First, an FeCl_3 droplet was introduced at the inlet (red arrow) and propelled forward at 10 mm/s to a reaction site (Stage 1, top panel of Fig. 4(f)). The magnetic field then returned to the inlet, where a pre-dispensed KSCN droplet was transported to mix with the first, forming the red complex $[\text{Fe}(\text{SCN})]^{2+}$ via the reaction $(\text{Fe}^{3+} + \text{SCN}^- \rightleftharpoons [\text{Fe}(\text{SCN})]^{2+})$ (Stage 2, middle panel of Fig. 4(f)). Subsequently, the magnetic field reverses again to deliver an ascorbic acid droplet, which reduced the red complex according to the reaction: $\text{Fe}(\text{SCN})]^{2+} + \text{C}_6\text{H}_7\text{O}_6^- + \text{H}_2\text{O} \rightarrow \text{Fe}^{2+} + \text{SCN}^- + \text{C}_6\text{H}_6\text{O}_6^{2-} + 3\text{H}^+$ (Stage 3, bottom panel of Fig. 4(f)). All steps were executed using only a reciprocating magnetic field. In contrast, under the same reciprocating field, a homogeneous hydrophobic array merely shifts droplets back and forth without selective pinning or controlled merging, thereby preventing sequential multi-droplet reactions (Fig. 4(g)). These results indicate that the propagating magnetic wave primarily acts as the driving source for droplet motion, whereas the Janus wettability asymmetry is responsible for breaking the reciprocal symmetry and generating net directional transport. Thus, the M-JAM platform converts a simple reciprocating magnetic motion into robust unidirectional droplet transport, establishing a versatile foundation for droplet-based microreactors.

3.3.2 Droplet capture and release

In addition to horizontal transport, the M-JAM platform also enables controllable capture and release of droplets. Upon applying a magnetic field, a traveling wave crest forms across the array, with one side presenting a hydrophobicity-weakened (high-adhesion) region and the other a hydrophobicity-enhanced (low-adhesion) region. By modulating the magnetic field, the position and extent of these regions can be dynamically controlled. As shown in Fig. 5(a),

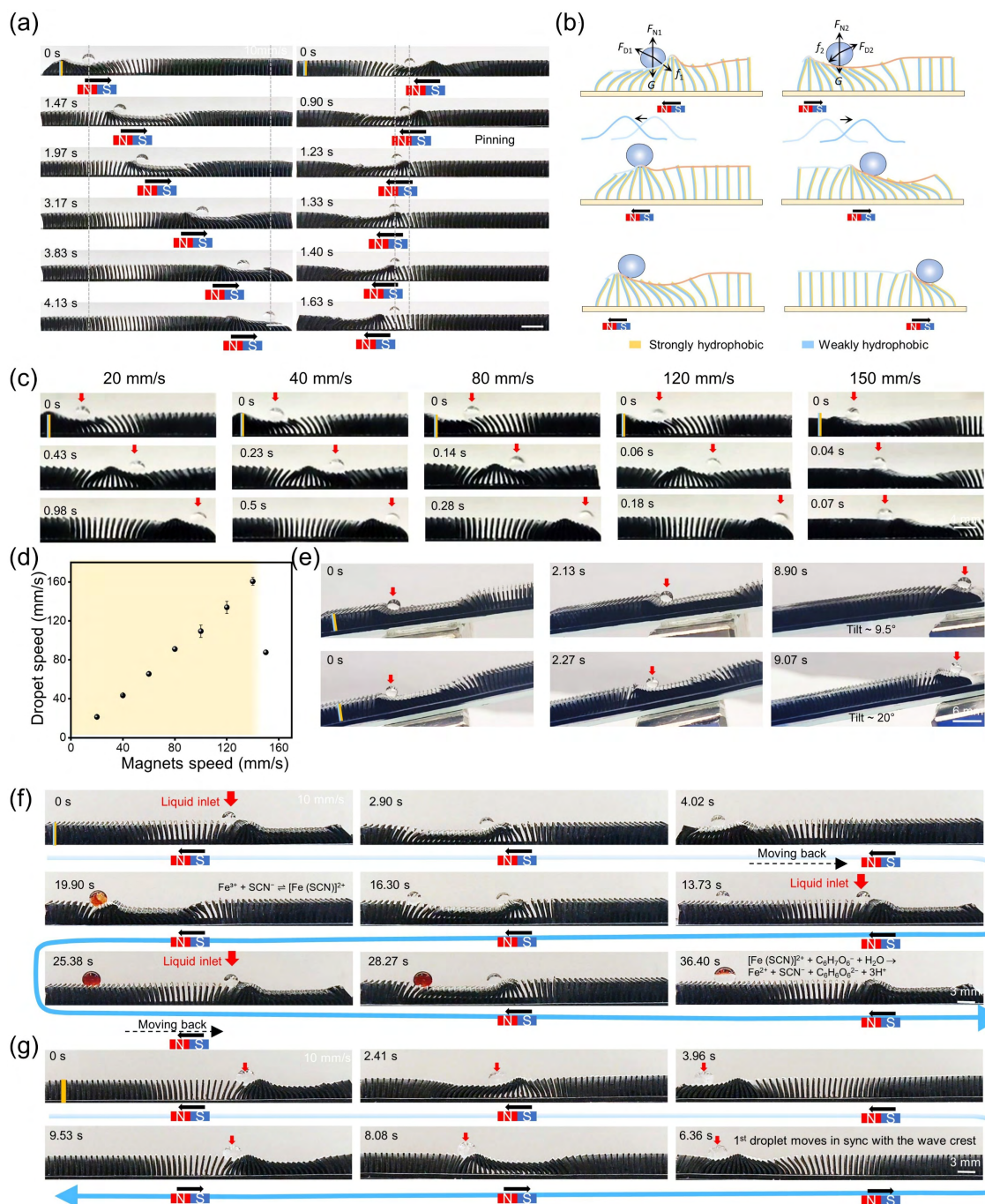


Figure 4 Rectified droplet transport on the M-JAM. (a) Snapshots of a 10 μL droplet at a magnetic field moving at 10 mm/s. Droplet remains pinned when the field moves toward the high-adhesion (hydrophobicity-weakened) side (right), and moves directionally when the field moves toward the low-adhesion (hydrophobicity-enhanced) side (left). (b) Transport mechanism: a droplet on the high-adhesion side is pinned ($F_{D1} < f_1$), whereas on the low-adhesion side it is propelled forward ($F_{D2} > f_2$) as the magnetic crest travels. (c) Snapshots of droplet-crest interaction under different field speeds: intermittent motion (< 150 mm/s), continuous transport (≈ 150 mm/s), and non-transport at higher speeds. (d) Droplet velocity versus magnetic field speed, showing the transport regime (shaded) and the non-transport regime. (e) Droplet transport against gravity on tilted M-JAM, effective up to inclines of $\sim 20^\circ$. (f) Sequential delivery and reaction driven by a single reciprocating magnetic field: Stage 1: delivery of FeCl_3 to a target zone; Stage 2: delivery of KSCN , forming the red complex $[\text{Fe}(\text{SCN})]^{2+}$ ($\text{Fe}^{3+} + \text{SCN}^- \rightleftharpoons [\text{Fe}(\text{SCN})]^{2+}$); Stage 3: delivery of $\text{C}_6\text{H}_5\text{O}_6\text{Na}$, which reduces the complex ($[\text{Fe}(\text{SCN})]^{2+} + \text{C}_6\text{H}_5\text{O}_6^- + \text{H}_2\text{O} \rightarrow \text{Fe}^{2+} + \text{SCN}^- + \text{C}_6\text{H}_5\text{O}_6^{2-} + 3\text{H}^+$). (g) Control experiment on a uniformly hydrophobic magnetic array under the same reciprocating field results only in oscillatory droplet shifting, without selective transport or sequential merging.

activating the magnetic field generates a trough with weakened hydrophobicity on one side of the wave crest. A droplet (10 μL) can be captured within this trough (at 0.55 s), where the extended solid-liquid contact area provides strong adhesion. This adhesive interaction is determined by the contact-step width l between two

adjacent bent microplates (Fig. 5(b)). As the crest advances toward the droplet following the moving magnetic field, l progressively decreases, thereby reducing the area of the high-adhesion interface (Fig. 5(a), from 4.83 to 5.40 s), and causing a corresponding decline in the adhesion force F_a (Fig. 5(b)). Once the crest moves directly

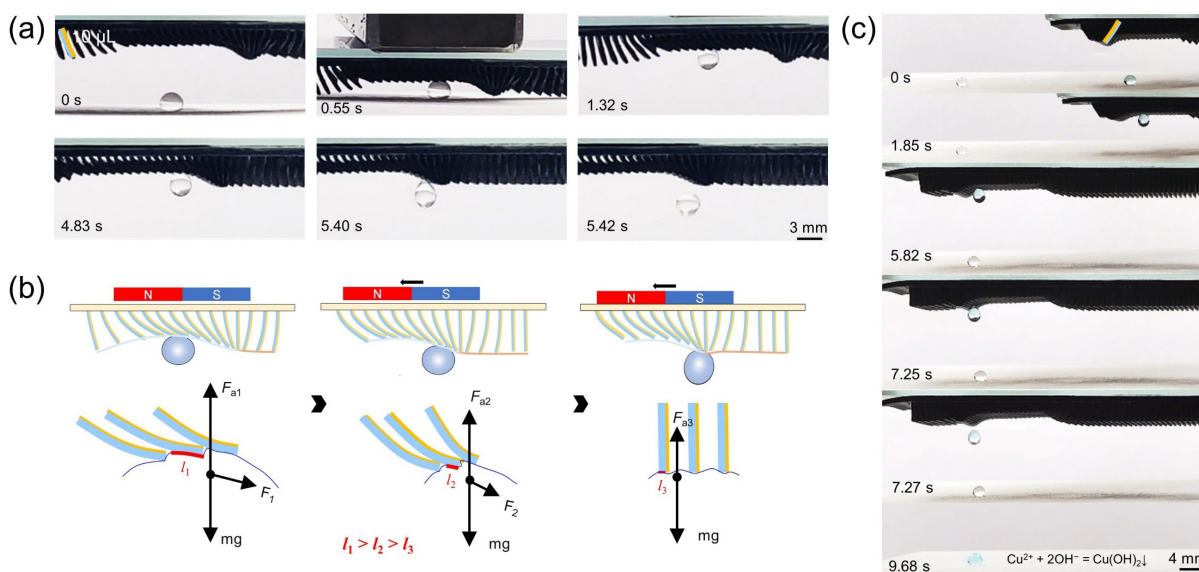


Figure 5 Droplet capture and release on the M-JAM. (a) Snapshots of vertical capture and release of a 10 μL droplet. The droplet is first captured within a high-adhesion (hydrophobicity-weakened) trough, then released as the traveling crest ($\sim 4 \text{ mm/s}$) continuously reduces the droplet-substrate contact area, thereby weakening the capillary adhesion force. (b) Schematic illustration and force analysis of the capture–release process. During wave propagation, the individual microplates do not flip; thus, no wettability transition occurs. Instead, the effective droplet-substrate contact area continuously decreases, resulting in a reduced adhesion force (F_a), which approximately scales with the effective contact length (L). Droplet release occurs when F_a becomes insufficient to balance the droplet weight (G). (c) Programmable capture and release for droplet-based reaction: a falling CuSO_4 droplet (10 μL) is captured and released onto a stationary NaOH droplet (10 μL), triggering the precipitation reaction: $\text{Cu}^{2+} + 2\text{OH}^- \rightarrow \text{Cu}(\text{OH})_2\downarrow$.

above the droplet, the remaining adhesion force can no longer balance the droplet's gravity, triggering its release (Fig. 5(a), at 5.42 s). The M-JAM surface retains minimal residual liquid after release, allowing for repeated capture–release operations. This vertical capture–release mode offers a versatile and contact-free strategy for droplet handling. As illustrated in Fig. 5(c), by manipulating the M-JAM within a magnetic field, the falling droplet can be rapidly intercepted at optimal heights and cleanly released at predefined locations. This capability significantly expands the platform's potential for spatially droplet manipulation in multi-step microreaction systems.

3.3.3 On-demand droplet splitting

Using a notched reservoir design in array, the M-JAM platform enables on-demand droplet splitting with tunable daughter-droplet volumes. Figures 6(a) and 6(b) show sequential images of droplet deformation and splitting under magnetic actuation for 60 μL volumes and magnet speeds. Upon actuation, the microplate array bends into a traveling wave crest, which draws the mother-droplet from the reservoir and stretches it into a liquid bridge spanning adjacent microplates. As the crest advances, the liquid bridge progressively elongates, and develops a pronounced neck at its midsection. Continued deformation further thins the neck until pinch-off occurs, yielding a separate daughter-droplet while the remaining liquid retracts and stabilizes on the top of array (Fig. 6(c)).

Owing to the Janus wettability of each microplate, splitting can proceed in two distinct configurations: Model 1, in which splitting occurs along the hydrophobicity-enhanced direction (exposing a strongly hydrophobic trough, Fig. 6(a)); and Model 2, in which splitting follows the hydrophobicity-weakened direction (exposing a weakly hydrophobic trough, Fig. 6(b)). The entire splitting process for both models can be described by four common stages: initial,

deformation, necking, and split (Fig. 6(c)). For example, a widened groove (3.6 mm) serves as a loading reservoir for the initial mother-droplet ($\approx 140 \mu\text{L}$). The splitting does not occur at low magnet speeds ($< 75 \text{ mm/s}$) for Model 1 (Fig. 6(d)), although a neck forms during elongation, the stretched liquid retracts back into the mother-droplet once the crest passes, preventing separation. At higher speeds, splitting succeeds, and the daughter-droplet volume decreases with increasing magnet speeds (e.g., from $\sim 117 \mu\text{L}$ at 75 mm/s to $\sim 110 \mu\text{L}$ at 100 mm/s). In Model 2 (Fig. 6(e)), splitting occurs over a wider speed range (25–100 mm/s), with daughter-droplet volume likewise declining as speed rises (e.g., from $\sim 132 \mu\text{L}$ at 25 mm/s to $\sim 114 \mu\text{L}$ at 100 mm/s). Similar trends are observed for initial volumes of 60 and 100 μL , confirming robust controllability across a wide volume range of mother-droplet sizes (Figs. S14 and S15 in the ESM).

A theoretical model was developed to describe the droplet-splitting process (see the ESM), treating droplet as an incompressible flow driven by the magnetically moving microplate boundary. Within this framework, the daughter-droplet volume V_d is given by the net rightward liquid influx accumulated before pinch-off

$$V_d = \int_0^{t_b} [Q_{\text{adv}}(t) + Q_{\text{cap,R}}(t)] dt \propto C_1 + \frac{C_2 \gamma}{U_m} + \frac{C_3 F_{\text{adh}}}{U_m} \quad (1)$$

where Q_{adv} is the boundary (deformation of M-JAM)-motion-induced entrainment flux (Fig. 6(f)), and $Q_{\text{cap,R}}$ is the rightward portion of the pressure-driven capillary flux, which depends on Laplace pressure $\Delta p_L \propto \frac{\gamma}{r_c}$ (with γ surface tension) and the adhesion-induced pressure Δp_{adh} arising from the surface adhesion force F_{adh} . The constants C_1 , C_2 , and C_3 depend on the fixed geometry and liquid properties. The pinch-off time t_b is inversely proportional to the magnet speed U_m .

Equation (1) predicts a monotonic decrease of V_d with

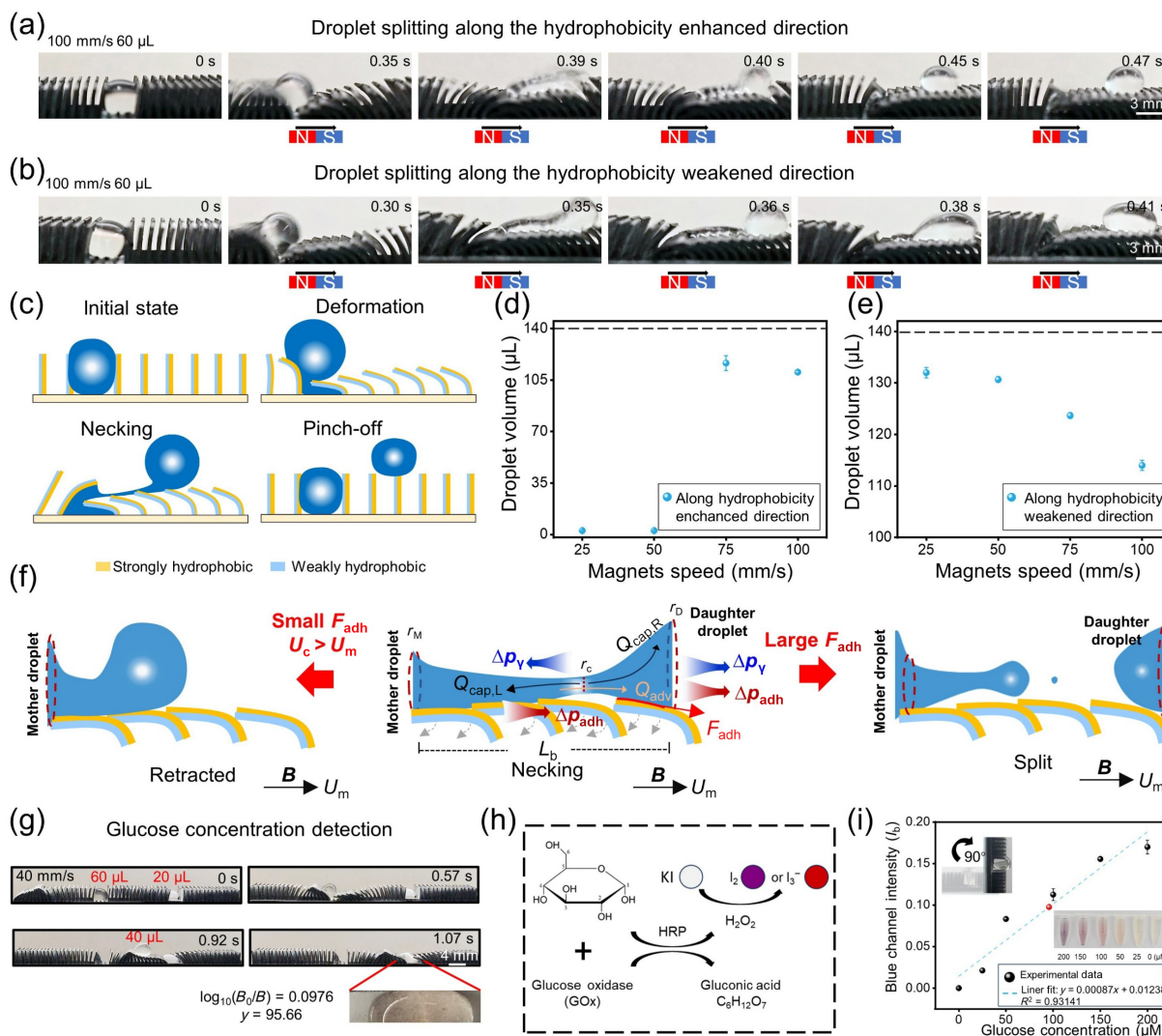


Figure 6 On-demand droplet splitting on M-JAM and its application in integrated glucose sensing. Snapshots of droplet splitting for a 60 μL mother-droplet at 100 mm/s: (a) Model 1, splitting along the hydrophobicity-enhanced direction and (b) Model 2, splitting along the hydrophobicity-weakened direction. (c) Schematic of the splitting stages: initial, deformation, necking, and split. Daughter-droplet volume as a function of magnetic field speed for a fixed 140 μL mother-droplet in (d) Model 1 and (e) Model 2. (f) Theoretical model of the splitting mechanism, illustrating the competition between boundary-induced flux $Q_{\text{cap},R}$, capillary-pressure flux $Q_{\text{cap},L}$, and adhesion forces F_{adh} . (g) On-chip glucose detection: a developer/enzyme droplet (left) is transported into a glucose droplet (right) along the hydrophobicity-weakened direction. (h) Enzymatic colorimetric mechanism for glucose detection. (i) Calibration curve showing the linear relationship between glucose concentration (0–200 μM) and the derived blue-channel intensity (I_b). $I_b = \lg(B_0/B)$, where B_0 and B are the blue-channel pixel values of the blank sample and the test sample, respectively. The inset shows the corresponding solution concentration gradient (200–0 μM) and the M-JAM after a 90° rotation.

increasing U_m (observed in both Model 1 and 2, most pronounced in Model 2) and an increase in V_d with larger F_{adh} , resulting in a notably larger droplet volume in Model 2 than in Model 1 (Figs. 6(d) and 6(e)). Moreover, for splitting under low adhesion (i.e., along hydrophobic enhanced direction, Model 1), a critical speed of moving crest U_c exists, and successful daughter-droplet separation occurs only when $U_m > U_c$. In this regime, the small adhesion pressure Δp_{adh} weakens the rightward capillary flux $Q_{\text{cap},R}$, making the neck highly susceptible to capillary-driven backflow into the mother droplet (Fig. 6(f)). Whether pinch-off occurs therefore depends on the competition between the pinch-off time t_b (inversely proportional to U_m (see the ESM) and the backflow time τ (Here τ is an effective backflow timescale of the liquid bridge, driven by γ but limited by dissipation, treated as an effective constant within a fixed droplet volume and substrate state)). Specifically, a shorter t_b (larger U_m) ensures that pinch-off

completes before significant backflow can occur. This competition establishes a critical velocity threshold: when $U_m > U_c$ and $t_b < \tau$, splitting succeeds; when U_m decreases and t_b increases, the droplet merely stretches and recoils without splitting (Fig. 6(f)). Hence, under weakly adhesive conditions, the onset of splitting is determined by this critical magnetic speed U_c . Overall, droplet splitting on the M-JAM is governed by the dynamic interplay between magnetically imposed boundary motion and Janus-wettability-mediated adhesion, thereby enabling direction-dependent, on-demand splitting with tunable daughter volumes.

3.3.4 Droplet-based glucose sensing

By integrating rectified droplet transport and on-demand splitting on an open surface, the M-JAM platform provides a versatile strategy for digital liquid handling and reaction execution. Unlike conventional open-surface droplet systems, which often suffer from

reversible droplet motion, undesired back-transport, and cross-contamination during sequential operations, M-JAM enables deterministic reagent delivery using only a reciprocating magnetic field. Its inherent direction-selective adhesion landscape allows droplets to be transported when required and securely pinned when not, creating an effective form of “droplet logic”. This capability is particularly useful for assays requiring precise dispensing, dosing, and mixing within a confined zone.

To illustrate this capability, we implemented an enzymatic colorimetric assay for glucose detection. As shown in Fig. 6(g), a color-developer/enzyme mixture (containing KI, GOx, and HRP) and a glucose solution ($C_6H_{12}O_6$) were loaded into two separate grooves on the M-JAM (left: color developer/enzyme mixture; right: glucose solution). Under magnetic actuation, the developer mixture was transported along the hydrophobicity-enhanced direction (40 mm/s) into the glucose droplet, initiating a cascade reaction: Glucose is enzymatically oxidized to gluconolactone and H_2O_2 , and the latter in the presence of HRP, oxidizes KI to form a brown-colored product whose color intensity correlates with glucose concentration (Fig. 6(h)). After reaction completion, the glucose level was quantified by blue-channel intensity analysis (Fig. 6(i)). The platform's reconfigurability was further demonstrated by guiding droplets along defined curved paths (Fig. S16 in the ESM). These results confirm that M-JAM serves as a reconfigurable, open-surface assay platform that offers a practical pathway toward integrated digital microfluidics and point-of-care biochemical analysis. Beyond glucose analysis, the multifunctional droplet operations including programmable transport and controllable splitting, may be valuable for digital dosing, sample partitioning, reagent distribution, and microreaction control in open-surface microfluidic systems. Moreover, the simple magnetic actuation strategy without complex electrode architectures may facilitate integration into portable biochemical analysis platforms. In addition, negligible liquid residue after droplet manipulation suggests a reduced risk of cross-contamination (Fig. S17 in the ESM).

4 Conclusions

In summary, we developed a M-JAM fabricated via 3D-printed molding/casting and asymmetric chemical modification, which endows each microplate the Janus wettability with a highly hydrophobic face and a weakly hydrophobic face. This built-in wettability asymmetry, coupled with field-induced collective bending, creates a direction-selective capillary adhesion landscape that rectifies droplet motion: Droplets are efficiently propelled along the low-adhesion (hydrophobicity-enhanced) pathway but remain pinned in reverse, enabling robust unidirectional transport with velocities up to 163 mm/s and reliable anti-gravity operation on inclined surfaces ($\approx 20^\circ$). Beyond transport, M-JAM provides deterministic capture–release by programming the high-adhesion trough to grip droplets and then reducing effective adhesion during crest translation to trigger clean, residue-minimal release. Moreover, the array supports on-demand splitting in two distinct modes (hydrophobicity-enhanced vs. hydrophobicity-weakened), where daughter-droplet volumes are tunable by the magnetic actuation speed and captured by a scaling model that rationalizes the critical-speed condition under weak adhesion. Finally, leveraging rectified transport, capture–release, and splitting as elementary operations, we demonstrate an integrated open-surface enzymatic glucose assay under a simple reciprocating magnetic

field. Overall, M-JAM establishes a scalable and reconfigurable framework for deterministic and multifunctional droplet manipulation on open surfaces. By coupling programmable magnetic deformation with asymmetric capillary adhesion, this strategy may open new avenues for digital microfluidics, portable biochemical analysis, and autonomous liquid handling systems.

Electronic Supplementary Material: Supplementary material (theoretical notes on the droplet-splitting model and supporting figures related to fabrication, magnetic actuation, wettability characterization, droplet transport/splitting, curved-path manipulation, and liquid-residue evaluation) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94908920>.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

R. Y. Y. and S. D. C.: Data curation, project administration, validation, writing manuscript, experimental design. Y. T. L. and Y. K. Z.: Data curation, project administration, validation. L. S. Z. and X. F. W.: Project administration, funding acquisition, writing manuscript. All the authors have approved the final manuscript.

Use of AI statement

None.

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