

Review

Microfluidic Droplet Splitting in T-Junction: State of the Art in Actuation and Flow Manipulation

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Abstract

Droplet-based microfluidics has emerged as a powerful platform for precise fluid manipulation in biomedical, chemical, and material science applications. Among various geometries, T-junction microchannels are widely utilized for droplet generation and splitting due to their simplicity and reliability. This review provides a comprehensive overview of droplet splitting mechanisms in T-junction microfluidic systems, with particular emphasis on the role of actuation methods in enhancing control and functionality. We first discuss the fundamental physics governing droplet behavior, including the influence of capillary and viscous forces, flow regimes, and geometric parameters. Passive strategies based on flow rate tuning and channel design are outlined, followed by an in-depth examination of active actuation techniques: thermal, electrical, magnetic, acoustic, and pneumatic and their effects on droplet dynamics. In addition, the review highlights computational modeling approaches and experimental tools used to characterize and predict splitting behavior. Finally, we explore the current challenges and future directions in integrating multifunctional actuation systems for real-time, programmable droplet control in lab-on-a-chip platforms. This article serves as a foundational resource for researchers aiming to advance microfluidic droplet manipulation through actuator-enabled strategies.

Keywords: microfluidics; droplet splitting; T-junction; active and passive method; actuation techniques

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1. Introduction

Microfluidics is an interdisciplinary domain focused on the precise manipulation and control of fluids at the microscale, typically within channels possessing characteristic dimensions ranging from tens to hundreds of micrometers. The field integrates concepts from transport phenomena, interfacial science, microfabrication, and systems engineering to enable the development of lab-on-a-chip platforms capable of executing complex physicochemical and biological processes on a miniaturized scale [1–3]. At these length scales, surface forces, viscous effects, and laminar flow regimes dominate over inertial forces, providing deterministic fluid handling and enabling high-resolution spatiotemporal control of multiphase and multicomponent systems. This scaling effect minimizes reagent

and sample consumption, enhances reaction kinetics and mass transfer rates, and allows for the precise modulation of thermal, chemical, and hydrodynamic conditions [1]. Owing to these advantages, microfluidics has become a cornerstone technology in biomedical diagnostics [4], high-throughput screening [5,6], chemical process intensification [2,7], and environmental sensing [8–10].

Among the diverse strategies employed in microfluidics, droplet-based microfluidics has emerged as a particularly powerful platform, as it is able to reliably generate and manipulate discrete droplets with volumes typically ranging from picoliters to nanoliters within an immiscible carrier phase [2,11–14]. Each droplet serves as an independent and isolated microreactor, enabling high-throughput screening and parallel processing of chemical and biological samples under well-defined microenvironments [13,14]. Compartmentalization inherent to this approach minimizes cross-contamination, enhances reaction fidelity, and leverages the high surface-area-to-volume ratio to accelerate mass and heat transfer, thereby improving reaction kinetics [15]. The fundamental principle of droplet microfluidics lies in the use of immiscible fluids, such as oil and water, flowing through microchannels to generate, control, and manipulate uniform, discrete droplets that act as isolated microreactors. These droplets provide well-defined and highly controlled microenvironments, enabling precise handling of minute fluid volumes for applications including biochemical analysis, chemical synthesis, and single-cell studies [11–14]. At the microscale, droplet behavior is governed by the balance between hydrodynamic forces and interfacial tension under predominantly laminar flow conditions. Interfacial tension resists droplet deformation, while viscous shear and pressure gradients imposed by the continuous phase drive droplet elongation, breakup, and transport. These competing effects are commonly characterized using dimensionless parameters such as the Capillary number and Reynolds number. The Capillary number ($Ca = \frac{\mu u_c}{\sigma}$) is defined as the viscous forces to the surface tension forces and the Reynolds number ($Re = \frac{\rho u_c w}{\mu}$) is defined as the ratio of the inertia forces and viscous forces, where ρ is the fluid density, u_c is the average velocity of the continuous phase, w is the characteristic channel width, μ is the dynamic viscosity, and σ is the interfacial tension between the dispersed and continuous phases. By carefully designing channel geometries and controlling flow conditions, and by optionally incorporating active actuation methods, droplet microfluidic systems achieve precise, high-throughput, and reproducible droplet generation and manipulation. The key advantage of droplet-based systems lies in their versatility of operations: droplet formation can be precisely controlled through shear-driven instabilities at microchannel junctions; droplet splitting allows for the partitioning of samples into smaller volumes for dilution or parallelization; droplet sorting provides active or passive discrimination based on physical or biochemical properties [16]; and droplet merging enables controlled coalescence of discrete droplets for reagent mixing or initiation of multistep reactions (see Figure 1). Droplet manipulation in microfluidic systems can be achieved through either passive or active methods, depending on whether external energy inputs are employed [3,16–20]. Droplet formation is the fundamental process in droplet-based microfluidics, typically achieved by shearing a dispersed phase against an immiscible continuous phase within microchannel geometries such as T-junctions [21–25] (see Figure 1I), flow-focusing devices [26–30], or co-flow arrangements [31,32]. The interplay of viscous, shear, interfacial tension, and flow rates determines the size, frequency, and monodispersity of the generated droplets [23–25,30,33]. Key dimensionless numbers such as the Capillary number (Ca) and Reynolds number (Re) govern the transition between squeezing, dripping, and jetting regimes [34–42]. Droplet splitting provides a means of partitioning larger droplets into two or more daughter droplets (see Figure 1III), thereby facilitating serial dilution, reagent distribution, or parallelization of reactions [43–54]. Splitting is

commonly achieved through geometric constrictions [46,49], bifurcating channels, or active methods such as electric, magnetic [20], heating and acoustic fields that induce instabilities [17] at the droplet interface [43]. The efficiency of splitting is influenced by channel geometry, droplet size relative to the constriction, and the balance between viscous and capillary stresses [44–46]. Droplet sorting enables selective separation of droplets based on their physical, chemical, or biological properties (see Figure 1VI). Sorting strategies can be broadly classified as passive or active [16,55–57]. Passive methods exploit hydrodynamic forces, channel bifurcations, or inertial effects to direct droplets into predefined outlets [55–57]. Active methods, in contrast, rely on external fields such as dielectrophoresis, magnetophoresis, acoustic actuation, or optical tweezers to impart directional forces on droplets in real time [16]. Active sorting allows for high-speed and high-precision discrimination, making it well-suited for applications such as single-cell analysis, digital PCR, and drug screening. Droplet merging, or coalescence, is essential for initiating reactions that require mixing of distinct reagents or samples encapsulated within separate droplets [58–63]. Passive merging (see Figure 1II) can be achieved by hydrodynamic confinement at designed channel junctions [58], while active merging is facilitated through the application of electric fields, thermal gradients, or surface acoustic waves [59] that destabilize the thin film between adjacent droplets. Once merged, rapid mixing (see Figure 1IV) occurs through chaotic advection driven by internal circulations within the droplet, significantly accelerating reaction kinetics [62,63]. Droplet catching (see Figure 1V) in microfluidic systems refers to the controlled trapping and temporary immobilization of individual droplets at predefined locations within microchannels or microchambers, enabling operations such as incubation, analysis, or reaction [14–16]. This is commonly achieved through passive geometric features, such as widened chambers, side pockets, or constrictions, which create local pressure minima or flow resistance contrasts that favor droplet retention due to the balance between hydrodynamic forces and interfacial tension. Active approaches further enhance controllability by using external actuation methods, including electric, magnetic, acoustic, or thermal fields, allowing for the selective trapping and on-demand release of droplets for advanced microfluidic applications. Collectively, these operations provide a comprehensive toolbox for manipulating discrete fluid volumes with spatiotemporal precision, establishing droplet-based microfluidics as a cornerstone technology for applications in biomedical diagnostics, drug discovery, synthetic biology, and chemical process intensification.

Droplet splitting in microfluidic systems is most commonly achieved through the introduction of geometric features that impose hydrodynamic asymmetry on a moving droplet [43]. Figure 2 illustrates the fundamental droplet splitting strategies employed in microfluidic systems, broadly classified into passive and active methods. Passive droplet splitting relies exclusively on microchannel geometry and intrinsic hydrodynamic forces, where droplet breakup is induced by pressure gradients, shear stresses, and interfacial tension effects. Common passive configurations include junctions with arbitrary angles (Figure 2I), channel obstructions (Figure 2II), T-junctions (Figure 2III), bypass channels (Figure 2IV), and Y-junctions (Figure 2V), each enabling droplet division through controlled flow resistance and geometric confinement. In contrast, active droplet splitting techniques incorporate external actuation mechanisms, such as electric, acoustic, thermal, or mechanical fields, to precisely manipulate droplet deformation and breakup dynamics (Figure 2). These active approaches provide enhanced control over splitting symmetry, timing, and droplet size compared to passive methods, making them particularly advantageous for applications requiring high precision and dynamic tunability. The simplest and widely used configuration is the bifurcating T-junction, where a parent droplet enters a channel that divides into two symmetric [45–50,64] or asymmetric branches [64–67]. As the droplet advances, pressure and viscous stresses cause it to elongate and eventually

pinch off into two daughter droplets. The size ratio of the daughter droplets can be tuned by altering the relative widths or flow resistances of the branch channels, thereby enabling either symmetric splitting or controlled asymmetric partitioning. Geometrical features strongly govern droplet generation, deformation and breakup dynamics in microfluidic T-junctions under both passive and active actuation approaches. In passive hydrodynamic systems, the ratio between the branch and the main channels (ω_1/ω_0) directly controls the droplets geometric constraints and the balance between viscous stress and interfacial tension. Chen and Deng [45] demonstrate that decreasing ω_1/ω_0 changes the transition boundaries between non-breakup, breakup with tunnels and breakup with permanent obstruction toward smaller dimensionless droplet length l_0/ω_0 , thus indicating that narrower channels increase earlier deformation and more reliable breakup. This behavior arises from enhanced geometric confinement at the junction, which increases droplet obstruction, increases extensional flow fields around the stagnation point, and induces localized vortex structures that accelerate neck thinning and pinch-off [44]. This geometry-based control enables passive droplet splitting, where daughter droplet size and symmetry are set by channel dimensions and branch resistance rather than by external forces. Under active actuation, such as pressure modulation, flow-rate control, and valve-induced resistance changes, geometry remains the fundamental control parameter. Channel width and junction architecture determine how efficient actuation-induced stresses interact with droplet interface. Constraint geometries amplify hydrodynamic and externally imposed stresses by focusing on deformation near the stagnation point, while wider geometries dissipate energy and reduce sensitivity to breakup [44,45]. Overall, geometry serves as a unifying design principle across both passive and active droplet generation strategies, governing breakup thresholds, daughter droplet size ratios and how uniform or non-uniform the sizes of particles or droplets are within the system.

The rheological properties of fluids, including viscosity, density, and interfacial tension, critically influence droplet generation and splitting in microfluidic systems. In Newtonian fluids, higher viscosity increases flow resistance, producing larger droplets and slower pinch-off, while lower viscosity promotes faster droplet detachment. Chen and Deng [45] demonstrated how deviations from Newtonian behavior significantly alter droplet deformation and breakup regimes, particularly under high strain rates near the junction point. Shear-thinning fluids exhibit locally reduced effective viscosity, accelerating neck thinning and causing earlier pinch-off, whereas viscoelastic stresses in elastic fluids resist interfacial thinning and increase breakup thresholds [44]. Fluid density affects inertial forces, influencing droplet stability and the ease of splitting under varying flow conditions. Interfacial tension governs the balance between cohesive and disruptive forces at the fluid–fluid interface, directly controlling droplet shape, size, and the efficiency of splitting. These rheological effects are particularly relevant in the present T-junction study, where active actuation enhances strain rates and amplifies elastic and shear-rate responses, improving predictive capabilities and enabling better control of droplet breakup in complex fluids, including biofluids, polymer solutions, and nanoparticle suspensions [44,45].

Another common design is the Y-junction geometry, in which the droplet is directed into diverging branches at an angle [68–73]. Compared to the T-junction, Y-junctions provide smoother transitions, reducing pressure fluctuations and allowing for higher throughput splitting with improved reproducibility. In addition to these passive geometric approaches, constriction-based and bypass channels are frequently employed, where a droplet is forced through a narrow throat that induces elongation and eventual breakup into multiple daughter droplets [74–77]. This method is particularly effective for generating evenly sized fragments and is compatible with serial splitting cascades for combinatorial applications. The efficiency of splitting across these configurations depends on the

balance between viscous shear forces, interfacial tension, and channel hydrodynamics, which are often characterized by the Capillary number (Ca) and Reynold number (Re) [43,45].

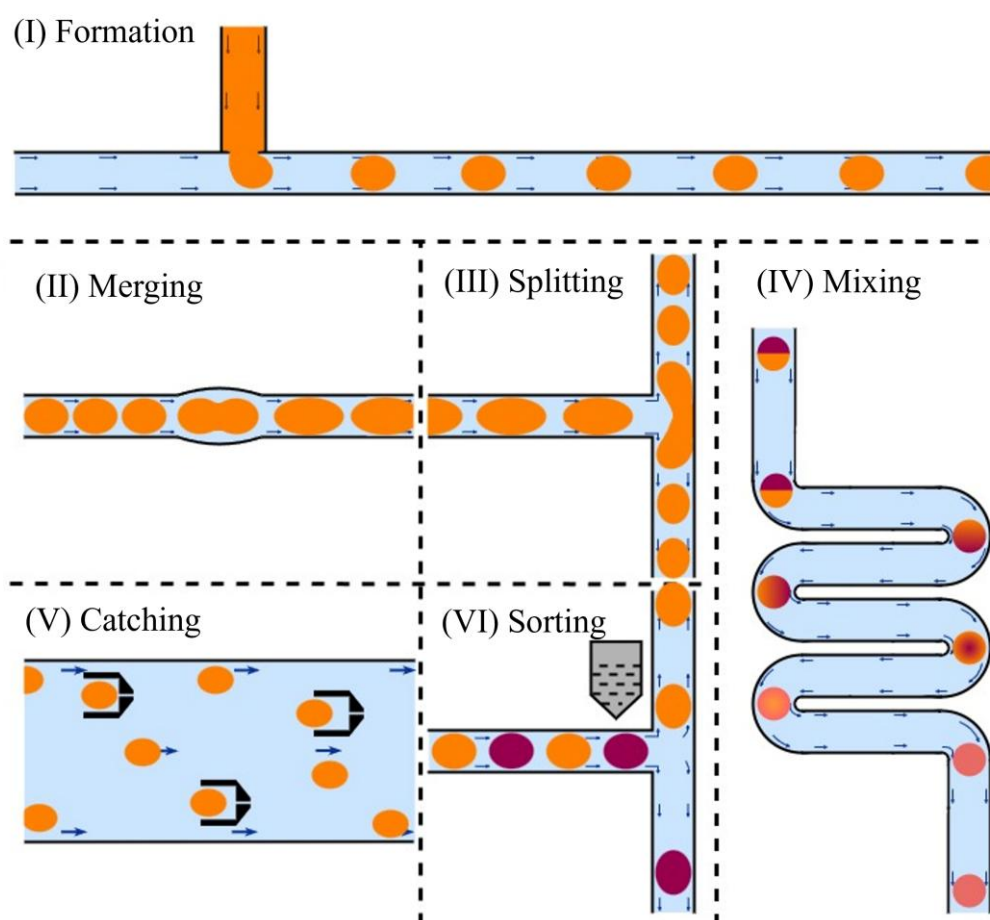


Figure 1. Schematic illustration of common droplet manipulations in microfluidic systems: (I) droplet generation at a T-junction, (II) droplet merging through hydrodynamic confinement, (III) droplet splitting at a channel bifurcation, (IV) internal chaotic advection enabling rapid mixing within droplets, (V) catching using geometric features, and (VI) droplet sorting via passive or active mechanisms.

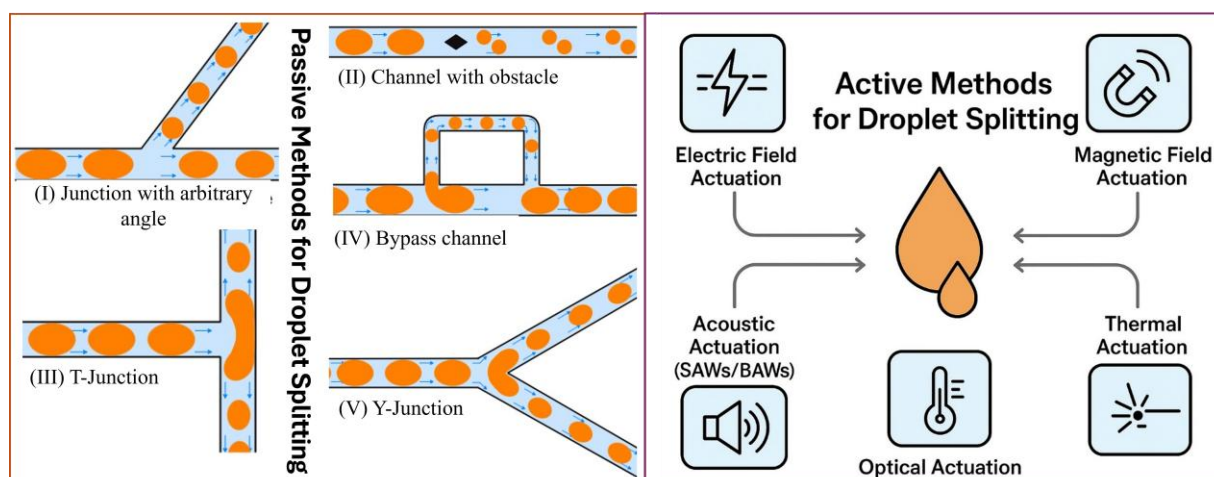


Figure 2. Schematic illustration of droplet splitting techniques in microfluidic systems using passive and active methods. The passive approaches rely solely on channel geometry and hydrodynamic

forces and include (I) junctions with arbitrary angles, (II) channel obstructions, (III) T-junctions, (IV) bypass channels, and (V) Y-junctions, where droplet breakup occurs due to interfacial tension, shear stress, and pressure redistribution. In contrast, active droplet splitting methods employ external actuation (such as electric, thermal, acoustic, or magnetic fields) to dynamically control the timing, location, and symmetry of droplet breakup, enabling enhanced precision and tunability compared to passive designs.

Active methods of droplet splitting utilize external fields (see Table 1) to precisely control breakup dynamics (see Figure 2), offering greater flexibility than purely geometry-driven passive techniques [43]. Electric fields deform and destabilize droplets through electrohydrodynamic forces, enabling asymmetric splitting and tunable daughter sizes, while magnetic fields act on ferrofluids or magnetically tagged droplets via localized gradients for non-contact manipulation [64,78,79]. Acoustic actuation, using surface or bulk waves, induces pressure nodes and streaming flows that accelerate neck thinning in a biocompatible and energy-efficient manner [80–82]. Thermal methods rely on localized heating to create Marangoni stress, which destabilize the droplet neck and promote splitting at lower flow rates [19,83–85], whereas optical techniques employ laser-induced radiation pressure or heating to selectively split individual droplets with high spatial precision [86]. Magnetic fields are actively used in micro-magnetofluidics as a powerful tool to manipulate ferrofluid microdroplet generation [87,88], splitting, and manipulation within T-junction geometries [89]. Ferrofluids respond to magnetic fields with controllable deformation and motion, enabling precise control over the droplet's breakup dynamics. Collectively, these approaches expand the design space of microfluidic platforms by allowing for programmable, on-demand droplet control, with applications spanning biochemical assays, diagnostics, and material synthesis [43].

Droplet splitting in microfluidic T-junctions constitutes a pivotal technique in contemporary microfluidics due to its capacity for precise partitioning and manipulation of microscale fluid volumes. T-junction microchannels are among the most widely used geometries in droplet-based microfluidics due to their simple design, ease of fabrication, and robust operational characteristics. Compared to other geometries such as flow-focusing or co-flow devices, T-junctions offer well-defined and highly reproducible control over droplet formation and splitting through the interplay of viscous forces and interfacial tension. Their geometric simplicity facilitates systematic experimental investigations and enables accurate theoretical and computational modeling of droplet dynamics. Moreover, T-junction configurations are readily compatible with both passive hydrodynamic control and a wide range of active actuation techniques, including electric, magnetic, acoustic, and thermal methods. This operation is integral to numerous scientific and engineering domains, enabling controlled modulation of droplet size, composition, and content. In digital PCR and nucleic acid assays, uniform droplet partitioning enhances amplification sensitivity and fidelity, thereby facilitating high-throughput genetic analysis and single-molecule detection [90–92]. In pharmaceutical research, controlled splitting enables generation of dosage-specific droplets from a single precursor stream, thereby supporting parallelized pharmacokinetic evaluations and high-throughput drug screening [93–96]. In single-cell analysis, droplet splitting facilitates isolation and concurrent processing of individual cells, enabling high-resolution transcriptomic and proteomic characterization [97–100]. Furthermore, in lab-on-a-chip diagnostics, droplet splitting allows for multiplexed assays, enhancing analytical throughput from minimal sample volumes [101–103]. In chemical and biochemical reaction screening, droplet splitting facilitates generation of combinatorial reaction conditions by modulating reactant ratios, expediting optimization of reaction pathways [97,104–106]. Synthetic biology [106] and metabolic engineering [107] exploit droplet splitting to compartmentalize and regulate reagent mixing in cell-

free expression systems [108]. In materials science, precise splitting enables consistent synthesis of nanoparticles and emulsions by maintaining uniform precursor ratios [109–111]. Applications extend to food safety and environmental monitoring, where droplet splitting enables parallel contaminant detection by dividing samples into smaller, equal volumes for simultaneous analysis [112,113]. In enzymology and protein assays, this technique enables time-resolved kinetic analyses and concentration-dependent evaluations, thereby augmenting throughput and resolution in biochemical investigations [114,115]. These multifaceted applications highlight the transformative role of droplet splitting in advancing microfluidic technologies.

Table 1. Comparison of Passive and Active Droplet Splitting Methods in Microfluidic.

Method	Driving Mechanism	Control Over Splitting	Key Advantages	Limitations
Passive (Geometry + Flow) [2,43]	Hydrodynamic forces governed by channel geometry and flow rate ratio	Limited, predefined by design	Simple, low-cost, robust	Lack of flexibility; sensitive to flow fluctuations
Electric Field Actuation [17,18,43]	Electrohydrodynamic stresses at fluid interface	High (asymmetric or symmetric splitting possible)	Precise, tunable control	Requires electrodes and high-voltage sources
Magnetic Field Actuation [17,18,43]	Magnetic body forces acting on ferrofluids/magnetic droplets	Moderate–High	Remote, non-contact manipulation	Droplet composition restricted
Acoustic Actuation (SAWs/BAWs) [17,18,43]	Pressure gradients and acoustic streaming forces	High	Biocompatible, tunable, scalable	Requires piezoelectric substrates and frequency tuning
Thermal Actuation [17,18,43]	Marangoni stresses from temperature-induced interfacial tension gradients	Moderate	Spatially selective; no chemical additives	Thermal damage risk; slower response
Optical Actuation [17,18,43]	Radiation pressure or laser-induced heating	Very High	High precision, selective manipulation	Expensive, low throughput, complex alignment

This review aims to present a comprehensive synthesis of contemporary advancements in droplet splitting within microfluidic T-junction configurations, with particular emphasis on actuation mechanisms and flow modulation strategies. Droplet splitting represents a fundamental operation in droplet-based microfluidics, enabling parallel processing, dividing, and controlled dilution across diverse chemical and biological assays. The precision and versatility of splitting within T-junction architectures are strongly dependent on the interplay between device geometry, interfacial dynamics, and actuation methodologies. Droplet splitting in T-junctions can be realized through both passive and active methods, each characterized by distinct physical principles and operational advantages (see Table 2). Passive methods leverage inherent hydrodynamic forces arising from channel geometry and interfacial tension, requiring no external energy input, thereby ensuring operational simplicity and energy efficiency. Active methods incorporate external stimuli, such as acoustic waves, electric fields, magnetic forces, or thermal gradients to dynamically modulate droplet deformation and splitting, offering enhanced precision and controllability. A systematic analysis of these approaches is critical for the rational design of droplet-based microfluidic systems tailored to specific application requirements.

Table 2. Active versus Passive Droplet Splitting in Microfluidic T-Junction [43].

Feature	Passive Droplet Splitting	Active Droplet Splitting
Mechanism	Relies on intrinsic hydrodynamic forces, interfacial tension, and channel geometry	Utilizes external actuation forces such as acoustic, electrical, magnetic, thermal, or pneumatic inputs
Energy Requirement	None (self-actuated by flow)	Requires external energy input
Control Precision	Limited, determined by channel design and flow conditions	High, tunable in real time
Complexity of Fabrication	Low—simpler device geometry	High—requires integration of external actuators
Flexibility	Low—fixed once fabricated	High—controllable dynamically during operation
Throughput	High—passive splitting is continuous	Moderate—dependent on actuation mechanism
Scalability	High	Limited by complexity and energy requirements
Applications	Droplet partitioning, dilution, basic assays	Complex assays requiring dynamic control, multiplexed operations, real-time droplet manipulation
Advantages	Simple, energy-efficient, robust	High precision, adaptive control, multifunctional
Limitations	Limited adaptability, geometry-dependent	Higher complexity, energy requirements, device cost

Despite extensive studies on droplet splitting in microfluidic T-junctions, the existing literature remains focused on isolated actuation methods and flow conditions, with limited cross-comparison of passive and active control strategies under unified scaling frameworks. In particular, the combined influence of channel geometry, fluid and material properties, surface modifications, and externally applied fields on splitting regimes, symmetry, and controllability is not systematically synthesized. To address this gap, this review systematically classifies and analyzes state-of-the-art passive and active droplet-splitting strategies in T-junction geometries. The review examines the governing physical principles, channel design considerations, and external actuation mechanisms, including electrical, thermal, magnetic, acoustic, and pneumatic control, alongside the roles of flow parameters, material properties, and surface modifications. Numerical modeling frameworks for predicting and optimizing droplet splitting performance are also discussed. Finally, the review highlights key applications in diagnostics, drug delivery, synthetic biology, and chemical screening, while outlining current challenges and future research directions in this rapidly evolving field.

2. Fundamental of Droplet Splitting in T-Junctions

Droplet splitting in T-junction microfluidic geometries is a fundamental operation that allows a single mother droplet to divide into two or more daughter droplets upon encountering a bifurcation (see Figure 3). The contour plot is intended solely to depict the evolution of the droplet shape during the sequential stages of droplet splitting in the microfluidic T-junction. The mechanism of splitting is governed by a complex interplay of interfacial tension, hydrodynamic pressure, viscous shear forces, and the geometric characteristics of the junction [43–45,47–51,53]. Figure 3 illustrates the sequential stages (i.e., entering, squeezing, breakup and post-breakup) of droplet splitting in a microfluidic T-junction. Initially, the incoming droplet enters the junction and begins to deform under the influence of viscous shear and pressure gradients imposed by the continuous phase [44,45]. As it elongates, the droplet fills the junction region, with its interface extending into both branch channels. At this stage, the balance between interfacial tension, which resists deformation, and hydrodynamic stresses, which promote stretching, becomes critical. With increasing confinement, a necking region forms near the junction, where the droplet thins progressively. Finally, the neck undergoes pinch-off, resulting in the division of the parent droplet into two daughter droplets, which may be symmetric or

asymmetric depending on the channel geometry [66], flow rates, fluid properties and external forces [65,116,117]. The dynamics of splitting process can be rationalized using dimensionless groups such as the Capillary number (Ca), which captures the competition between viscous and interfacial forces; the Reynolds number (Re), which characterizes inertial-to-viscous effects; and the Weber number (We), which reflects inertial-to-capillary force ratios. These parameters establish scaling laws that help predict the onset and outcome of droplet division [44,48,49]. The symmetry and efficiency of the splitting process depend on key parameters such as the viscosity ratio (μ_d/μ_c), wettability and flow rate ratio (Q_d/Q_c) between the continuous and dispersed phases [43,45,117]. The geometry of the T-junction is equally critical, as channel width ratios, junction angles, and aspect ratios directly influence stress distribution and partitioning symmetry. For instance, asymmetrical channel designs can be used to intentionally control the size ratio of daughter droplets [66]. Additionally, channel surface properties, such as wettability, roughness, and chemical modifications, further modulate droplet behavior, with hydrophobic coatings often employed to stabilize splitting and prevent wetting along channel walls [116,117]. In addition to passive methods, active modulation of flow parameters or the use of external fields (e.g., electric, magnetic, acoustic, thermal and optical) can offer precise control over the splitting process [20,62,88]. Understanding these fundamental principles is essential for designing microfluidic systems that require high precision, reproducibility, and adaptability in droplet handling. These foundational concepts serve as the basis for more advanced manipulations such as selective splitting, volume-controlled division, and integration with downstream processing steps in microfluidic networks.

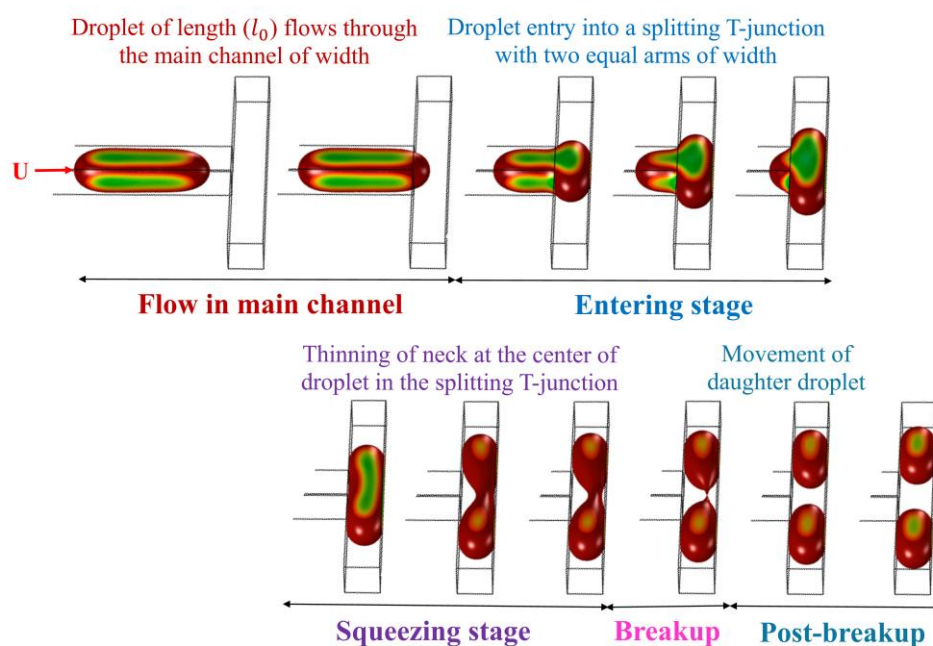


Figure 3. Schematic representation of the characteristic stages of droplet breakup: entering, where the incoming droplet deforms symmetrically upon reaching the junction; squeezing, during which the droplet elongates into both branch channels as upstream pressure increases; necking and breakup, where the droplet thins at the junction and undergoes pinch-off due to the balance of hydrodynamic and interfacial forces; and post-breakup, in which the resulting daughter droplets are transported downstream. The figure illustrates the evolution of droplet morphology during the splitting process.

A widely accepted framework for classifying droplet behavior in microfluidic T-junctions distinguishes three primary flow regimes (see Figure 4): Type I splitting with

permanent obstruction, Type II splitting with tunnels, and Type III non-splitting [45,47–51]. The discerning factor between splitting with obstruction and splitting with tunnels lies in the presence of visible tunnels between the droplet's tips and the channel walls during the squeezing stage of the droplet splitting (see Figure 4). This classification, though primarily based on geometrical observations, provides meaningful insight into the physical dynamics governing droplet splitting. In Type I, the droplet occupies the entire cross-section of the main and branch channels, temporarily obstructing the continuous phase and eventually breaking due to the buildup of pressure and interfacial forces (see Figure 4I). In Type II, small tunnels or gaps remain between the droplet and the channel walls during squeezing stage, allowing for limited flow of the continuous phase around the droplet before it breaks (see Figure 4II). Type III, by contrast, represents a non-splitting regime in which the droplet deforms but does not split, often due to insufficient shear or capillary number (see Figure 4III).

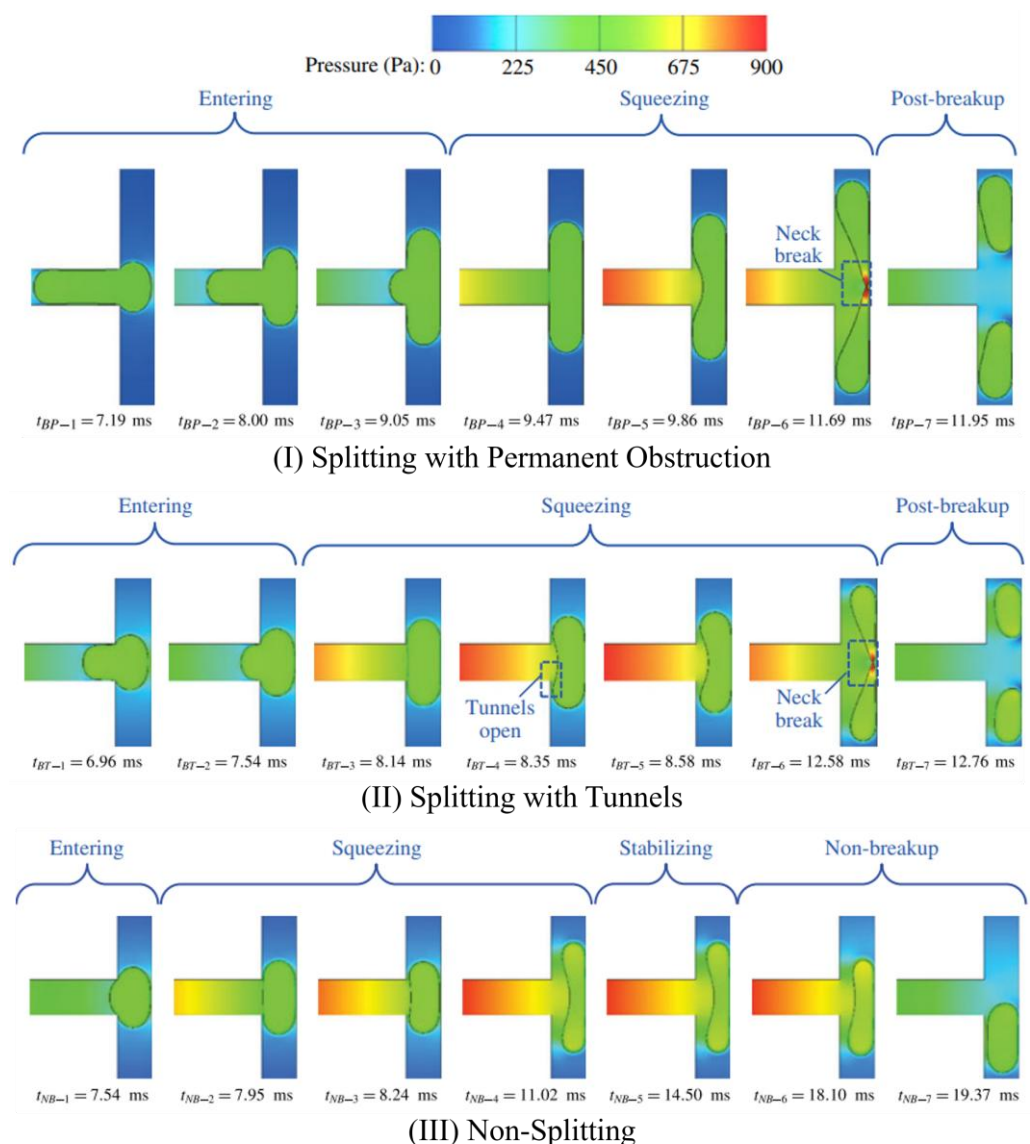


Figure 4. Different flow regimes of droplet behaviors in a microfluidic T-junction under controlled hydrodynamic conditions. Representative pressure contour plots illustrating three characteristic droplet flow regimes observed at a viscosity ratio of: $\frac{1}{8}$ and $Ca = 0.05$ (I) splitting with permanent obstruction ($\frac{l_0}{w} = 3.73$), where the droplet fully blocks the channel cross-section prior to breakup; (II) splitting with tunnels ($\frac{l_0}{w} = 2.33$) characterized by the formation of thin continuous-

phase films between the droplet interface and channel walls during squeezing; and **(III)** non-splitting ($\frac{l_0}{w} = 2.13$), where the droplet deforms but does not divide due to insufficient hydrodynamic stress. The figure highlights the dependence of droplet breakup behavior on the initial droplet length relative to the channel width under fixed flow conditions. Reproduced with permission from Chen and Z. Deng, *J Fluid Mech*, vol. 819, 2017. Copyright (2017) Cambridge University Press [45].

At the T-junction, the droplet undergoes an entering stage characterized by symmetric deformation into two branch channels, while the rear interface remains convex and its Laplace pressure constant [45,47–50]. As the advancing contact angle of the two fingers decreases, inlet pressure rises gradually to overcome capillary hysteresis (see Figure 5I–III). Once this stage concludes, upstream pressure flattens the rear interface, leading to a rapid drop in Laplace pressure and a sharp increase in inlet pressure (see Figure 5). When the rear interface is fully flattened, the droplet transitions to the squeezing stage, as shown in Figure 4. The rear becomes concave, initiating neck formation at the junction center. The neck progressively thins until droplet breakup occur. Compared to breakup with permanent obstruction, droplet breakup with tunnels follows similar dynamics in the entering and post-breakup stages but differs during squeezing. In this case, two tunnels form between the droplet and channel sidewalls at the onset of squeezing. Despite their presence, inlet pressure continues to rise sharply, primarily driving the rear interface concavity, indicating limited tunnel influence at this stage. After some time, neck thinning and elongation persist, but the rear curvature radius and corresponding Laplace pressure remain constant, unlike the obstructed case, as shown in Figure 5I,II. This steady Laplace pressure evolution continues until breakup, after which upstream pressure immediately returns to baseline.

When no breakup occurs, the droplet undergoes similar entering and squeezing stages (see Figure 4), followed by stabilizing and non-breakup stages. In the stabilizing stage, elongation ceases and the droplet remains symmetric, with both inlet and Laplace pressures constant. This persists until a disturbance arises at outlet I, increasing its pressure above outlet II (see Figure 5III). The resulting imbalance initiates the non-breakup stage. Initially, Laplace pressure is unaffected, but as the droplet tip crosses the symmetry axis, balance is lost. The droplet then rapidly exits through one daughter channel without breakup, causing abrupt changes in both Laplace and upstream pressures. In the non-breakup case, the droplet undergoes a stabilizing stage characterized by the opening of two tunnels, which is essential for preventing breakup. Figure 5V shows the evolution of shear stress at the droplet tips. When the channels are fully blocked, tip shear stress is negligible. Once tunnels form, shear stress decreases and reaches a steady state, while shear action within the tunnels induces vortices at the droplet tips. As shear stress decreases, vortex vorticity increases until saturation, indicating a transfer of shear momentum into vortex motion. These vortices strongly inhibit droplet deformation, explaining why tunnel formation slows droplet elongation. Thus, shear effects in the tunnels do not promote elongation but instead generate vortices that resist it. With shorter initial droplet lengths, elongation ceases earlier, and the droplet reaches a symmetric steady state at the T-junction without breakup. To clarify the role of vorticity during tunnel formation, Figure 5VI shows the variation in final steady vorticity and droplet deformation rate as a function of droplet size. As initial droplet length decreases, the final steady vorticity increases, leading to a reduced deformation rate. This inverse relationship highlights the suppressing effect of vortices on breakup. When vorticity exceeds a critical threshold, the evolution exponents drop to zero, and breakup no longer occurs.

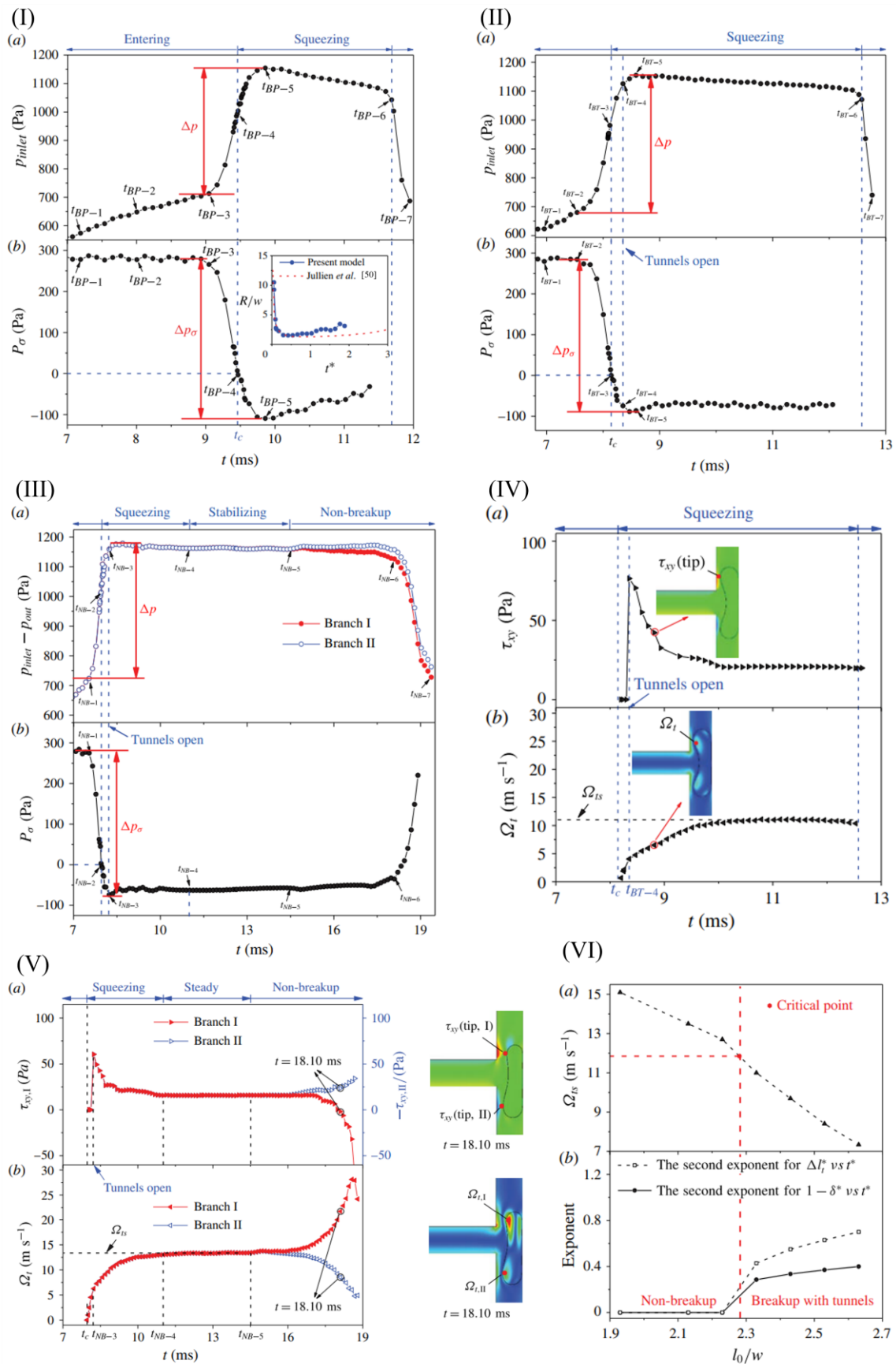


Figure 5. Time evolution of pressure, interfacial forces, and internal flow structures for different droplet behaviors in a microfluidic T-junction. (I) Time evolution of (a) the inlet–outlet pressure drop and (b) the Laplace pressure at the bottom droplet interface for the droplet breakup with

permanent obstruction case obstruction ($\lambda = 1/8, Ca = 0.05, l_o/w = 3.73$) [50]. (II) Time evolution of (a) the inlet–outlet pressure drop and (b) the Laplace pressure at the rear droplet interface for the droplet breakup with tunnels case ($\lambda = 1/8, Ca = 0.05, l_o/w = 2.33$). (III) Time evolution of (a) the inlet–outlet pressure drop and (b) the Laplace pressure at the rear droplet interface for the droplet non-breakup case ($\lambda = 1/8, Ca = 0.05, l_o/w = 2.13$). (IV) Evolution of (a) the shear stress acting on the droplet tip and (b) the vorticity of the characteristic internal vortex for the droplet non-breakup case with ($\lambda = 1/8, Ca = 0.05, l_o/w = 2.33$) (V) Evolution of (a) the shear stress at the droplet tip and (b) the vorticity of the characteristic internal vortex for the droplet non-breakup case with case ($\lambda = 1/8, Ca = 0.05, l_o/w = 2.13$). (VI) (a) Final steady-state vorticity and (b) deformation rate as a function of droplet size under fixed flow conditions ($\lambda = 1/8, Ca = 0.05$). Reproduced with the permission from Y. Chen and Z. Deng, J Fluid Mech, vol. 819, 2017. Copyright (2017) Cambridge University Press [45].

3. Passive Flow Manipulation Techniques

Passive flow manipulation in microfluidic systems leverages the intrinsic coupling between interfacial forces, viscous stresses, and microchannel geometry to regulate droplet behavior without external actuation. These techniques exploit deterministic fluid mechanics such as, variations in local hydrodynamic resistance, capillary pressure gradients, and confinement effects to achieve splitting, merging, sorting, or redirection of droplets [24]. The absence of auxiliary energy input not only simplifies device design and operation but also enhances robustness, scalability, and throughput in lab-on-a-chip applications [104,105]. In T-junction microchannels, passive splitting is governed by the balance between the continuous-phase shear stress and the Laplace pressure within the dispersed phase, which together dictate whether a droplet undergoes symmetric or asymmetric division. Careful engineering of the microchannel architecture enables predictable droplet partitioning, making passive techniques indispensable in applications that demand reproducibility and low-cost integration.

The paper by Link et al. [44] pioneered the splitting mechanism of confined droplets in a T-junction and employed a stability criterion, derived a critical droplet length to predict splitting versus non-splitting conditions. They further proposed an analytical expression to predict the critical Capillary number (Ca_{cr}) required for droplet breakup in symmetric T-junctions as a function of the non-dimensional initial droplet length (L^*), given by:

$$Ca_{cr} = \psi L^* \left(L^{*\frac{2}{3}} - 1 \right)^2 \quad (1)$$

where ψ is a dimensionless constant dependent on the viscosity ratio (λ). Jullien et al. [3] classified droplet splitting into three distinct flow patterns, i.e., no splitting, splitting with tunnels, and splitting with permanent obstruction, based on Ca and the dimensionless initial droplet length l_o/w , delineating their parametric boundaries. Subsequent studies have established empirical and theoretical correlations linking the critical capillary number for breakup to droplet extension, often expressed through power-law relationships or derived from analytical models [44,45,47–49]. Utilizing lubrication theory, Leshansky and Pismen [48] and Leshansky et al. [49] formulated analytical criteria for regime transitions, deriving scaling laws such as

$$l_o/w = 1.3Ca^{-0.21} \quad (2)$$

for the no-splitting to splitting with tunnels transition, and

$$l_o/w = 1.76(\alpha/3Ca)^{1/3} + 1 \quad (3)$$

where $\alpha = 0.25$, for the splitting with tunnels to permanent obstruction transition. Hoang et al. [53] implemented a fully three-dimensional numerical model, revealing a two-stage breakup mechanism comprising an initial quasi-steady deformation phase governed by external flow and a subsequent autonomous surface-tension-driven pinching phase [45,118]. They also concluded that increasing the viscosity ratio (λ) reduces the neck-thinning rate, thereby prolonging droplet splitting time. Additionally, decreasing the channel height further increases splitting time. Chen and Deng [45] employed a phase-field multiphase lattice Boltzmann framework to resolve droplet dynamics, demonstrating that the magnitude and structure of internal vortices critically modulate splitting, with vortex intensities above a threshold inhibiting breakup. Their analysis further quantified the effects of viscosity ratio and channel width ratio on splitting behavior. Chen and Deng [45] reported that the boundaries between flow patterns for splitting with permanent obstruction and splitting with tunnels exhibit minor variation with viscosity ratio, particularly at low Capillary numbers. In contrast, the transition boundary between splitting and non-splitting ($\frac{l_o}{w} = \beta C a^{-0.29}$) shifts markedly toward smaller l_o/w with increasing viscosity ratio ($\lambda = \mu_d/\mu_c$), consistent with both numerical findings (De Menech [119], Afkhami et al. [120]) and experimental observations (Jullien et al. [50]; Fu et al. [51]). Most recently, Mandal and Sarkar [47] performed comprehensive 3D numerical simulations to construct a regime map for droplet splitting in symmetric T-junctions and proposed a correlation for the critical capillary number as a function of viscosity ratio and dimensionless droplet length

$$Ca_{cr} = a \left(\frac{l_o}{w} \right)^b \left(\frac{\mu_d}{\mu_c} \right)^c \quad (4)$$

where a is prefactor, and b and c are constants that depend only on the geometry). Nguyen et al. [121] proposed a theoretical model to predict the critical Capillary number

$$Ca_{cr} > \frac{a_1 \left(\frac{w}{l_o} \right)^{a_2} (\lambda + 1)}{2.5\lambda + 1} \quad (5)$$

for the transition from the no-splitting to splitting as a function of the length ratio and viscosity ratio, showing an increase in λ prolongs splitting time.

Sun et al. [122] investigates the dynamics of droplet breakup with tunnels and formation of satellite droplets in a symmetric microfluidic T-junction. The droplet breakup process is divided into four stages: squeezing, transition, pinch-off, and thread rupture each with specific scaling laws that depend on the viscosity ratio, capillary number, and dimensionless droplet length. In the squeezing stage, the thinning of the droplet neck is controlled by the squeezing pressure, while the transition and pinch-off stages are dominated by fluid velocity and capillary force, respectively. The thread rupture stage follows a linear thinning relationship, with the coefficient dependent on the viscosity ratio. The size of satellite droplets is determined by the filament volume and increases with higher superficial velocity and droplet viscosity, with a critical capillary number observed below which the satellite droplet size remains constant. Zhang et al. [118] demonstrated that at small to moderate initial droplet lengths, partial blockage of the branch channels leads to an uneven distribution of surfactants along the droplet interface. This nonuniform surfactant concentration generates Marangoni stresses, which, in turn, induce additional viscous drag stresses to maintain interfacial force balance. The resulting interplay between these stresses enhances droplet deformation and facilitates breakup. However, at larger initial droplet lengths values, where the branch channels are completely obstructed by the droplet, the neck contraction process becomes governed by the injection rate of the continuous phase, thereby significantly weakening the influence of surfactants on the breakup dynamics [45,53]. Zhou et al. [123] identified a previously unreported lateral breakup regime

in the canonical T-junction microchannel geometry, wherein droplet pinch-off occurs within the two outlet branches rather than at the junction center, resulting in the formation of three daughter droplets instead of the conventional two. This lateral breakup mechanism is governed primarily by interfacial tension and is associated with the development of a carrier fluid pocket beneath the droplet. A predictive model was formulated for low Capillary numbers (Ca), capturing the initiation and growth dynamics of this fluid pocket responsible for lateral pinch-off. As Ca increases, viscous stresses dominate over interfacial effects, and the system transitions back to the conventional central breakup regime. Based on these findings, a geometric design criterion for T-junctions was proposed to delineate the operational boundaries between lateral and central breakup modes. Deng et al. [124] formulated a theoretical model to describe the sequential droplet splitting process in fractal tree-shaped microchannel networks with arbitrary branching, elucidating the role of hydraulic imbalance in high-throughput droplet generation. The study identified two dominant dimensionless parameters governing droplet uniformity: the initial operating conditions, encompassing droplet length, viscosities of both phases, channel width, and capillary number and the pressure distribution characterized by outlet pressure and phase-specific pressure drops at the primary channel. Results showed that droplet monodispersity deteriorates with lower initial driving conditions and higher outlet pressures. Based on these findings, optimal design strategies were proposed to enhance droplet uniformity, including increasing the capillary number, extending the continuous-phase flow length in the main channel, and lengthening branch channels across successive levels.

Double Emulsions

Fan et al. [125] systematically investigated the splitting dynamics of double emulsions in Y-shaped microchannels, analyzing the velocity fields and pressure distributions to reveal that the upstream pressure induced by the obstruction of the continuous phase flow around the double emulsions plays a dominant role in achieving stable and symmetric splitting. Additionally, the complex and chaotic flow structures within the middle phase were found to significantly influence the overall splitting behavior. The study by Liu et al. [72] comprehensively elucidated the dynamic mechanisms governing the splitting of double emulsion droplets flowing through a microfluidic T-junction and identified three primary flow regimes: non-breakup, once-breakup, and twice-breakup, each defined by the interplay of droplet geometry, capillary number, and viscosity ratio. Figure 6 The schematic illustrates the splitting of a double emulsion droplet in a microfluidic T-junction, where an inner droplet encapsulated within an outer droplet is divided into two daughter double emulsions as it passes through the junction. The figure emphasizes the preservation of the core-shell structure during splitting and highlights the role of geometric confinement and flow distribution in achieving controlled and symmetric division within the microchannel. By constructing flow pattern maps and state diagrams, the study quantitatively related droplet deformation dynamics to dimensionless parameters, revealing that higher viscosity ratios reduce deformation resistance and promote breakup due to weakened coupling effects. Importantly, the work establishes twice-breakup as an effective strategy to precisely control shell thickness, enabling stable production of double emulsions with thin and uniform shells, which is valuable for applications in encapsulation, drug delivery, and microreactor design. Liu et al. [68,126] experimentally study the dynamic behaviors of double emulsion droplets flowing through a Y-shaped bifurcation and categorize the flow patterns based on the number of interfacial breakups and the coupling effect between the inner and outer interfaces: non-breakup (NB), once breakup (OB) with or without coupling effect, and twice breakup (TB) with or without coupling effect. They concluded that the coupling effect was found to hinder the breakup of the outer droplet but facilitate the breakup of the inner droplet [127].

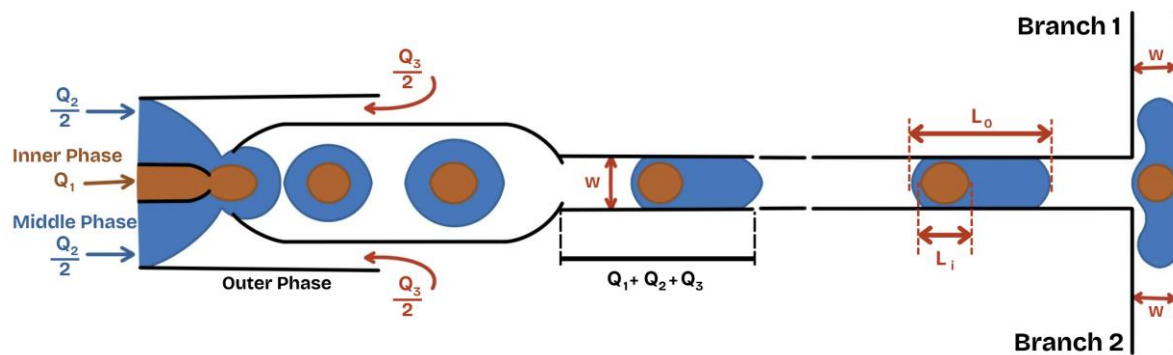


Figure 6. Schematic illustration of double emulsion droplet splitting in a microfluidic T-junction, highlighting the controlled division of inner and outer phases into daughter droplets within confined microchannels.

The breakup dynamics and mechanisms of viscous droplets in Y-shaped microchannels were systematically examined by Ma et al. [128], revealing four distinct flow patterns: non-breakup, breakup without obstruction, breakup with partial obstruction, and breakup with permanent obstruction, with the partial obstruction mode exhibiting the widest operational range. The breakup process under partial obstruction was characterized by three sequential stages: squeezing, transition, and rapid pinch-off. During the squeezing stage, the dimensionless neck width exhibited a power-law dependence on time ($1 - \frac{w_m}{w_c} = m \left(\frac{t}{t_c} \right)^\alpha$), where the power-law index (α) decreased with increasing viscosity ratio (λ). In the transition stage, the neck width varied linearly with time ($1 - \frac{w_m}{w_c} = \frac{k(t-t_s)}{T_c} + b$), with the slope (k) decreasing as λ increased but rising with higher capillary numbers (Ca_c) and longer initial droplet lengths (l_o/w_c). Finally, in the rapid pinch-off stage, the neck width again followed a power-law relation ($1 - \frac{w_m}{w_c} = n \left(\frac{t}{t_c} \right)^\beta$), with the exponent (β) decreasing as λ increased yet increasing with l_o/w_c . These results highlight the strong coupling between viscous and interfacial effects in determining the breakup dynamics of confined droplets. Wang et al. [129] investigate the transportation behaviors of double emulsion droplets in symmetric microfluidic Y and T-junctions. The dynamics of the interface evolution in different patterns (i.e., No Breakup (NB), Outer droplet Breakup (OB), and Both droplet Breakup (BB)) are analyzed, revealing the influence of the core droplet on the breakup threshold and the asymmetric breakup. A geometric model is proposed to estimate the maximum extension length, which helps explain the different breakup behaviors in T-junctions and Y-junctions. Two thread pinch-off regimes are identified, with the Y-junction favoring smaller and fewer satellite droplets compared to the T-junction. Lemeski et al. [130] investigated the influence of triangular microchannel obstructions on droplet breakup dynamics by examining two configurations: Case I, with the obstacle positioned at the bifurcation center, and Case II, with the obstacle aligned along the main flow direction. The results revealed that droplet breakup occurs more rapidly when the triangular obstruction is located at the channel center due to enhanced local shear and pressure gradients. In contrast, the flow-aligned configuration governs whether the mother droplet undergoes asymmetric breakup into unequal daughter droplets or remains intact, depending on the imposed flow conditions. The study demonstrated that droplet deformation and breakup behavior are highly sensitive to both the geometric placement of the obstacle and the hydrodynamic parameters, establishing a clear correlation between obstruction topology and breakup regime transition.

The high surface-to-volume ratio inherent to microfluidic platforms amplifies the influence of channel walls on droplet behavior [131]. At the macroscopic scale, surface wettability governs macroscopic observables such as contact angle and spreading along solid interfaces. By contrast, at the microscale, additional interfacial effects emerge, most notably wall slip, which modifies near-wall momentum transfer and, in turn, affects the onset and stability of droplet dynamics [132–135]. Early investigations primarily emphasized wettability as a controlling factor in droplet splitting at T-junctions, highlighting the sensitivity of droplet dynamics to contact angle variations [43]. More recent studies have shifted attention toward wall slip [132,133,135], described as the occurrence of a finite tangential velocity at solid–liquid boundaries. This deviation from the classical no-slip assumption alters velocity gradients, reshapes local shear fields, and consequently regulates droplet formation, elongation, and transport. The long-standing assumption of a universal no-slip condition, while valid for most macroscopic flows, is increasingly questioned in micro- and nanoscale contexts [136–138]. Both theoretical analyses [139–141] and experimental measurements [142–144] now provide evidence for slip lengths ranging from nanometers to micrometers, with pronounced effects observed on hydrophobic and microstructured surfaces. This condition reduces frictional resistance, alters near-wall flow organization, and diminishes shear stress [138,142,143].

More recently, the scope has extended to multiphase microfluidics, where wall slip has been shown to significantly modify interfacial dynamics during droplet generation [132,133,135] and splitting [134,138]. Kumar and Pathak [134] numerically examined slip effects on droplet splitting in microfluidic T-junctions using a conservative two-phase level set method (see Figure 7). Varying slip length from **0.2** to **3 μm** , they showed that small slip lengths enhance wall resistance (see Figure 7I,II), delaying splitting as the droplet penetrates further into the daughter channel (see Figure 7III,IV). In contrast, larger slip lengths promote faster neck thinning, reduced splitting times, and a neck center shifted toward the junction inlet (see Figure 7III–VI). Moreover, the critical thresholds for splitting with obstruction, splitting with tunnel, and no-splitting regimes shift to higher droplet lengths with increasing slip, establishing slip length as a key parameter in governing splitting dynamics. These findings suggest that wettability and wall slip should be treated as coupled interfacial phenomena rather than independent boundary conditions, underscoring their central role in the design and optimization of microfluidic T-junction systems.

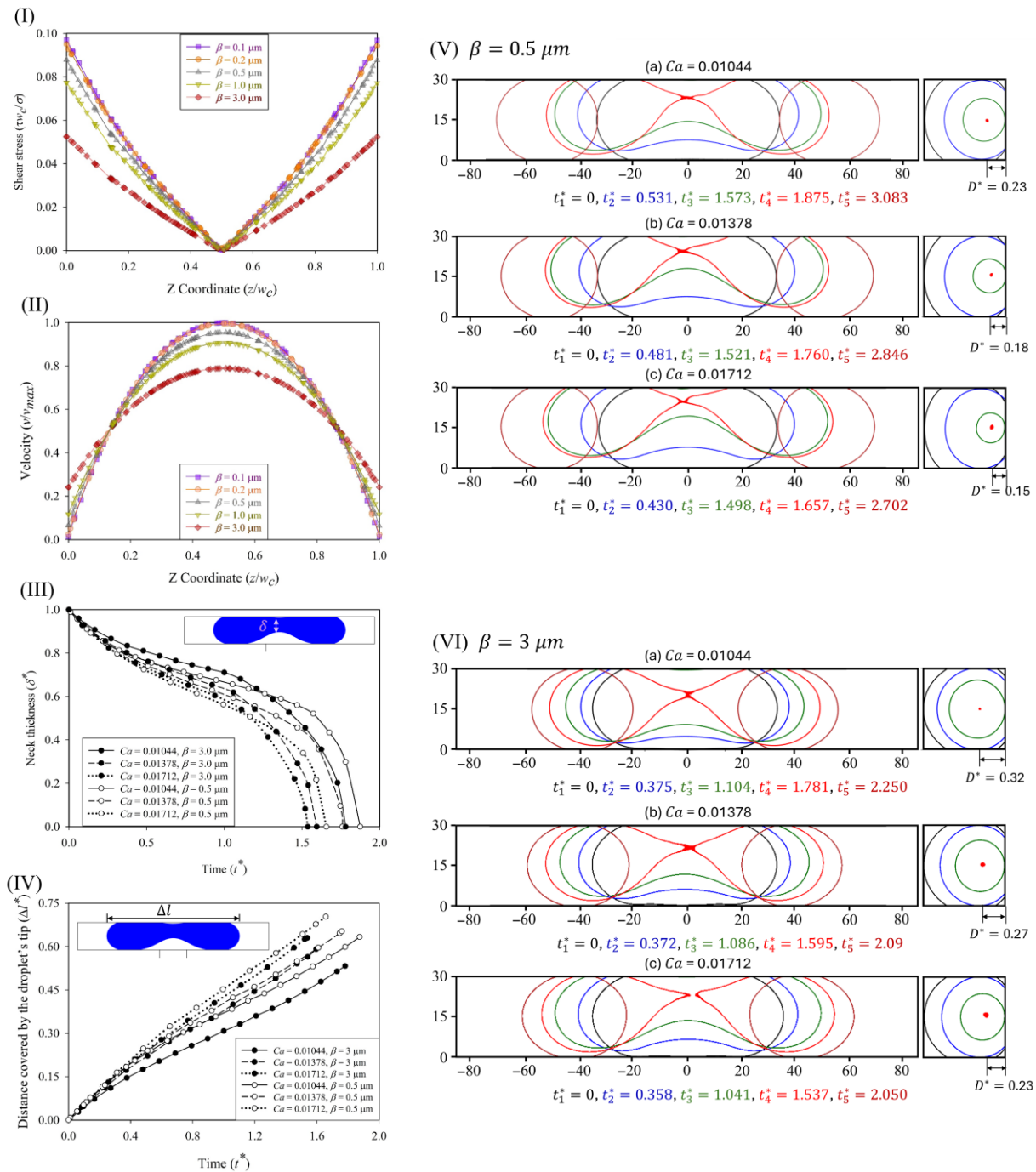


Figure 7. Velocity, shear stress, and interfacial evolution during tunnel-mediated droplet splitting in a microfluidic T-junction. (I) Velocity distribution and (II) shear stress distribution along the channel width, evaluated at $x = 400 \mu m$ and $y = 15$, for a droplet with $l_0/w_c = 2.345$, $Ca = 0.01044$, and $\lambda = 4.16$. (III) Evolution of the dimensionless neck thickness (δ^*) and (IV) the dimensionless distance traveled by the droplet tip (Δl^*) as functions of Capillary number (Ca) for two slip ($\beta = 0.5$ and $3 \mu m$) at $l_0/w_c = 2.345$ and $\lambda = 4.16$. (V,VI) The droplet profiles are analyzed at five key non-dimensional time instances [$t^* = (t - t_c) \times U/w_d$], denoted as follows: t_1^* marks the onset of the squeezing stage, t_2^* represents the last moment at which the droplet interface contacts both the top and bottom walls in Plane 2, t_3^* signifies the complete formation of a circular droplet interface in Plane 2, t_4^* indicates the instant of droplet splitting, marked by complete neck rupture, and t_5^* corresponds the post-splitting phase, characterized by the downstream motion and stabilization of the daughter droplets within the branch channels. Instantaneous droplet shapes during the squeezing stage of tunnel-mediated droplet splitting for different slip lengths: (V) $\beta = 0.5$

μm and (VI) ($\beta = 3 \mu\text{m}$, illustrating the influence of slip length and Capillary number on necking dynamics and interface deformation under identical geometric and fluid conditions $l_0/w_c = 2.345$ and $\lambda = 4.16$. Reproduced with permission from Kumar, Piyush, and Manabendra Pathak. *Physics of Fluids* 37.9 (2025). Copyright (2025) AIP Publishing [134].

4. Active Actuation Mechanisms

While passive droplet splitting in T-junctions relies solely on flow conditions and channel geometry, active droplet splitting introduces external fields to dynamically control the splitting process with greater precision and flexibility. This approach is particularly useful for applications requiring tunable droplet volumes, on-demand operation, or asymmetric splitting. Figure 8 schematically illustrates droplet formation in a microfluidic T-junction, where an initially formed droplet is subsequently regulated by active external actuation to control the splitting process. As the dispersed phase enters the junction, hydrodynamic shear and interfacial tension govern droplet growth and necking, leading to droplet formation in the passive regime. Superimposed active actuation (such as electric, acoustic, thermal, or pneumatic fields) locally modifies the force balance at the interface, enabling dynamic regulation of droplet deformation, breakup onset, and daughter droplet size. The combined passive and active mechanism provide enhanced control, repeatability, and adaptability of droplet splitting compared to purely geometry-driven approaches. Among the most widely used active methods is electrical actuation, where electric fields typically through electrowetting or dielectrophoresis alter the interfacial tension or exert directional forces on the droplet, thereby influencing its deformation and division at the junction. Thermal actuation, using localized heating elements, induces thermocapillary flows that can asymmetrically alter viscosity or surface tension across the droplet interface, steering it preferentially into one outlet channel. Similarly, magnetic actuation, often involving magnetic nanoparticles within the droplet, enables selective manipulation via external magnetic fields, offering a contactless and biocompatible method for splitting control. In addition, acoustic actuation using surface acoustic waves (SAWs) can induce localized pressure gradients that deform droplets or modify the flow field, enabling precise modulation of the splitting point. Pneumatic and mechanical actuators, such as on-chip valves or deformable membranes, can dynamically adjust local flow resistance, diverting portions of the droplet into desired branches at the T-junction. These active methods provide enhanced functionality compared to passive systems by enabling real-time, programmable control over droplet volume ratios, timing, and pathway selection. Moreover, combining active splitting with real-time feedback (e.g., from optical sensors) paves the way for intelligent droplet operations in complex microfluidic workflows. However, integration of active components often adds to system complexity and fabrication requirements, which must be balanced against the desired level of control. Despite these challenges, active droplet splitting has become a cornerstone for applications in adaptive diagnostics, single-cell assays, and automated high-throughput screening.

Hybrid actuation-based droplet generation and splitting in microfluidic T-junctions leverages the complementary strengths of both passive and active mechanisms to achieve enhanced control, robustness, and operational flexibility (see Figure 8). In these systems, passive hydrodynamic effects governed by channel geometry, flow-rate ratios, viscous stresses, and interfacial tension, establish the fundamental droplet formation and breakup behavior. Active actuation methods, such as electric (electrowetting or dielectrophoresis), magnetic, acoustic, or thermal fields, are then superimposed to dynamically modulate interfacial forces or local pressure fields. This combined influence enables precise tuning of droplet size, splitting symmetry, breakup timing, and frequency, even under varying flow conditions. Hybrid actuation is particularly advantageous in overcoming the limitations of purely passive systems, such as sensitivity to flow fluctuations, and purely active

systems, which may require higher energy input or complex control. By synergistically integrating passive and active effects, hybrid strategies enable wider operating regimes, improved repeatability, and on-demand droplet manipulation, making them highly attractive for advanced lab-on-a-chip applications, including biochemical assays, cell handling, and adaptive microfluidic platforms.

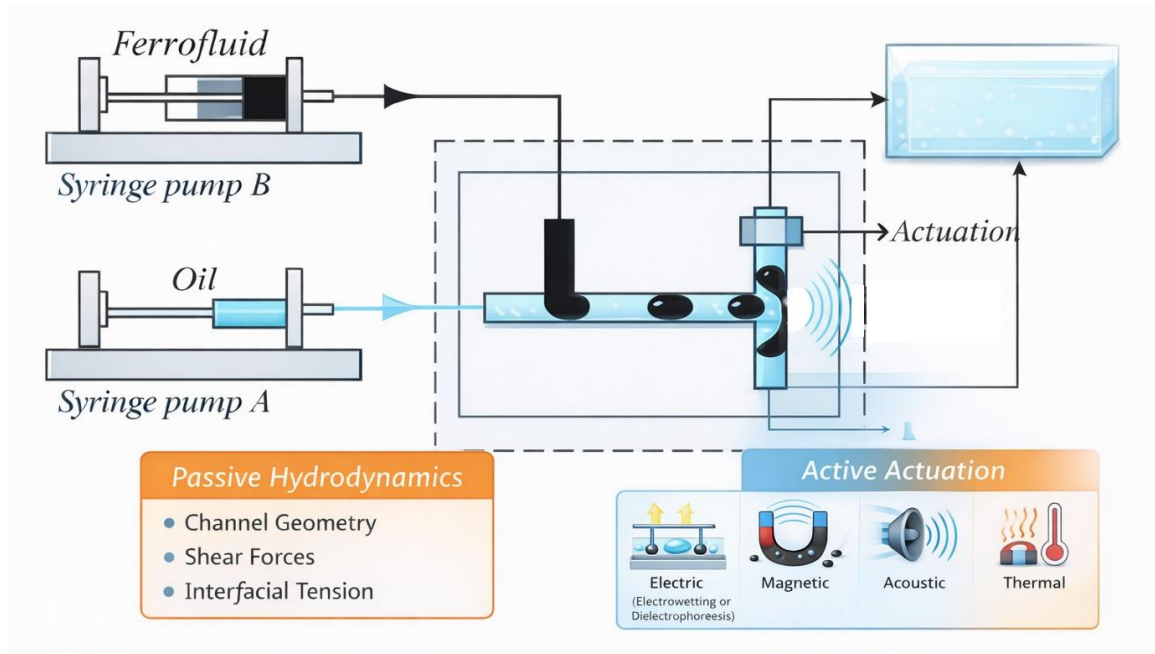


Figure 8. Schematic illustration of passive flow-driven droplet formation at a T-junction combined with localized active actuation to control the droplet splitting behavior.

4.1. Electric Actuation

Several studies have demonstrated that applying an electric field is a robust and fast method for actively controlling droplet behavior in microfluidic devices, often outperforming other actuation strategies in terms of responsiveness and precision [64,78,79,145–153]. Link et al. [145] were among the first to experimentally validate the efficacy of electric fields in manipulating droplet breakup, sorting, and coalescence within a symmetric T-junction microchannel. By applying an electric field parallel to the flow direction downstream of the junction, they showed that the breakup dynamics could be significantly influenced in a controlled manner. Building on this, Jafari and Fallah [78] conducted numerical simulations to investigate the effect of electric fields on droplet splitting in symmetric T-junctions. Their results confirmed that droplets split faster in the presence of an electric field compared to identical conditions without the field, highlighting the role of electric stresses in accelerating interfacial deformation and pinch-off. In flow-focusing geometries, Yin et al. [146] applied an alternating current (AC) electric field to regulate droplet formation and observed that the frequency of the electric signal directly impacted the transition between different droplet formation regimes. Similarly, Hatami et al. [147] numerically modeled droplet dynamics in flow-focusing devices under electric actuation, offering insights into droplet generation mechanisms under different electrical conditions. Xi et al. [79] conducted an experimental investigation into the deformation behavior of droplets under the influence of an alternating current (AC) electric field in a microfluidic device. Their study revealed that droplet deformation increases almost linearly with the intensity of the applied electric field, indicating a direct relationship between the electric stress imposed on the interface and the degree of deformation. Furthermore, they observed that higher frequencies of the AC electric field lead to stronger deformation,

suggesting that both amplitude and frequency contribute synergistically to the droplet's interfacial dynamics. Notably, the study demonstrated that droplets could be reversibly and repeatedly deformed using an amplitude-modulated (AM) AC signal, offering a novel method for non-invasive, tunable, and dynamic control over droplet morphology without requiring physical contact or permanent channel modifications. This ability to induce controlled deformation through AM signals introduces opportunities for cyclical droplet manipulation, which can be useful in processes such as on-demand droplet re-shaping, fusion preparation, or volume control prior to splitting in complex microfluidic workflows. Fallah and Fattahi [64] investigated the motion and breakup behavior of droplets in an asymmetric T-junction microchannel under the influence of an asymmetrically applied electric field using the Level Set Method implemented in COMSOL Multiphysics. Their work systematically explored the effects of key dimensionless parameters, including the non-dimensional droplet length (L^*), Capillary number (Ca), and electric Capillary number (Ca_e), on the droplet splitting process. The study revealed that the application of an asymmetric electric field significantly modifies the flow dynamics and splitting behavior, resulting in unequal daughter droplets, where a departure from the symmetric splitting typically observed in passive T-junctions. Notably, they identified two novel flow regimes: the Hybrid Asymmetric Splitting Mode (HASM) and electric-field-induced sorting patterns that emerge specifically due to the asymmetric actuation. These patterns suggest that electric fields can be used not only to control droplet size but also to selectively direct droplets into preferred branches, enabling programmable droplet routing. Furthermore, their results identified the existence of a critical electric Capillary number, referred to as the sorting electric Capillary number, above which the droplet enters a non-splitting (NS) regime. This threshold behavior underscores the importance of balancing electrical and hydrodynamic forces to achieve desired splitting outcomes. Zhu et al. [148] describe how the electric field force can manipulate the balance of the forces and enable the transitions between the flow regimes. Higher electric field strength can accelerate the breakup of the discrete phase, transitioning the flow from jet to drip or even slug. Additionally, the electric field force can cause the discrete phase to block the channel, transitioning the flow from parallel to slug. Table 3 presents a comparative summary of electric field-based actuation strategies for droplet control in microfluidic devices, outlining the employed geometries, electric field type, and key operating parameters, along with a short description of the main findings involving droplet deformation, breakup and splitting.

Table 3. Summary of Electric Actuation Methods for Droplet Control in Microfluidic Devices.

Reference	Methodology	Geometry	Electric Field Type	Key Parameters	Main Findings
Fallah et al. [64]	Numerical	T-Junction	DC (Asymmetric)	- Capillary Number. - Length of mother droplet. - Electric capillary number.	Demonstrated precise control over droplet size and splitting ratio can be achieved by tuning the electric field strength. Showed hybrid asymmetric splitting and droplet sorting.
Jafari et al. [78]	Numerical	T-Junction	DC	- Droplet length. - Electric capillary number. - Permittivity ratio.	Confirmed droplet splitting under electric fields. Showed electric stresses accelerate interfacial deformation and pinch-off compared to passive cases.
Xi. et al. [79]	Experimental	Main Channel	AC	- Field Intensity - Frequency - Modulation amplitude	Droplets can undergo repeated, controllable deformation using an amplitude modulated (AM) electric signal. Deformation of the droplet increases with an increase in electric field intensity and frequency.

Link et al. [145]	Experimental T-Junction	DC (Parallel to flow)	• Electric field strength	A charged-droplet, electric-fields platform enables precise droplet generation, coalescence, breakup, recharging, and sorting.
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4.2. Magnetic Actuation

Magnetic fields are actively used in micro-magnetofluidics as a powerful tool to manipulate ferrofluid microdroplet generation [87,154,155], splitting, and manipulation within T-junction geometries [88]. Ferrofluids respond to magnetic fields with controllable deformation and motion, enabling precise control over the droplet's breakup dynamics. Magnetic fields offer a significant advantage as they do not alter the chemical environment of the fluids, and ferrofluids respond faster with reversible magnetization. The main purpose of applying magnetic fields is to control the droplets splitting asymmetrically without altering the microchannel's geometry or the fluid's properties. Traditional passive splitting methods in symmetric T-junctions only produce splitting ratios of 1 (non-breakup) or 0.5 (symmetric breakup) due to symmetric flow resistance. Introducing an asymmetric magnetic field generates a volumetric magnetic force that leads the droplet towards one branch, rather than the other. This allows for asymmetric breakup with a controllable splitting ratio between 0.5 and 1 [89,156,157].

The dominant forces governing ferrofluid droplet dynamics include inertia, surface tension, and magnetic forces. The magnetic volumetric force $\vec{f}$ exerted on the droplet is described as

$$\vec{f} = \mu_0 \vec{M} \cdot \nabla \vec{H} \quad (6)$$

In which μ_0 represents the magnetic permeability, $\vec{M} = \chi_m \vec{H}$ is the magnetic vector, and $\vec{H}$ is the magnetic field strength [156,157]. The behavior of the droplet's splitting is characterized by two main dimensionless parameters, Capillary number ($C_a = \frac{\mu_c v}{\sigma}$) which represents the ratio of viscous to surface tension forces and Magnetic Bond number ($B_o = \frac{\mu_0 W H}{\sigma}$) that represents the ratio of magnetic to surface tension forces [156,157].

Some have investigated ferrofluid droplet breakup under steady magnetic fields [89,158], in which three main types of breakup regimes are observed. Breakup with permanent obstruction (BPO), where the droplet completely blocks both branches until it splits asymmetrically; Breakup with temporary obstruction (BTO), where small tunnels form between the droplet and the branch's wall after an obstruction and before full asymmetrical splitting; Breakup without obstruction (BNO), where the continuous phase fluid flows uninterruptedly before, during and after the asymmetric splitting of the droplet. Under a uniform magnetic field, the splitting with temporary obstruction (BTO) region expands toward the splitting with permanent obstruction (BPO) regime, resulting in an extended splitting duration [89]. The splitting frequency can be effectively tuned by varying the strength of the applied magnetic force [67,89,159]. In contrast, when a non-uniform magnetic field is applied, the droplet divides into two daughter droplets of unequal sizes. Increasing the magnetic field gradient amplifies the asymmetry in the splitting process, whereas higher total flow rates or shorter droplet spacing diminish the magnetic field's influence [89]. Additionally, the presence of a non-uniform magnetic field promotes the transition toward non-breakup behavior, stabilizing the droplet against division [89]. Li et al. [71] numerically investigated the magnetically induced control of ferrofluid droplet breakup in a symmetric Y-junction microchannel. The study demonstrated that applying an external magnetic field enables selective manipulation of droplet trajectories, facilitating asymmetric breakup or controlled redirection of the mother droplet into a desired branch for separation from satellite droplets. Systematic analyses of cases with and without magnetic fields revealed that both the flow rate ratio between the continuous and dispersed phases and the magnetic flux density significantly influence daughter droplet

sizes. The magnetic force was found to shift the droplet's mass center upstream, promoting asymmetric breakup downstream. A power-law correlation incorporating the magnetic Bond number (Bo_m) was proposed to predict daughter droplet size

$$\frac{V_u}{V_l} = 1 + 0.05 \left(\frac{Q_d}{Q_c} \right)^{-0.95} Ca^{0.06} Bo_m^{0.38} \quad (7)$$

confirming that controlled magnetic actuation can effectively induce transitions between breakup and non-breakup regimes.

Leshansky and Pismen [48] formulated a correlation defining the critical boundary between droplet splitting and non-splitting regimes in the absence of magnetic effects, expressed as

$$L_c/W = 1.3 Ca^{-0.21} \quad (8)$$

Subsequently, Aboutalebi et al. [157] incorporated magnetic interactions into this framework, extending the empirical relation to include the influence of magnetic stresses via the magnetic Bond number (Bo), thereby refining the predictive capability of the model for magnetically actuated microfluidic systems,

$$\frac{L_c}{W} = 1.3 Ca^{-0.21} + 0.011 Bo^{0.21} Ca^{-1.23} \quad (9)$$

Ma et al. [158] investigated the splitting dynamics of ferrofluid droplets in a microfluidic T-junction under an external magnetic field. Three distinct breakup modes were identified: splitting with permanent obstruction, splitting with partial obstruction, and splitting without obstruction. For the first two modes, the splitting process was divided into three stages: squeezing, transition, and pinch-off, whereas the splitting without obstruction involved only the latter two stages, following similar dynamic trends. The minimum neck width (δ) in each stage (i.e., Squeezing ($1 - \delta/w_c \propto t^\alpha$) and during the transition and pinch-off ($\delta \propto t^{\beta,\gamma}$)) was found to scale with time through power-law relationships, characterized by stage-dependent exponents. The influence of the magnetic field manifested primarily in the variation in these exponents: during the squeezing stage, the exponent decreased with increasing flow rate but increased with higher magnetic flux density; during the transition stage, it increased with both flow rate and magnetic field strength. Additionally, for partial and non-obstructed splitting, the pinch-off exponent increased with magnetic flux density. Overall, the results demonstrated that magnetic forces accelerate droplet splitting by modulating interfacial stress and thinning dynamics. Bijarchi et al. [67] conducted a numerical investigation of ferrofluid droplet splitting in a T-junction microchannel subjected to an asymmetric Pulse-Width-Modulated (PWM) magnetic field. Unlike steady magnetic fields, the PWM magnetic field enabled enhanced control over droplet breakup behavior and revealed two previously unreported splitting regimes: Flowing through the Same Branch (FSB) and Double Splitting (DS). In the FSB regime, both daughter droplets exit through the same outlet branch, whereas in the DS regime, the parent droplet undergoes sequential fragmentation, producing three daughter droplets. The application of a PWM magnetic field effectively mitigated the issue of daughter droplet trapping, a common limitation under steady magnetic actuation. The trapped and escaped regions were systematically characterized as functions of the duty cycle and the dimensionless magnetic field frequency. Results further demonstrated that the droplet splitting ratio increases with higher magnetic Bond numbers or duty cycles and decreases with increasing magnetic field frequency, underscoring the tunability of droplet dynamics through magnetic field modulation. Shyam et al. [159] performed a numerical investigation of ferrofluid droplet breakup in a T-junction microchannel of a lab-on-a-chip (LOC) system subjected to a non-uniform magnetic field, focusing on the breakup with permanent obstruction regime (see Figure 9). The analysis showed that the magnetic field

gradient induces an asymmetric internal flow, where a hump-like feature forms within the left-moving portion of the droplet, intensifying internal circulation and promoting deformation (see Figure 9). The breakup characteristics were primarily governed by the magnetic Bond number (Bo_m) and the flow rate ratio ($R = Q_c/Q_d$). A critical magnetic Bond number ($Bo_{m,crt}$) and a threshold flow ratio (R_{crt}) were identified, corresponding to the maximum normalized droplet length (l_f^*) in the left branch. When these parameters exceeded their critical values, the left droplet length decreased due to altered flow resistance. A detailed time-scale analysis revealed that magnetic field non-uniformity reduces the local flow time in the left branch, leading to asymmetric breakup. At $Bo_{m,crt}$, the left-branch droplet length increased by nearly 33% compared to the case without magnetic influence, highlighting the significant impact of spatial magnetic field variations on ferrofluid droplet dynamics.

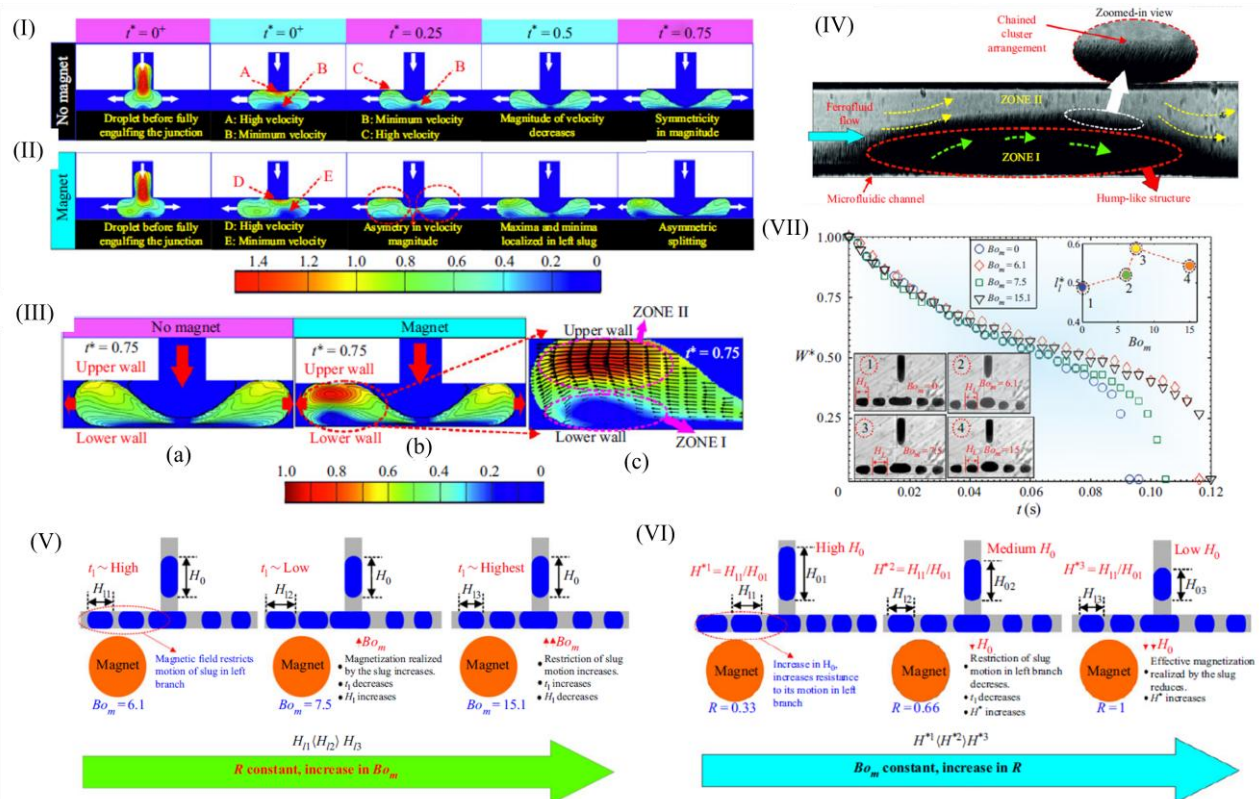


Figure 9. Influence of a non-uniform magnetic field on droplet splitting dynamics in a microfluidic T-junction. **(I,II)** Temporal evolution of droplet deformation and velocity magnitude during the splitting process obtained from numerical simulations **(I)** without a magnetic field and **(II)** with a non-uniform magnetic field. Color contours indicate velocity magnitude, highlighting changes in flow symmetry, velocity distribution, and droplet deformation induced by magnetic actuation. **(III)** Magnified visualization at $t^* = 0.75$ comparing **(a)** the case without a magnetic field and **(b)** the case with a magnetic field. **(c)** Enlarged view of the region marked by the red ellipse, where black arrows denote local velocity vectors, illustrating the redistribution of flow and enhanced asymmetry under magnetic influence. **(IV)** Experimental visualization of a hump-like deformation formed in the ferrofluid region when subjected to a static magnet. The inset shows the formation of chained magnetic nanoparticle structures within the hump. Yellow and red dotted arrows indicate flow motion in Zone I and Zone II, respectively, demonstrating magnetically induced flow redistribution within the microchannel. **(V)** Schematic illustration of droplet splitting behavior for a constant flow rate ratio (R) with increasing magnetic Bond number (Bo_m), showing enhanced magnetic forcing and its effect on droplet deformation and breakup. **(VI)** Schematic illustration of droplet splitting behavior for a constant magnetic Bond number (Bo_m), with increasing flow rate ratio (R)

highlighting the competing roles of hydrodynamic and magnetic forces. (VII) Temporal evolution of the normalized droplet neck width (W^*) for different magnetic Bond numbers, demonstrating accelerated neck thinning with increasing magnetic field strength. The upper-right inset shows the evolution of the normalized daughter-droplet length in the left branch under varying magnetic field intensities, while the lower-left inset (labeled 1–4) presents corresponding droplet morphologies at selected time instants. Reproduced with permission from Shyam, Sudip, Bhavesh Dhapola, and Pranab Kumar Mondal, *Journal of Fluid Mechanics* 944 (2022). Copyright (2022) Cambridge University Press [159].

Outokesh et al. [160] propose and develop a new numerical model for in-droplet manipulation of high-concentration magnetic particles in an integrated microfluidic system. The system consists of three modules: generator, spacer, and splitter. The model considers various interactions, including particle-magnet, particle-particle, and particle-droplet interface. The results show that although the presence of an external magnetic force can improve the separation/enrichment of magnetic particles, the magnet's location must be carefully determined to avoid the inverse effect on the separation/enrichment efficiency. A magnetic to drag force ratio of $> 0.8\%$ and a magnetic velocity to the mean fluid velocity ratio of $> 6\%$ resulted in almost full separation for both $2.83 \mu\text{m}$ and $4.4 \mu\text{m}$ magnetic beads. Naseri et al. [73] conducted a numerical analysis of droplet splitting within a symmetric Y-junction under a uniform magnetic field. The study revealed that applying a magnetic field significantly accelerates the breakup of the parent droplet relative to non-magnetic conditions. Additionally, the breakup time was found to decrease progressively with increasing magnetic Bond number, indicating a strong dependence of the fragmentation dynamics on magnetic field strength. Aboutalebi et al. [156] investigated the influence of an asymmetric magnetic field on droplet breakup dynamics in a symmetric T-junction and demonstrated the application of an asymmetric magnetic field alters both the splitting ratio and the critical boundary between splitting and non-splitting regimes. Under a constant magnetic field, larger mother droplets exhibit more symmetrical splitting behavior, with the breakup ratio approaching 0.5. Increasing the magnetic field intensity at the T-junction center further enhances asymmetry, resulting in higher splitting ratios and a greater likelihood of uneven droplet division. The presence of an asymmetric magnetic field also shifts the boundary between splitting and non-splitting regions upward in the nondimensional length and Ca parameter space. Moreover, a predictive correlation,

$$\frac{L_c}{W} = 1.3Ca^{-0.21} + 0.0003 \frac{WB_0^2}{\sigma\mu} Ca^{-0.46} \quad (10)$$

was established to quantify how variations in magnetic flux density modify this boundary behavior. Recently, Wu et al. [161] numerically analyzed the influence of magnetic field intensity and source positioning on ferrofluid droplet dynamics in a microfluidic T-junction, focusing on interface deformation, flow structure, splitting time, splitting frequency, and droplet size. The results showed that increasing the magnetic field strength up to 0.18 T did not significantly alter daughter droplet size but shortened the splitting time by approximately 30% . Beyond this threshold, as the field intensity increased to 0.6 T , the generated droplet size decreased, accompanied by a notable rise in pressure drop across the microchannel following each breakup event. In the lower magnetic field range ($0 - 0.18 \text{ T}$), the pressure and pressure drop remained nearly unchanged during droplet movement and post-splitting stages. Pressure field analysis revealed a pronounced pressure drop and elevated velocity gradient at the splitting point, with the affected region extending further along the main channel under stronger magnetic fields. Additionally, variations in magnetic source position under constant power demonstrated that

increasing the distance from the channel reduced the effective magnetic field strength; when the separation reached **750 μm** , magnetic influence on the splitting process became negligible. Table 4 summarizes previously mentioned studies utilizing magnetic actuation for droplet control, highlighting the microchannel geometry, magnetic field configuration, and governing parameters employed, along with main findings on ferrofluid droplet's response. Overall, the use of asymmetric magnetic fields in T-junction microfluidic systems provides an innovative, non-invasive method for actively controlling ferrofluid microdroplet splitting. By controlling a magnetic field strength and flow conditions, the manipulation of precise splitting ratio can be achieved without altering the devices geometrically, or the chemical structure of the fluid [141]. Steady fields provide a fundamental insight but have some droplet trapping and limited flexibility. PWM fields overcome these limitations by dynamically altering field applications, introducing new splitting regimes. Non-uniform fields extend control by enabling asymmetric and branch-specific droplet sizing [141]. The integration of these methods establishes some magnetic control as a versatile strategy for microfluidic systems, especially in some biomedical and diagnostic applications where precision and adaptability are essential.

Table 4. Summary of Magnetic Actuation Methods for Ferrofluid Droplet Splitting and Manipulation in Microfluidic Devices.

Reference	Methodology	Geometry	Magnetic Field Type	Key Parameters	Main Findings
Wu et al. [89]	Experimental	T-Junction	Uniform and non-uniform	- Flow rate - Magnetic flux density	Magnetic fields actively control ferrofluid droplet breakup and frequency. Breakup asymmetry depends on magnetic strength and flow conditions. Non-uniform fields can bias droplets to suppress breakup.
Aboutalebi et al. [157]	Numerical	T-Junction	Non-uniform	- Capillary number - Length of droplet - Magnetic bond number	Magnetic-field control enables precise tuning of droplet splitting ratio and size, with stronger fields promoting asymmetric splitting and higher splitting ratios. A predictive correlation based on Magnetic Bond number accurately defines the boundary between splitting and non-splitting regimes.
Ma et al. [158]	Experimental	T-Junction	Uniform	- Magnetic flux density - Flow rate	Three breakup modes with stage-wise dynamics (Squeezing, transition, pinch-off) were generated. Showed magnetic field alters power-law scaling exponents and accelerates breakup.
Shyam et al. [159]	Numerical	T-Junction	Non-Uniform	- Magnetic Bond number - Flow ratio	The asymmetric magnetic force creates a flow hump and increases convection inside the droplet, driving asymmetric splitting into two differently sized sister droplets. At critical Magnetic Bond number, a larger droplet is produced, showing how magnetic force gradient can independently control droplet size.

4.3. Thermal Actuation

Control of droplet through the induced thermocapillary effect has recently attracted significant attention due to its non-invasive and multifunctional characteristics [19,83,84,162,163]. Thermal actuation approaches comprising mechanical [164], optical [86], and acoustic heating [165] operate by inducing localized temperature gradients that alter droplet motion and interfacial behavior within microchannels. In mechanical heating [164], integrated microheaters or Joule heating elements are employed to deliver controlled, localized thermal energy directly to the working fluid. Optical heating [86] utilizes focused laser irradiation to achieve non-contact, spatially confined temperature modulation, allowing for precise control of droplet position and deformation. In acoustic heating [165], surface acoustic waves (SAWs) generated by interdigitated transducers (IDTs) transfer energy through a thin substrate layer, producing localized heating within the fluidic domain. These thermally driven methods have demonstrated efficacy in droplet formation [27,132,166], sorting, fusion, and trapping processes [19,83,84]. Nonetheless, their application in droplet splitting remains constrained by the potential for thermal stress and degradation of thermally sensitive biological or chemical species at elevated temperatures. Thermocapillarity arises from the temperature-induced surface tension gradient, which strongly influences the fluid dynamics of liquid interfaces [83]. Depending on the relative orientation of the temperature gradient to the liquid interface, various forms of instabilities may develop [83]. When the temperature gradient is oriented perpendicular to the interface, thermocapillary instabilities manifest as Marangoni convection, which can further be classified into linear or nonlinear steady states. In such cases, the resulting surface tension gradients along the interface serve as a driving mechanism for droplet actuation.

Thermally mediated droplet breakup within a T-junction microchannel is strongly influenced by the combined effects of viscosity, surface tension and wettability [27,85,167]. The temperature difference between the heated branch and the reference state modifies the interfacial tension ($\sigma = \sigma_0 e^{-0.0144\Delta T}$) and viscosities of the continuous ($\mu_c = \mu_{c0} e^{-0.0344\Delta T}$) and dispersed phases represented by,

$$\mu_d = \mu_{d0}(1 - 2.55 \times 10^{-2}\Delta T + 6 \times 10^{-4}\Delta T^2 - 9 \times 10^{-6}\Delta T^3) \quad (11)$$

according to its empirical relationship with the effects previously mentioned [167], where $\Delta T = T - T_0$ represent the temperature rise above the reference temperature T_0 . These thermal effects govern the relative breakage of daughter droplets at the junction [132,166,168], the dependencies demonstrate that viscosity decreases significantly with temperature rather than with interfacial tension, delaying droplet splitting and leading to larger droplet volumes at elevated temperatures [169]. The interplay of inertial, viscous and interfacial forces is further characterized by using dimensionless groups such as the Reynolds number ($Re = \frac{\rho_c U_c D_h}{\mu_c}$), the Capillary number ($Ca = \frac{\mu_c U_c}{\sigma}$) and the Marangoni number,

$$Ma = \frac{(\frac{\partial \sigma}{\partial T}) \Delta T D_h}{\mu_c \alpha_c} \quad (12)$$

where $\sigma_T = \partial \sigma / \partial T$ is the surface tension gradient and α_c is the thermal diffusivity of the continuous phase [168,170].

Ting et al. [167] and Yap et al. [171] demonstrated the effectiveness of thermal actuation as a precise mechanism for droplet manipulation at microfluidic bifurcations. By imposing localized temperature gradients, thermocapillary forces were induced, leading to controlled variations in interfacial tension and flow resistance between branches. Ting et al. highlighted that increasing the branch temperature from 27 °C to 40 °C transitioned the droplet behavior from passive splitting to complete sorting, while Yap et al. showed

that the combined influence of thermocapillarity and reduced hydraulic resistance directed droplets toward the heated branch. Collectively, these studies establish thermal control as a robust and tunable method for achieving droplet splitting, sorting, and switching within microfluidic T-junctions. Simulations performed by Nath et al. [170] and Hoa et al. [169] demonstrate that increasing single-sided heater temperature enhances the thermocapillary force, hence biasing droplet splitting towards the heated branch. However, at critical temperatures, asymmetric or even non-splitting regimes emerge due to dominant viscosity reduction and strong interfacial gradient. On the other hand, double-sided heating generates a more uniform field, enhancing thermal penetration and producing larger, more symmetric droplets. Each research shows that thermal actuation serves not only to bias droplet splitting, but also to actively control size and detachment timing, underscoring its potential for tunable and non-invasive droplet manipulation in microfluidics. Further, Nath et al. [170] simulated the effect of wettability of the channel walls and temperature during the splitting. The interaction between the channel's walls and the fluids is described through the equilibrium contact angle θ ,

$$(\cos\theta = \frac{\sigma_{wc}-\sigma_{wd}}{\sigma}) \quad (13)$$

in which σ_{wc} , σ_{wd} and σ define the surface tension between the continuous and dispersed fluids and the wall, respectively. To capture how wall wettability influences the breakup dynamics, three conditions were considered, hydrophilic ($\theta = 78^\circ$), neutral ($\theta = 90^\circ$) and hydrophobic ($\theta = 150^\circ$). They observed that at a baseline of 25°C , the mother droplet splits symmetrically into two equal daughter droplets regardless of the wettability condition. However, as temperature increases, the interaction between thermocapillary forces and viscous reduction affects the droplet splitting behavior. During hydrophilic conditions and higher temperatures of 65°C , one branch pulls a larger volume of the mother droplet creating an asymmetric breakup. This asymmetric breakup happens under neutral wettability conditions and hydrophobic conditions as well, demonstrating that wettability combined with thermal gradients, can play a critical role in determining the asymmetry of droplet splitting and the flow distribution in microchannels. Thermal splitting of droplets offers a versatile and precise means of manipulating droplet behavior in microfluidic systems through localized temperature control. Table 5 provides an overview of thermally mediated droplet control approaches mentioned in the text, emphasizing heating placement, geometry of the channel, key parameters studied, and important findings on the impact of droplet formation regimes and breakup mechanisms.

While thermal methods enable high spatial and temporal control, their broader application remains limited by potential thermal damage to temperature-sensitive materials. Nevertheless, advancements in localized and transient heating technologies continue to enhance the feasibility of thermal splitting as a reliable and non-mechanical approach for droplet manipulation in lab-on-a-chip and bio-microfluidic platforms.

Table 5. Summary of Thermal Actuation Methods for Droplet Control in Microfluidic Devices.

Reference	Methodology	Geometry	Heating Mechanism	Key Parameters	Main Findings
Ting et al. [167]	Experimental	T-Junction	Single branch heating	- Surface tension gradient - Temperature difference	Demonstrated transition from passive symmetric splitting to complete droplet sorting due to thermocapillary forces created by localized heating.
Hoa et al. [169]	Numerical	T-Junction	Single branch heating	- Viscosity reduction - Interfacial tension - Temperature	Increased heater temperature enhances thermocapillary forces, but excessive heating suppresses splitting due to dominant viscosity reduction.

Nath et al. [170]	Numerical	T-Junction	Single- and double-sided heating	• Viscosity reduction • Marangoni number • Wettability	Higher thermal contrast drives asymmetric or non-splitting breakup. Wall wettability tuning enables precise control of daughter droplet size ratios.
Murshed et al. [171]	Experimental	T-Junction	Double-sided heating	• Flow resistance • Temperature gradient	Droplets preferentially migrate towards heated branches due to combined effects of thermocapillarity and reduced hydraulic resistance.

4.4. Acoustic Actuation

Among the active methods, acoustic actuation has emerged as one of the most versatile and biocompatible approaches due to its non-invasive nature, tunable energy application, and ability to handle delicate biological samples [80–82,172,173]. Acoustic methods rely on sound waves interacting with droplets, where oscillating pressure fields generate forces that deform, move, and eventually split droplets [81,82,173,174]. These forces can arise from acoustic radiation pressure [174], which directly pushes on the droplet interface, or from acoustic streaming, where micro-vortices induce shear stress that destabilize the droplets shape and promotes breakup. Depending on the operating configuration, these forces can be tuned to achieve control and repeated droplet splitting [173,174].

Two dominant acoustic approaches are employed in microfluidic systems: Surface Acoustic Waves (SAWs) [174–178] and Bulk Acoustic Waves (BAWs) [179,180]. SAWs are produced by interdigital transducers (IDTs) patterned on piezoelectric substrates such as lithium niobate (LiNbO₃). When radiofrequency (RF) signals are applied, the substrates generate surface waves that propagate along their boundary in the MHz range. When these waves encounter a droplet confined in a microchannel or resting on the substrate, part of their energy propagates into the fluid, producing localized deformations. Depending on the transducer configuration, three operational modes can be established: traveling SAWs, which exert unidirectional pressure to elongate and split droplets, standing SAWs, created by counter-propagating waves that establish periodic pressure nodes and antinodes to symmetrically pinch droplets, and focused SAWs, where curved IDTs concentrate energy at specific regions of the interface for spatially selective splitting [175–177,181]. The total acoustic radiation force $\mathbf{F}_{rad} = -\nabla U$ acting on a droplet can be expressed as the negative gradient of the Gor'kov potential

$$U = \frac{V}{2} (f_1 \frac{p^2}{\rho_0 c_0^2} - f_2 \rho_0 (v^2)) \quad (14)$$

where V is the droplet volume, p and v are the acoustic pressure and velocity amplitudes, ρ_0 is the fluid density, c_0 is the sound speed, and f_1, f_2 are the acoustic contrast factors dependent on the droplet's movement and deformation, with splitting occurring once the induced pressure gradient exceeds the restoring surface tension force [174].

In a study by Jung et al. [175], a PDMS microchannel was integrated with a slanted-finger interdigital transducer (SF-IDT) to generate a narrow SAW sound field capable of splitting droplets on-demand. The SAW beam applied directional acoustic radiation pressure that elongated droplets until breakage. By tuning the input power and flow rate, precise control over the daughter droplet's volume ratio and splitting location was shown, demonstrating accurate repeatability. The experiment also revealed that the degree of splitting is dependent on the droplet's alignment relative to the SAW field and channel's geometry, as small variations alter how the wave interacts with the droplet. The intensity of the applied acoustic field, which is governed by both voltage amplitude and frequency, plays an important role in determining droplet breakup dynamics in SAW-based devices.

Increasing the applied voltage enhances the acoustic pressure amplitude, this increases the acoustic radiation force and streaming velocity acting on the droplet's interface. At low voltages, the acoustic stress remains below the capillary restoring force, and droplets show deformation but not splitting (Park et al. [172]). When the voltage exceeds a critical level, the droplet's neck length decreases until pinch-off occurs (see Figure 10). In both studies, the transition between no breakup and breakup can be characterized by the dimensionless acoustic capillary number,

$$Ca_{ac} = \frac{\rho u_{ac}^2 D}{\sigma} \quad (15)$$

which compares the acoustic stress to surface tension force, where u_{ac} is the characteristic streaming velocity, D is the droplet diameter, and σ is the interfacial tension. Ca_{ac} increases with voltage as the induced streaming velocity increases. Experimental observations performed by Jung et al. [175] and Park et al. [172] show that droplet breakup occurs when Ca_{ac} passes its critical value. As applied voltage increases, breakup happens earlier along the droplet's trajectory, producing larger daughter droplets in the direction of acoustic propagation (see Figure 10) [172,174].

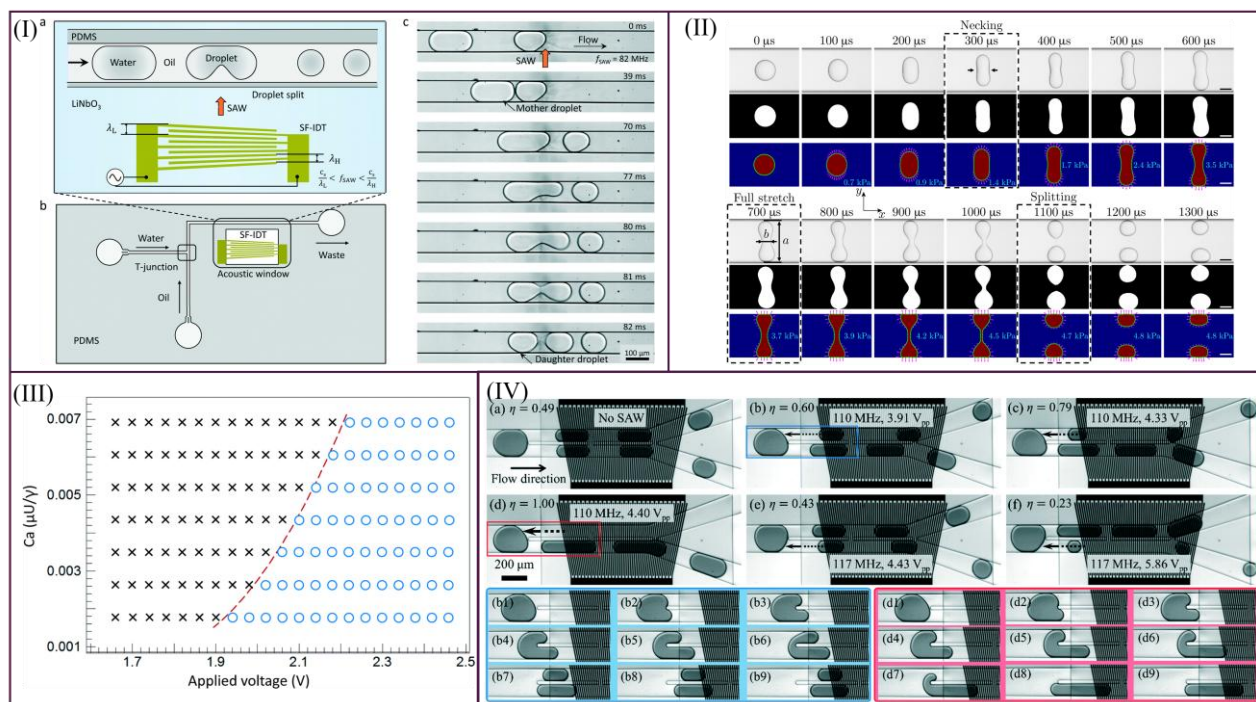


Figure 10. (I) (a) Schematic of the acoustofluidic droplet-splitting device, consisting of a PDMS microchannel and a slanted-finger interdigitated transducer (SF-IDT). The SF-IDT generates a narrow surface acoustic wave (SAW) beam at various frequencies (f_{SAW}) to divide droplets into two daughter droplets. (b) A water-in-oil droplet forms at the T-junction and is carried downstream to the SAW region for splitting; an acoustic window in the PDMS minimizes energy loss and enhances coupling into the fluid. (c) Experimental images of SAW-driven splitting at 82.5 MHz, where droplets move left to right and the SAW travels from bottom to top. The droplet splits within 50 ms at a flow rate of 100 μL·h⁻¹ and a SAW voltage of 2.19 V. Reproduced with the permission from J. H. Jung, G. Destgeer, B. Ha, J. Park and H. J. Sung, Lab on a Chip, 2016, 16, 3235. Copyright (2016) The Royal Society of Chemistry [175]. (II) Dynamic splitting sequence over 1.3 ms showing raw high-speed images (top), binarized images (middle), and simulations (bottom), with magenta arrows indicating acoustic radiation pressure and cyan shading indicating its magnitude. Necking, stretching, and final breakup occur at 300, 700, and 1100 μs. Experiments used 324 mW input power, and simulations matched the acoustic energy density in water (568.3 J m⁻³); scale bar = 100 μm.

Reproduced with the permission from Xu, Duo, Yongmao Pei, and Wei Qiu, Lab on a Chip (2025). Copyright (2025) The Royal Society of Chemistry [181]. (III) Regime diagram showing capillary number vs. applied voltage, where ‘o’ marks successful splitting and ‘x’ marks failures. Reproduced with the permission from J. H. Jung, G. Destgeer, B. Ha, J. Park and H. J. Sung, Lab on a Chip, 2016, 16, 3235. Copyright (2016) The Royal Society of Chemistry [175]. (IV) (a–f) Stacked microscopy images showing droplet bi-splitting and steering at different acoustic positions and amplitudes. (b1–b9) Time-lapse images (10 ms intervals) of asymmetric splitting from (b), and (d1–d9) time-lapse images (10 ms intervals) showing droplet steering into the lower branch in (d). Reproduced with the permission from J. Park, J. H. Jung, K. Park, G. Destgeer, H. Ahmed, R. Ahmad and H. J. Sung, Lab on a Chip, 18, 422, 2018. Copyright (2018) The Royal Society of Chemistry [172].

While SAWs provide excellent spatial precision and tunability, their influence is typically confined near the substrate surface. Bulk Acoustic Waves (BAWs), on the other hand, propagate through the substrate’s entire thickness and into the fluid domain, allowing for deeper penetration and uniform field generation within enclosed channels [179,180]. When droplets are exposed to standing BAW fields, they migrate toward pressure fields or antinodes depending on their acoustic impedance contrast. Once the acoustic pressure exceeds the Laplace pressure $\Delta P = 2\sigma/R$, the droplet interface becomes unstable and splits into smaller volumes. The interplay between viscous, inertial, and acoustic forces in these systems can be further represented by the acoustic Bond number,

$$Bo_{ac} = \frac{p_{ac}D}{\sigma} \quad (16)$$

where p_{ac} is the amplitude of acoustic pressure. As Bo_{ac} increases, the droplet undergoes a transition from stable deformation to breakup, similar to the transition observed in magnetically and thermally actuated systems. Increasing the applied voltage enhances the acoustic pressure amplitude and streaming velocity, this increasing Bo_{ac} and Ca_{ac} until the acoustic stresses exceeds surface tension. Adjusting the frequency or voltage allows for control over the splitting ratio, as observed by Park et al. [172]. This relationship can be described by the acoustic pressure amplitude,

$$p_{ac} = \rho_0 c_0 v_{ac} \quad (17)$$

where ρ_0 and c_0 represent the density and sound speed of the medium, and v_{ac} is the particle velocity proportional to the input voltage. As Bo_{ac} and p_{ac} increase, droplets undergo more pronounced deformations, moving from symmetric breakup to complex multibranch splitting.

In Standing BAW fields, droplets experience alternating compressive and tensile stresses that lead to migration, deformation and breakup depending on the balance between acoustic and interfacial forces. Numerical simulations performed by Thirisangu et al. [173] have shown that droplets move toward pressure nodes when acoustic stresses f_{ac} are smaller than interfacial stresses f_{σ} . However, as f_{ac} approaches or f_{σ} , significant deformations occur and droplets larger than half the acoustic wavelength ($\lambda/2$) may form multiple internal pressure nodes, leading to splitting. Experimental configuration plays a crucial role in determining the performance of both SAW and BAW devices. Factors such as the piezoelectric substrate’s orientation, IDT geometry, and the distance between droplet and transducer directly affect acoustic energy effects [173,174,181]. In closed channel BAW devices, reflection from channel walls can form complex standing waves patterns, influencing the droplets position and symmetry at breakup. In contrast, open surface SAW systems require precise droplet placement to ensure consistent interaction with the acoustic fields. Despite these challenges, both methods achieve remarkable controllability without physical contact, preserving contamination risks [81,82,172]. Table 6 provides a compilation of key studies on acoustic actuated droplet control in microfluidic systems,

emphasizing the channel geometry, acoustic actuation type employed and characteristic parameters that govern droplet deformation, manipulation and breakup response. In conclusion, acoustic actuation represents a powerful and adaptable technique for microfluidic droplet splitting. Surface acoustic waves provide unparalleled precision in localized droplet manipulation, while bulk acoustic waves extend control to enclosed and larger-scale channel systems. Together, these methods demonstrate how sound can be harnessed as a clean, contactless, and tunable tool for advancing droplet-based microfluidics in biomedical research, chemical processing, and material science.

Table 6. Summary of Acoustic Actuation for Droplet Splitting in Microfluidic Devices.

Reference	Methodology	Geometry	Acoustic Actuation Type	Key Parameters	Main Findings
Park et al. [172]	Experimental/Numerical	Microchannel	SAW	- Applied Voltage - Acoustic Capillary number	ON-demand multichannel droplet splitting was demonstrated with precise control of splitting ratios using TDM AC signals. Increased branch channels and disposable chips with a reusable substrate enhance systems flexibility, functionality and throughput.
Thirisangu et al. [173]	Numerical	Microchannel	BAW	- Acoustic Bond number - Acoustic force - Interfacial stress	After splitting the acoustic bond number further characterizes the deformation of the daughter droplets. As the relevant characteristic length and acoustic forces increase, the deformation and subsequent breakage of the mother droplet increase.
Park et al. [174]	Experimental	Microchannel	SAW	- Acoustic pressure - Streaming velocity	Hydraulic resistance modulation governs breakup location and symmetry. Droplet breakup transitions depend on capillary number and droplet length. Programmable microvalves outperform passive geometries in flexibility and control.
Jung et al. [175]	Experimental	Microchannel	SAW	- Voltage - Frequency - Flow rate	Demonstrated that the splitting size of the droplet could be controlled by varying the input voltage, and the balance between the acoustic gradient force and the drag force.

4.5. Pneumatic and Hydraulic Actuation (Valve-Controlled Channels)

Pneumatic and hydraulic actuation use pressure-driven valves to actively control how and where droplets split inside a microfluidic T-junction. Instead of relying solely on channel geometry and passive flow resistance, these valves reshape the channel in real time, changing the local hydraulic resistance and guiding droplets into symmetric or asymmetric breakup [182–186]. By adjusting actuation pressure, flow conditions, or valve timing, researchers can control the droplet's size, splitting ratios, and decide at which junction the mother droplet will split (see Figure 11I,II) [183,184,186]. This approach not only overcomes the limitations of passive designs, but also enables droplet division to be performed selectively, on-demand and at multiple sites within a system, an important

feature in multiplex reactions biochemistry and reagent routing. Some have used pneumatic microvalves embedded in polydimethylsiloxane (PDMS) devices establishing their capability to trigger droplet breakup or generation by applying pressure to deform thin channel membranes [182]. Pressurizing the valve chamber locally reduces the channel's cross-section, increasing the hydraulic resistance and altering the pressure distribution around the droplets approaching the junction [183–185]. This adjustment creates the conditions necessary for droplet pinching and subsequent breakup. Importantly, the breakup behavior could be activated in real-time, allowing for precise control over the mother droplet size, generation frequency and splitting ratio.

Hydraulic resistance plays an important role in valve-based splitting. For rectangular channels of width (w), height (h) and length (l), with a continuous phase viscosity (μ_c), the hydrodynamic resistance (R) can be approximated as:

$$R = \frac{12\mu_c l}{wh^3 \left(1 - 0.63 \frac{h}{w}\right)} \quad (18)$$

This relation allows for direct mapping of channel geometry to flow resistance, establishing a strong analogy with Ohm's law in electrical circuits [183,184]. Flow rate (Q) is analogous to current, pressure drop (ΔP) to voltage and resistance (R) to hydraulic obstruction [183]. Agnihotri et al. [183] used the resistive network approach to investigate splitting at multiple junctions beyond the droplet generator (see Figure 11III,IV). In conventional design, droplets consistently divided at the first junction but bypassed the following sites. By redesigning one branch into an expansion channel, the resistance balance was adjusted, producing comparable flow fields at consecutive junctions. When integrated with microvalves, this allowed for selective breakup at multiple sites, an essential feature for applications that require to guide droplet into different reaction chambers.

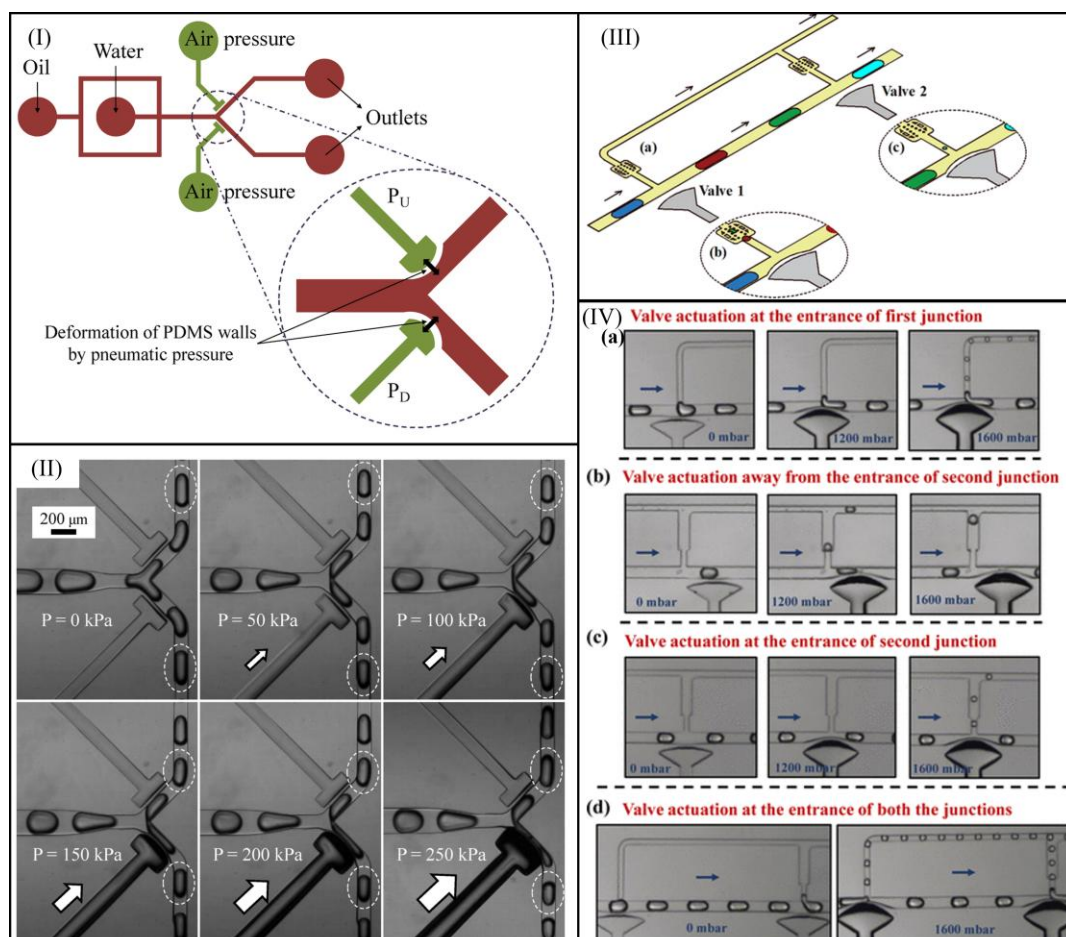


Figure 11. (I) Schematic representation of the complete microfluidic device incorporating a droplet-division section regulated by horizontally oriented pneumatic microvalves. The valves locally deform the channel ceiling to modulate flow resistance and induce controlled droplet breakup [186]. (II) Experimental visualization of droplet splitting during pneumatic valve actuation under equal flow-rate conditions of $Q_{\text{water}} = Q_{\text{oil}} = 2 \mu\text{L}/\text{min}^{-1}$, illustrating valve-induced deformation and subsequent droplet division [186]. (III) Conceptual illustration of selective droplet breakup using two independently actuated microvalves. (a) Mother droplets generated upstream travel along the main channel, and (b,c) pressurizing either valve produces localized constriction that selectively divides the droplet. The resulting smaller daughter droplets are directed into side branches for downstream operations such as merging or chemical reaction. Reproduced with the permission from Agnihotri, Sagar N. et al. *Langmuir* 36.5, 1138–1146 (2020). Copyright (2020) American Chemical Society [183]. (IV) High-speed microscopy images showing droplet behavior at two junctions under different valve-operation scenarios: (a) only the first valve actuated, (b) only the second valve actuated away from the junction entrance, (c) the second valve actuated at the junction entrance, and (d) both valves actuated simultaneously. These cases demonstrate the ability of pneumatic actuation to precisely control droplet splitting location, symmetry, and routing. Reproduced with the permission from Agnihotri, Sagar N., et al. *Langmuir* 36.5, 1138–1146 (2020). Copyright (2020) American Chemical Society [183].

For valve-controlled channels, the effective local capillarity is regulated not only by flow rate but also by pressure-induced deformation of the channel walls. In this way, valves can flexibly control the transition between non-breakup and breakup regimes without altering the channel's characteristics. Experimental visualization confirmed that pneumatic valves can accurately switch droplets splitting behavior between symmetric breakup, asymmetric breakup and no breakup regimes depending on the actuation pressure [182–186]. Some complex implementations extend the valve-controlled channels, the effective local capillarity is regulated not only by flow rate but also by pressure-induced deformation of the channel walls. In this way, valves can flexibly control the transition between non-breakup and breakup regimes without altering the channel's characteristics. Experimental visualization confirmed that pneumatic valves can accurately switch droplets splitting behavior between symmetric breakup, asymmetric breakup and no breakup regimes depending on the actuation pressure [182–186]. Some complex implementations extend the idea even further; Li et al. [187] integrated chips with arrays of pneumatic microvalves enabling modular droplet generation, selective splitting and droplet merging within the same system. Here, valves act as dynamic gates, guiding droplets into specific outlets or temporarily blocking the flow to induce asymmetric breakups. This integration allows for programmable droplet handling, making it possible to automate processes such as reagent delivery, dilution at microscales, and aliquoting. Compared to steady magnetic or thermal fields, pneumatic actuation provides a fast, reversible, and geometrically independent control method, though at the expense of added fabrication complexity and the need for external pressure controllers.

Furthermore, hydraulic actuation principles are supported by geometric studies of multifurcating channels (Li et al. [187]), where splitting behavior were analyzed in terms of capillary number and the dimensionless droplet length (ϵ_0). The transition from non-breakup to breakup regimes was shown to react to the increase in the critical capillary number following

$$Ca_{cr} = \alpha \epsilon_0^2 \left(\frac{1}{\epsilon_0^{2/3}} - 1 \right)^2 \quad (19)$$

where (α) depends on the viscosity and geometry. While this relation was derived from passive devices, an inference relation can be made that valves effectively manipulate the

same hydraulic resistance pathway that governs transitions, but in an adjusted, active manner. Moreover, Poiseuille’s law for laminar flow pressure drop ($\Delta p = \frac{8\mu L Q}{\pi R^4}$) demonstrates how altering the channels length or width, either physically or by valve compression, directly influences droplet sizing distribution between channels. Table 7 summarizes pneumatic actuation techniques previously used for droplet control, providing information on pressure modulation mechanisms, channel geometry and controlled parameters that enable on-demand droplet generation, splitting and size tunability, as well as some main findings on each individual investigation.

Pneumatic and hydraulic valve actuation offers high precision and flexibility for droplet splitting in microfluidic T-junctions. By actively modifying the channel resistance, these valves enable precise control over droplet breakup timing, location, and daughter droplet size. Unlike passive approaches, valve-based systems provide real-time, selective manipulation at multiple channel sites. Their compatibility with resistive system modeling also supports accurate prediction and optimization of droplet behavior. Although the use of external pneumatic controllers adds some system complexity, recent advancements in compact pressure regulation are mitigating these challenges. With ongoing improvements, valve-based designs are expected to play a key role in advancing programmable microfluidics, bridging the transition from passive devices to fully integrated droplet-control platforms.

Table 7. Summary of Pneumatic and Hydraulic Actuation Methods for Droplet Splitting in Microfluidic Devices.

Reference	Methodology	Geometry	Actuation Mechanisms	Key Parameters	Main Findings
Unger et al. [182]	Experimental	T-Junction	Pneumatic microvalves	- Actuation Pressure. - Membrane deformation	Demonstrated real-time triggering of droplet breakup via valve-induced channel constriction.
Agnihotri et al. [184]	Experimental	T-Junction	Pneumatic microvalves	- Actuation pressure - Flow rate	Showed controllable switching between symmetric, asymmetric, and non-splitting regimes on demand.
Raveshi et al. [185]	Experimental	T-Junction	Pressure-driven valve actuation	- Channel deformation - Capillarity	Demonstrated valve-controlled transition between breakup regimes without changing channel geometry.
Yoon et al. [186]	Experimental	T-Junction	Pneumatic valve timing	- Valve timing - Pressure	Enabled precise control over droplet size, breakup location, and splitting ratio through timed actuation.

4.6. Asymmetric Breakup

Asymmetric droplet breakup in T-junction microfluidic devices can arise not only from externally applied forces but also due to inherent physical asymmetries in channel geometry and pressure imbalances within the device itself. When the two outlet branches of a T-junction differ in length [44,188], the droplet experiences unequal hydrodynamic resistance during its transit, causing a pressure gradient that drives more fluid toward the shorter branch. This results in the formation of asymmetrically sized daughter droplets, with the smaller droplet typically forming in the channel offering higher resistance. Similarly, asymmetric branch widths introduce variations in cross-sectional area and local flow velocity, affecting the distribution of shear stress and interfacial tension on the droplet. A wider branch channel can accommodate a larger portion of the droplet volume, leading to unequal splitting ratios. In addition to geometric parameters, imposing different outlet pressures further enhances asymmetric splitting behavior. For example, applying a lower pressure at one outlet effectively “pulls” more of the droplet into that branch,

while a higher back-pressure on the opposite side resists flow, skewing the splitting point toward the high-resistance channel [65,118]. These effects can be intentionally exploited to control droplet volume ratios for downstream applications or must be carefully managed in systems where consistent, symmetric droplet division is required. Understanding the influence of these passive physical factors is critical for designing predictable and robust droplet manipulation schemes in T-junction-based microfluidic networks.

When the lengths of the outlet branches are unequal, the hydraulic resistance R of each branch differs significantly, as resistance in microchannels is governed by a modified form of Hagen–Poiseuille’s law, where $R \propto \frac{l}{wh^3}$ for rectangular channels (with l as length, w as width, and h as height). A longer branch thus offers greater resistance to flow, leading to pressure asymmetry across the droplet interface during splitting. This imbalance causes a larger volume of the dispersed phase to enter the shorter (lower resistance) branch, resulting in unequal daughter droplets. Similarly, when branch widths are unequal, the variation in cross-sectional area influences local shear stress and Laplace pressure gradients, which affect how the continuous phase shears the mother droplet. A wider branch provides lower viscous resistance and a larger space for the droplet to expand, which favors the flow of more volume into that branch during splitting. This can also reduce the local shear-induced breakup force in the narrower branch, leading to non-uniform pinch-off dynamics and asymmetric splitting outcomes.

Link et al. [44] proposed an analytical expression to predict the critical Capillary number (Ca_{cr}) required for droplet breakup in symmetric T-junctions as a function of the non-dimensional initial droplet length (L^*), given by:

$$Ca_{cr} = \psi L^* \left(L^{*\frac{2}{3}} - 1 \right)^2 \quad (20)$$

where ψ is a dimensionless constant dependent on the viscosity ratio (λ). To extend this model to more practical asymmetric configurations, Cheng et al. [2] developed a novel correlation accounting for unequal outlet lengths and pressure gradients, given by:

$$Ca_{cr} = \psi(\rho^*, \lambda, \zeta) L^* \left(L^{*\frac{2}{3}} - \zeta^{-\frac{1}{2}} \right)^2 \quad (21)$$

Here, $\psi(\rho^*, \lambda, \zeta)$ is an empirical parameter incorporating the density ratio ($\rho^* = \frac{\rho_d}{\rho_c}$), viscosity ratio (λ) and the geometric asymmetry (ζ), defined as the ratio of longer to shorter outlet branch lengths. The continuous phase viscosity has a strong effect on the breakup/non-breakup regime criteria. This extended correlation has shown strong predictive accuracy for determining breakup versus non-breakup regimes in axisymmetric T-junctions, providing valuable design insight for engineering droplet-splitting microfluidic systems.

In addition to geometrical factors, differences in outlet pressure can also profoundly affect droplet splitting [65]. Imposing lower pressure at one outlet effectively reduces the downstream pressure in that channel, which in turn increases the local pressure gradient across the droplet during its entry into the junction. This pressure imbalance accelerates the flow of the droplet toward the lower-pressure branch, creating a preferential flow path. On the other hand, higher outlet pressure opposes droplet movement, increasing the resistance in that arm and reducing the volume that enters it. At constant outlet pressure difference, the final splitting volume ratio is not influenced by flow rate ratio but also by initial droplet size, capillary number and viscosity ratio. As the initial droplet length increases, the breakup regime transitions from non-breakup to asymmetric breakup with tunnels, and finally to asymmetric breakup with permanent obstruction. The relationship between splitting volume ratio and initial droplet length follows a V-shaped curve, with a minimum splitting ratio occurring at intermediate droplet lengths. Capillary number further modulates this behavior: for tunnel-mediated breakup, increasing Ca initially

raises volume ratio during the squeezing stage, but final volume ratio decreases due to vortex formation that hinders tip movement. For permanent obstruction regimes, Ca raises volume ratio during the squeezing stage but has minimal influence on final volume ratios because the large droplet completely blocks both branches. The viscosity ratio significantly alters flow resistance during splitting. At low viscosity ratios, final volume ratio increases linearly with droplet size. In contrast, at high viscosity ratios, the volume ratio decreases linearly, as high droplet viscosity increases resistance in one branch, diverting flow to the opposite side. Higher viscosity also prolongs residence time, causing breakup to occur closer to the centerline of the main channel, further affecting volume symmetry. Additionally, Zhang et al. [65] concluded that the increasing outlet pressure difference amplifies flow asymmetry, accelerating droplet movement toward the lower-resistance branch and increasing the splitting volume ratio. These pressure-driven asymmetries can be intentionally engineered to tune the droplet size ratio in applications where differential volume control is desired, such as in dilution, gradient generation, or asymmetric cell encapsulation.

Under asymmetric boundary conditions, Zhang et al. [118] examined the influence of surfactants on droplet splitting by varying the pressure difference ($\Delta P^* = P_1^* - P_2^*$) and bulk surfactant concentration (ψ_b). The study found that as ΔP^* increases, the volume ratio of the resulting daughter droplets (V_1/V_2) decreases toward zero in both clean and surfactant-laden systems, though the decline is slower in the latter due to reduced interfacial tension. The presence of surfactants induces asymmetric Marangoni stresses that alleviate overall microchannel blockage and decrease the pressure difference between droplet tips, thereby facilitating the formation of daughter droplets with nearly equal volumes. Under the action of ΔP^* , the droplet exhibits asymmetric deformation at the T-junction, accompanied by unequal velocity magnitudes along the left and right sides of the bottom interface. This generates two distinct Marangoni stresses and corresponding viscous drag stresses that counteract the asymmetry in deformation and splitting. Moreover, with increasing ψ_b , the volume ratio (V_1/V_2) initially rises rapidly, then stabilizes, and finally decreases slightly, reflecting a non-monotonic relationship between surfactant concentration and droplet symmetry during splitting.

Chen and Deng [45] concluded that the two boundaries separating the three flow patterns shift toward smaller droplet lengths as the branch channel width decreases. This is because droplets in narrower branch channels are more prone to obstruction, which enhances small vortex formation and facilitates breakup. Thus, reducing branch channel width promotes droplet breakup at the T-junction. Furthermore, Kumar and Pathak [46], in their numerical investigation, introduced ribbed arrangements in the main channel of the T-junction to promote the formation of smaller droplets. These droplets can then be efficiently split into two daughter droplets in a sequential T-junction, particularly when the branch channel width is narrow.

Stable asymmetric splitting of plugs has been achieved through the use of a fluidic loop structure, as reported by [44,189,190]. In this configuration, droplets or plugs are introduced into a microfluidic loop with unequal arm lengths, where the difference in hydrodynamic resistance between the two arms naturally dictates the splitting ratio. As plugs enter the loop, they encounter a choice between the two branches; the lower-resistance (shorter) arm receives a larger portion of the plug volume, resulting in a predictable and repeatable asymmetrical division. Fu et al. [190] investigated the breakup dynamics of bubbles in a microfluidic T-junction embedded within an asymmetric loop, with particular focus on the role of hydrodynamic feedback from downstream channels. The study demonstrates that bubble breakup is significantly influenced not just by the local geometry and flow conditions, but also by the presence of bubbles in downstream channels, which alters flow resistance and thereby affects pressure distribution and breakup

symmetry. The authors developed a theoretical model accounting for both coherent channel resistance and additional resistance induced by bubbles, successfully predicting the splitting volume ratio between daughter bubbles in the two branches of the junction. Nie and Kennedy [189] demonstrated that the split ratio in a fluidic loop structure is influenced by both the geometric dimensions of the loop channels and the frequency at which plugs are introduced into the loop. By adjusting these parameters, a wide range of asymmetrical splitting behaviors could be achieved, enabling precise control over the volume of daughter plugs. The system demonstrated excellent long-term stability and reproducibility, with consistent plug sizes maintained by over thousands of splitting cycles.

5. Extended Considerations in Droplet Splitting Microfluidic Systems

Beyond geometric design, passive regimes, and active methods, an integrated understanding of dynamic control strategies, material and surface effects, and advanced computational and data-driven modeling frameworks are required for precise and scalable droplet splitting in microfluidic junctions. These extended considerations collectively enable robust manipulation of droplet size, symmetry, and reproducibility, particularly under fluctuating operating conditions or in high-throughput, multiplexed, and long-duration applications. As microfluidic systems continue to evolve toward greater functional complexity and automation, these extended considerations become essential for overcoming the constraints of purely geometry-driven droplet manipulation.

Active control mechanisms enable real-time regulation in interfacial dynamics, allowing for droplet size, symmetry and breakup mode to be dynamically tuned in response to changing flow conditions or performance objectives. Simultaneously, channel material selection and surface wettability govern droplet-wall interactions, influencing adhesion, detachment, and preferential splitting pathways that can either enhance or impede controlled breakup. Complementing these experimental strategies, computational and data-driven modeling framework provide predictive insight into multiphase flow behavior, enabling systematic exploration of parameters spaces that are difficult or impractical to access experimentally. Together these approaches establish a comprehensive foundation for achieving robust, reproducible, and application-specific droplet splitting, supporting technologies ranging from single-cell analysis and drug delivery to digital microfluidics and autonomous lab-on-chip systems.

Accordingly, this section first examines active control and dynamic regulation strategies for droplet splitting (Section 5.1), followed by a discussion of the influence of channel material and surface properties on breakup behavior (Section 5.2), and concludes with an overview of computational, data-driven, and AI-enabled modeling frameworks that support predictive design an autonomous microfluidic system (Section 5.3).

5.1. Active Control and Dynamic Regulation of Droplet Splitting

Precise regulation of droplet splitting in microfluidic T-junctions is essential for achieving reproducibility, tunability, and scalability in a wide range of applications, including single-cell assays, drug delivery, and digital microfluidics. To overcome the inherent limitations of passive systems, advanced active control strategies have been developed which dynamically manipulate flow conditions and interfacial forces. These strategies can be broadly categorized into flow rate modulation, feedback and closed-loop control, real-time imaging and adaptive control, and synchronization of multiple droplet splitting events.

Modulating the flow rates of the continuous and dispersed phases remains one of the most direct and widely adopted methods for controlling droplet splitting behavior. Adjusting the upstream flow rates tunes to the Capillary number (Ca), which determines the balance between viscous shear and interfacial tension forces. Small variations in Ca can

significantly alter the breakup regime and the resulting daughter droplet size ratio [191]. Introducing outlet channel asymmetry via length or pressure differences enables precise control of droplet size ratios when combined with optimized flow rates [192]. Flow-rate pulsation has also been explored as dynamic control mechanism. Kovalev et al. [192] demonstrate that pulsation frequency and amplitude strongly affect plug length distributions and breakup modes, with higher viscosity-ratio systems showing increased sensitivity.

Closed-loop control introduces automation by incorporating real-time feedback from sensors or detectors to dynamically adjust parameters such as flow rate, pressure, or voltage. These systems are particularly beneficial in high-throughput or long-duration experiments, where variations in fluid properties or environmental drift can lead to performance degradation. Feedback-controlled platform employing on-chip sensors and a PID controllers have been shown to maintain consistent splitting ratios by compensating for any disturbance [193].

Coupling high-speed imaging with adaptive algorithms enables responsive, data-driven manipulation of droplets. Real-time imaging provides instantaneous feedback on droplet position, shape, and deformation, which can be processed to inform control actions within milliseconds. Employing high-frame-rate optical microscopy integrated with custom image-processing algorithms to dynamically adjust electric field intensities, achieving precise asymmetric droplet splitting [194]. This adaptive framework allows for individualized droplet handling, particularly advantageous for heterogeneous systems such as drug screening, combinatorial synthesis, and multiplexed diagnostics. Current challenges in this domain include computational latency and integration of image analysis with hardware actuation, though emerging advances in embedded processing and machine learning are rapidly addressing these limitations [195].

In microfluidic networks with multiple parallel or sequential droplet operations, synchronization is essential to maintain consistency, prevent coalescence, and avoid channel blockage. Synchronization strategies focus on aligning droplet arrival times and spacing through coordinated control of flow rates, actuation timing (via electric, magnetic, or pneumatic stimuli), or phase-locked feedback systems. Abate and Weitz [191] achieved synchronization by balancing flow resistances and implementing feedback to harmonize droplet generation and downstream processes. More recently, Wang et al. [196] developed an electro-pneumatic actuation platform synchronized to droplet arrival events, maintaining consistent splitting under fluctuating upstream conditions. Such approaches are critical for droplet-on-demand systems, digital microfluidic logic, and multiplexed biochemical assays.

5.2. Influence of Channel Material and Surface Properties

Channel material selection and surface wettability play a central role in droplet-based microfluidic systems by governing fluid-wall interactions that influence droplet formation, deformation, detachment, and splitting [15]. Wettability determined whether droplet adhere to channel walls or move freely, directly affecting flow regimes, droplet size, and breakup dynamics [197–199]. Hydrophilic walls tend to promote stronger adhesion between the droplet and the surface, resisting droplet splitting and elongating the squeezing phase [15]. Compared to hydrophobic walls, lower wall adhesion, encouraging faster detachment, promote flowability and asymmetric splitting [197]. Droplets have preferential splitting toward the most wettable surface, as surface energy gradients induce asymmetric pressure fields at the T-junction [15]. This is advantageous when directional control or sorting of droplets is desired without using external actuation. Surface functionalization and wettability modification are therefore closely intertwined in determining the performance and application range of microfluidic devices [197,200,201].

Microfluidic channels can be fabricated using various materials, including glass, silicon, polymers, or composites thereof. Among these, polymer-based microfluidic systems are particularly advantageous due to their flexibility, biocompatibility, low environmental footprint, and suitability for large-scale manufacturing through diverse surface modification techniques [197,198,202,203]. Polymers commonly employed in microfluidic fabrication include polydimethylsiloxane (PDMS) [204,205], poly (methyl methacrylate) (PMMA) [206,207], and cyclic olefin copolymer (COC) [208–212]. Of these, PDMS has become the preferred material in academic research for constructing microfluidic devices. Its popularity arises from several key features: excellent optical clarity, minimal autofluorescence, non-toxicity when cured, ease of molding, biocompatibility, and high gas permeability, all of which make PDMS ideal for experimental studies and rapid device prototyping. From an industrial standpoint, however, PDMS remains relatively costly, which limits its feasibility for large-scale, low-cost manufacturing of microfluidic devices. Consequently, industry tends to favor thermoplastic-based microfluidics over those made from PDMS, glass, or silicon. Thermoplastics offer a more economical alternative and are compatible with high-throughput fabrication techniques such as injection molding and hot embossing, making them well-suited for mass production [213–215].

Nonetheless, various wet and dry surface modification techniques can be employed to tune the surface properties of polymeric microchannels. Methods such as plasma treatment [216,217], ultraviolet (UV) irradiation [218], piranha etching [219], salinization [220], graft polymerization [200], chemical vapor deposition (CVD) [201], sol–gel processing [221], and the formation of three-dimensional scaffolds (e.g., hydrogels) [222,223] enable precise control over wettability and surface chemistry to meet specific biotechnological needs [224,225]. Beyond modifying surface energy, immobilizing target biomolecules on the channel surface is essential for creating application-specific microfluidic systems. Introducing functional groups such as hydroxyl, thiol, epoxy, NHS-ester, amine, carboxyl, acrylic, aldehyde, carbodiimide, maleimide, isocyanate, and isothiocyanate enables covalent attachment of biological molecules to the polymer surface [226–230]. Typically, these functional groups are introduced after device fabrication to avoid interference with bonding processes and to ensure optimal functionalization.

5.3. Computational and Data-Driven Modeling of Droplet Splitting in Microfluidics

Computational modeling provides a quantitative framework for analyzing droplet splitting in microfluidic T-junctions under well-controlled conditions [50,53,231]. Due to the complexity of droplet deformation, interfacial instabilities, and capillary-driven breakup phenomena, numerical methods are essential for predicting droplet morphology, breakup ratios, and critical operating parameters [43,47]. These approaches integrate continuum hydrodynamics with mesoscopic formulations to capture the coupled effects of viscous, inertial, and interfacial forces. The motion of immiscible fluids is commonly described by the incompressible Navier–Stokes equations coupled with interfacial force models such as continuum surface force (CSF) formulation introduced by Brackbill et al. [232]. Interface-capturing techniques including Volume of Fluid (VOF), Level Set (LS), Phase Field (PF), and Front Tracking (FT) methods are widely used to resolve interfacial dynamics [233–235], with hybrid methods such as CLSVOF improving numerical stability and curvature estimation [234]. VOF-based studies have been widely applied to droplet formation and breakup in T-junctions [236,237].

The Lattice Boltzmann Method (LBM) has gained prominence for simulating multiphase flows in microfluidic environments [14,238–240]. Derived from the Boltzmann transport equation, LBM offers computational efficiency, natural parallelizability, and suitability for GPU acceleration. Additionally, LBM accommodates complex channel geometries and realistic wetting behaviors, making it suitable for simulating surfactant-

contaminated droplets and patterned microchannels [14]. Accurate simulation requires careful specification of inlet, outlet, and wall boundary conditions, as well as appropriate treatment of wettability through contact-angle models. Local mesh refinement near interface is commonly used to resolve capillary stresses. Validation is typically performed through comparison with high-speed visualization experiments, focusing on metrics such as capillary number, breakup time, elongation, and daughter-droplet volume ratio [53,77,231].

Recent advancements have coupled conventional numerical solvers with data-driven and machine learning (ML) frameworks to accelerate parametric studies and optimize device geometries. Neural-network-assisted reduced-order models have demonstrated the ability to predict breakup regimes with reduced computational costs [43], while hybrid methods such as LBM–DEM and LBM–PF capture complex droplet–solid interactions, surfactant effects, and nanoparticle-stabilized emulsions [14].

AI-driven approaches have further expanded modeling capabilities by enabling direct inference of droplet behavior from data. As demonstrated by Liu et al. [241], applications now span droplet generation, breakup dynamics, material synthesis, and biomedical analysis [241–243]. Neural networks and regression models have been trained to predict droplet size, deformation, and breakup regimes with high precision, while reinforcement and Bayesian learning frameworks enable adaptive optimization of flow parameters and geometries [241,243]. In material synthesis, AI-assisted droplet reactors autonomously tune reaction conditions for nanoparticle and microparticle fabrication. In biomedical contexts, convolutional neural networks (CNNs) and object detection algorithms such as YOLO facilitate high-throughput, label-free droplet classification, advancing single-cell encapsulation, sorting, and screening. These methods enhance reproducibility, scalability, and efficiency, marking a transition toward autonomous lab-on-a-chip systems [241,242,244].

Despite significant progress, AI frameworks still face challenges in interpretability, generalization to complex geometries, and dependence on extensive, high-quality datasets. A promising solution lies in hybrid modeling, where AI is coupled with physics-based solvers to leverage the strengths of both. Physics-Informed Neural Networks (PINNs) represent a leading approach in this domain. Instead of relying purely on data, PINNs embed governing equations such as Navier–Stokes and Cahn–Hilliard directly into the learning process through automatic differentiation [245], this eliminates the need for mesh generation and allows for seamless integration of multifidelity or noisy data [246,247]. While PINNs currently trail traditional CFD solvers in benchmark precision, their capacity to perform inverse modeling and parameter inference makes them particularly useful when boundary conditions or material parameters are partially unknown [245]. Recent developments, including XPINNs (domain-decomposed architectures), adaptive activation functions, and Bayesian uncertainty quantification, further enhance accuracy and robustness [247]. When properly implemented, PINNs can reconstruct velocity fields and estimate unknown PDE parameters from sparse data [248]. In biomedical flow studies, they have been applied to infer thrombus deformation using coupled Navier–Stokes and Cahn–Hilliard equations, achieving convergence errors below 10^{-2} . The Auto-PINN framework, which applies neural architecture search (NAS) to optimize network depth, width, and activation functions, has further improved solver stability and efficiency [249]. Together, these computational and data-driven approaches are transforming droplet microfluidics into a predictable and design-oriented discipline, enabling virtual prototyping, optimization, and autonomous control of droplet splitting behavior.

6. Challenges and Limitations

As droplet splitting becomes more prevalent in microfluidic systems, maintaining stability and reproducibility remains a major challenge. Small fluctuations in flow, fabrication defects, and interfacial instabilities often determine whether breakup occurs, reflecting the high sensitivity of T-junctions to subtle variations [43]. The capillary number (Ca) plays a crucial role in this transition; minor deviations from the critical Ca can shift behavior between complete breakup and failure [84]. Fabrication asymmetries or surface imperfections such as wall roughness create uneven pressure distributions, destabilizing the droplet neck and producing inconsistent daughter droplet volumes [66]. Instabilities can also arise from the formation of a thin tunnel between the droplet and channel wall, which suppresses breakup and leads to non-splitting outcomes under otherwise identical flow conditions [66]. In contrast, high-viscosity systems may generate satellite droplets that reduce control and uniformity across experiments [30]. Although numerical models such as CLSVOF and lattice Boltzmann simulations can predict breakup boundaries under ideal conditions, experimental results often diverge due to unaccounted flow disturbances and fabrication imperfections [43].

Droplet coalescence during or after splitting further complicates repeatability. Rapid film drainage between neighboring droplets can collapse the interface and cause merging, which may cascade through droplet trains as larger droplets slow and collide with trailing ones [250]. The probability of coalescence depends strongly on surfactant coverage; droplets with high surface coverage ($> 98\%$) remain stable, while under-coated ones ($< 16\%$) fuse rapidly [251]. Adjusting surfactant concentration and contact time enables selective fusion ratios (1:1, 2:1, or 3:1), which is critical for applications such as single-cell assays and digital PCR [251]. Collision velocity also influences coalescence; slow impacts favor merging, intermediate speeds cause slipping, and high-speed collisions can fragment droplets [252]. Around $Ca \approx 0.02$, small variations in flow can shift behavior between stable and merging regimes [252]. Surfactant-induced Marangoni stresses enhance droplet stability by rigidifying interfaces and suppressing stagnation points, reducing the likelihood of fusion [253]. Nevertheless, breakup and coalescence remain interconnected; during pinch-off, filament thinning can produce satellite droplets that may re-merge with primary ones if not stabilized [30]. Using inertial microflows to remove these satellites improves uniformity and splitting fidelity.

At the device level, scalability and integration introduce additional design challenges. Lab-on-PCB technology provides a promising route for scalable microfluidic systems, combining fluidic, electronic, and sensing elements on a single, manufacturable platform [254]. PCB-based devices with integrated thermal microchannels demonstrate that complex structures can be directly fabricated on electronic substrates, reducing cost and simplifying scale-up. However, achieving precise droplet control in high-throughput systems remains difficult. Passive geometries such as T-, Y-, and bypass junctions are simple and robust but limited in adaptability when scaled. Active mechanisms, such as, pneumatic, acoustic, electric, magnetic, or thermal, enable real-time control of droplet size and frequency, though they increase system complexity and energy consumption [43,255]. At the device level, scalability and integration introduce additional design challenges. PCB-based devices with integrated thermal microchannels demonstrate that complex structures can be directly fabricated on electronic substrates, reducing cost and simplifying scale-up. Overall, droplet stability, interfacial control, and system scalability must be optimized together to ensure reproducible splitting performance. Understanding how flow parameters, surface conditions, and actuation methods interact is key to developing high-fidelity, large-scale droplet-based microfluidic platforms.

7. Emerging Trends and Future Directions

Recent advances in microfluidic droplet splitting are trending toward systems that are adaptive, intelligent, and multifunctional, combining physical modeling with data-driven design [43,47]. Droplet breakup in non-Newtonian and viscoelastic fluids are more complex than simple Newtonian ones; shear-thinning and elastic effects slow down droplet splitting, forming thin filaments and bead-like structures that allow for the generation of daughter droplets with controlled sizes [256,257]. Studies have shown that these elastic stresses stabilize the droplet neck through repeated stretching and relaxation cycles, improving control for encapsulation, slow release, and micro-scale reactions [231]. At the same time, digital microfluidics and 3D printing are revolutionizing device design. Reconfigurable digital systems now allow for droplet creation, movement, and splitting without fixed channel geometries [43], while high-resolution 3D printing enables rapid fabrication of junctions and embedded sensors with features smaller than 50 μm [192]. Using multiple materials during printing also allows for control over droplet wetting and flow behavior by tuning surface properties.

The integration of artificial intelligence (AI) and machine learning (ML) represents a major shift in the field. AI models trained on experimental and simulated datasets can predict breakup behavior, classify droplet morphologies, and optimize control parameters such as capillary number, viscosity ratio, and droplet length in real time [231]. These data-driven tools accelerate experimentation and enable adaptive feedback, allowing for devices to self-correct for flow instabilities. Together, AI, digital microfluidics, and additive manufacturing are paving the way for self-optimizing systems capable of learning from experimental results and automatically adjusting their performance for greater stability and throughput. Looking ahead, future developments in acoustic droplet splitting may involve hybrid systems that combine SAWs and BAWs to exploit the strengths of both methods [172,179]. Managing the heat generated during high-power acoustic actuation is an area of active research, as is the design of biocompatible acoustic protocols that avoid damaging sensitive biomolecules or cells [43,256,258]. Integration of machine learning for real-time optimization of acoustic parameters could further enhance precision and adaptability, while three-dimensional acoustic fields may enable more complex droplet manipulations in volumetric microfluidic networks [43,78,231,259]. In synthetic biology, diagnostics, and single-cell research, these advances open new frontiers; controlled droplet splitting enables high-throughput screening, digital PCR, and precise single-molecule assays, improving efficiency while minimizing reagent use [258–260]. The combination of intelligent control, flexible fabrication, and precise fluid handling will define the next generation of lab-on-chip platforms, systems that not only manipulate droplets but also analyze, predict, and adapt autonomously.

8. Conclusions

Microfluidic droplet splitting in T-junction geometries has evolved into a highly versatile and foundational operation in droplet-based microfluidics, enabling precise and reproducible volume partitioning for applications ranging from single-cell analysis and digital assays to chemical synthesis and material fabrication. This review has synthesized the current state of the art in droplet splitting in T-junction microchannel, with particular emphasis on the underlying flow physics, the role of channel geometry and material properties, and passive and active control strategies. By organizing existing studies around shared physical mechanisms and governing parameters, this work provides a unified perspective on how droplet splitting behavior can be predicted, controlled, and tailored for specific applications.

Passive droplet splitting approaches, driven by hydrodynamic resistance, shear stress, interfacial tension, and channel architecture, remain attractive for their simplicity, robustness, and ease of integration into large-scale microfluidic networks. These methods

are well-suited for high-throughput and low-complexity systems where reproducibility and operational stability are paramount. In contrast, active actuation strategies, including electric, magnetic, thermal, acoustic, and pneumatic, enable on-demand modulation of droplet breakup, offering enhanced tunability, asymmetry control, and adaptability to changing flow conditions. Such approaches are particularly valuable in dynamic, feedback-driven environments where precise control over splitting ratios and timing is required.

Despite significant progress, several challenges continue to limit the widespread deployment of T-junction droplet splitting systems in complex, real-world applications. These include maintaining consistent splitting ratios at high throughput, reducing sensitivity to fabrication tolerances and device-to-device variability, and integrating multiple droplet operations, such as splitting, merging, sorting, and sensing, within compact and scalable platforms. Addressing these challenges will require closer integration of experimental design, computational modeling, and real-time sensing. Looking forward, hybrid systems that combine the inherent robustness of passive geometries with the precision and adaptability of active actuation represent a particularly promising direction. The incorporation of computational modeling, data-driven optimization, and machine learning-enabled control is expected to further enhance predictability and performance, enabling autonomous adjustment of operating conditions in response to fluctuations in flow or material properties. Concurrent advances in fabrication techniques, surface engineering, and microscale sensing are also anticipated to expand the functional envelope of T-junction droplet systems.

Overall, continued research into actuation strategies, flow manipulation, and physics-guided design will pave the way toward next-generation microfluidic platforms that are scalable, programmable, and application-specific. As these technologies progress, T-junction-based droplet splitting is shown to remain a cornerstone of droplet microfluidics, creating future advances in biomedical diagnostics, high-throughput screening, drug delivery, synthetic biology, and emerging lab-on-a-chip technologies.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating Current
AI	Artificial Intelligence
AM	Amplitude-Modulated
BAW	Bulk Acoustic Waves
BB	Both droplet Breakup
BNO	Breakup with No Obstruction

BPO	Breakup with Permanent Obstruction
BTO	Breakup with Temporary Obstruction
Ca	Capillary number
CFD	Computational Fluid Dynamics
CLSVOF	Coupled Level-Set and Volume-Of-Fluid method
CNNs	Convolutional Neural Network
COC	Cyclic Olefin Copolymer
CSF	Continuum Surface Force
CVD	Chemical Vapor Deposit
DEP	Dielectrophoresis
DS	Double Splitting
FSW	Flowing through the Same Branch
FT	Front Tracking
HASM	Hybrid Asymmetric Splitting Mode
IDT	Interdigitated Transducer
LBM	Lattice Boltzmann Method
LOC	Lab-On-Chip
LS	Level Set
ML	Machine Learning
NAS	Neutral Architecture Search
NB	No Breakup
OB	Outer droplet Breakup
O/W	Oil-in-Water
PCB	Printed Circuit Board
PCR	Polymerase Chain Reaction
PDE	Phosphodiesterase
PDMS	Polydimethylsiloxane
PF	Phase Field
PINN	Physics-Informed Neural Network
PWM	Pulse-Width-Modulated
Re	Reynolds number
RF	Radiofrequency
SAW	Surface Acoustic Waves
SF-IDT	Slanted-Finger Interdigitated Transducer
TB	Twice Breakup
UV	Ultraviolet
VOF	Volume-of-Fluid method
We	Weber number

References

1. Bhatia, S.N.; Ingber, D.E. Microfluidic organs-on-chips. *Nat. Biotechnol.* **2014**, *32*, 760–772. <https://doi.org/10.1038/nbt.2989>.
2. Moragues, T.; Arguijo, D.; Beneyton, T.; Modavi, C.; Simutis, K.; Abate, A.R.; Baret, J.-C.; Demello, A.J.; Densmore, D.; Griffiths, A.D. Droplet-based microfluidics. *Nat. Rev. Methods Primers* **2023**, *3*, 32. <https://doi.org/10.1038/s43586-023-00212-3>.
3. Seemann, R.; Brinkmann, M.; Pfohl, T.; Herminghaus, S. Droplet based microfluidics. *Rep. Prog. Phys.* **2012**, *75*, 016601. <https://doi.org/10.1088/0034-4885/75/1/016601>.
4. Yeo, L.Y.; Chang, H.C.; Chan, P.P.Y.; Friend, J.R. Microfluidic devices for bioapplications. *Small* **2011**, *7*, 12–48. <https://doi.org/10.1002/sml.201000946>.
5. Du, G.; Fang, Q.; den Toonder, J.M.J. Microfluidics for cell-based high throughput screening platforms—A review. *Anal. Chim. Acta* **2016**, *903*, 36–50. <https://doi.org/10.1016/j.aca.2015.11.023>.
6. Brouzes, E.; Medkova, M.; Savenelli, N.; Marran, D.; Twardowski, M.; Hutchison, J.B.; Rothberg, J.M.; Link, D.R.; Perrimon, N.; Samuels, M.L. Droplet microfluidic technology for single-cell high-throughput screening. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 14195–14200. <https://doi.org/10.1073/pnas.0903542106>.
7. Marques, M.P.C.; Fernandes, P. Microfluidic devices: Useful tools for bioprocess intensification. *Molecules* **2011**, *16*, 8368–8401. <https://doi.org/10.3390/molecules16108368>.
8. Maguire, I.; O’Kennedy, R.; Ducreé, J.; Regan, F. A review of centrifugal microfluidics in environmental monitoring. *Anal. Methods* **2018**, *10*, 1497–1515. <https://doi.org/10.1039/c8ay00361k>.

9. Yew, M.; Ren, Y.; Koh, K.S.; Sun, C.; Snape, C. A Review of State-of-the-Art Microfluidic Technologies for Environmental Applications: Detection and Remediation. *Glob. Chall.* **2019**, *3*, 1800060. <https://doi.org/10.1002/gch2.201800060>.
10. Abdelhamid, M.A.A.; Ki, M.-R.; Yoon, H.J.; Pack, S.P. Microfluidic Sensors for Micropollutant Detection in Environmental Matrices: Recent Advances and Prospects. *Biosensors* **2025**, *15*, 474. <https://doi.org/10.3390/bios15080474>.
11. Amirifar, L.; Besanjideh, M.; Nasiri, R.; Shamloo, A.; Nasrollahi, F.; de Barros, N.R.; Davoodi, E.; Erdem, A.; Mahmoodi, M.; Hosseini, V.; et al. Droplet-based microfluidics in biomedical applications. *Biofabrication* **2022**, *14*, 022001. <https://doi.org/10.1088/1758-5090/ac39a9>.
12. Barea, J.S.; Lee, J.; Kang, D.K. Recent advances in droplet-based microfluidic technologies for biochemistry and molecular biology. *Micromachines* **2019**, *10*, 412. <https://doi.org/10.3390/mi10060412>.
13. Trinh, T.N.D.; Do, H.D.K.; Nam, N.N.; Dan, T.T.; Trinh, K.T.L.; Lee, N.Y. Droplet-Based Microfluidics: Applications in Pharmaceuticals. *Pharmaceuticals* **2023**, *16*, 937. <https://doi.org/10.3390/ph16070937>.
14. Fan, R.; Wu, J.; Duan, S.; Jin, L.; Zhang, H.; Zhang, C.; Zheng, A. Droplet-based microfluidics for drug delivery applications. *Int. J. Pharm.* **2024**, *663*, 124551. <https://doi.org/10.1016/j.ijpharm.2024.124551>.
15. Teh, S.Y.; Lin, R.; Hung, L.H.; Lee, A.P. Droplet microfluidics. *Lab Chip* **2008**, *8*, 198–220. <https://doi.org/10.1039/b715524g>.
16. Xi, H.-D.; Zheng, H.; Guo, W.; Gañán-Calvo, A.M.; Ai, Y.; Tsao, C.-W.; Zhou, J.; Li, W.; Huang, Y.; Nguyen, N.-T.; et al. Active droplet sorting in microfluidics: A review. *Lab Chip* **2017**, *17*, 751–771. <https://doi.org/10.1039/c6lc01435f>.
17. Zhu, P.; Wang, L. Passive and active droplet generation with microfluidics: A review. *Lab Chip* **2017**, *17*, 34–75. <https://doi.org/10.1039/C6LC01018K>.
18. Shi, N.; Mohibullah, M.; Easley, C.J. Active Flow Control and Dynamic Analysis in Droplet Microfluidics. *Annu. Rev. Anal. Chem.* **2021**, *14*, 133–153. <https://doi.org/10.1146/annurev-anchem-122120-042627>.
19. Miralles, V.; Huerre, A.; Malloggi, F.; Jullien, M.C. A review of heating and temperature control in microfluidic systems: Techniques and applications. *Diagnostics* **2013**, *3*, 33–67. <https://doi.org/10.3390/diagnostics3010033>.
20. Huang, G.; Li, M.; Yang, Q.; Li, Y.; Liu, H.; Yang, H.; Xu, F. Magnetically actuated droplet manipulation and its potential biomedical applications. *ACS Appl. Mater. Interfaces* **2017**, *9*, 1155–1166. <https://doi.org/10.1021/acsami.6b09017>.
21. Kumar, P.; Kumar, V.; Pathak, M. Droplet formation dynamics under perpendicular and head-on dispersed phase configuration in a microfluidic T-junction. *Phys. Fluids* **2024**, *36*, 113347.
22. Li, X.B.; Li, F.C.; Yang, J.C.; Kinoshita, H.; Oishi, M.; Oshima, M. Study on the mechanism of droplet formation in T-junction microchannel. *Chem. Eng. Sci.* **2012**, *69*, 340–351. <https://doi.org/10.1016/j.ces.2011.10.048>.
23. Gupta, A.; Murshed, S.M.S.; Kumar, R. Droplet formation and stability of flows in a microfluidic T-junction. *Appl. Phys. Lett.* **2009**, *94*, 164107. <https://doi.org/10.1063/1.3116089>.
24. Jena, S.K.; Srivastava, T.; Bahga, S.S.; Kondaraju, S. Effect of channel width on droplet generation inside T-junction microchannel. *Phys. Fluids* **2023**, *35*, 022107. <https://doi.org/10.1063/5.0134087>.
25. Kumar, P.; Pathak, M. Dynamic wetting characteristics during droplet formation in a microfluidic T-junction. *Int. J. Multiph. Flow* **2022**, *156*, 104203. <https://doi.org/10.1016/j.ijmultiphaseflow.2022.104203>.
26. Sontti, S.G.; Atta, A. Numerical Insights on Controlled Droplet Formation in a Microfluidic Flow-Focusing Device. *Ind. Eng. Chem. Res.* **2020**, *59*, 3702–3716. <https://doi.org/10.1021/acs.iecr.9b02137>.
27. Tan, S.H.; Murshed, S.M.S.; Nguyen, N.T.; Wong, T.N.; Yobas, L. Thermally controlled droplet formation in flow focusing geometry: Formation regimes and effect of nanoparticle suspension. *J. Phys. D Appl. Phys.* **2008**, *41*, 165501. <https://doi.org/10.1088/0022-3727/41/16/165501>.
28. Fu, T.; Wu, Y.; Ma, Y.; Li, H.Z. Droplet formation and breakup dynamics in microfluidic flow-focusing devices: From dripping to jetting. *Chem. Eng. Sci.* **2012**, *84*, 207–217. <https://doi.org/10.1016/j.ces.2012.08.039>.
29. Wu, Y.; Fu, T.; Ma, Y.; Li, H.Z. Ferrofluid droplet formation and breakup dynamics in a microfluidic flow-focusing device. *Soft Matter* **2013**, *9*, 9792–9798. <https://doi.org/10.1039/c3sm51860d>.
30. Bai, F.; He, X.; Yang, X.; Zhou, R.; Wang, C. Three dimensional phase-field investigation of droplet formation in microfluidic flow focusing devices with experimental validation. *Int. J. Multiph. Flow* **2017**, *93*, 130–141. <https://doi.org/10.1016/j.ijmultiphaseflow.2017.04.008>.
31. Deng, C.; Wang, H.; Huang, W.; Cheng, S. Numerical and experimental study of oil-in-water (O/W) droplet formation in a co-flowing capillary device. *Colloids Surf. A Physicochem. Eng. Asp.* **2017**, *533*, 1–8. <https://doi.org/10.1016/j.colsurfa.2017.05.041>.
32. Pan, D.; Zhang, Y.; Zhang, T.; Li, B. Flow regimes of polymeric fluid droplet formation in a co-flowing microfluidic device. *Colloids Interface Sci. Commun.* **2021**, *42*, 100392. <https://doi.org/10.1016/j.colcom.2021.100392>.

33. Kumar, P.; Phukan, A.; Kumar, A.; Pathak, M.; Kumar, V. Deciphering the multifaceted impact of nanoparticle concentration on droplet generation dynamics within microfluidic systems. *J. Mol. Liq.* **2024**, *412*, 125807. <https://doi.org/10.1016/j.mol-liq.2024.125807>.
34. De Menech, M.; Garstecki, P.; Jousse, F.; Stone, H.A. Transition from squeezing to dripping in a microfluidic T-shaped junction. *J. Fluid. Mech.* **2008**, *595*, 141–161. <https://doi.org/10.1017/S002211200700910X>.
35. Kovalchuk, N.M.; Sagisaka, M.; Steponavicius, K.; Vigolo, D.; Simmons, M.J.H. Drop formation in microfluidic cross-junction: Jetting to dripping to jetting transition. *Microfluid. Nanofluid.* **2019**, *23*, 103. <https://doi.org/10.1007/s10404-019-2269-z>.
36. Fu, T.; Ma, Y.; Funfschilling, D.; Zhu, C.; Li, H.Z. Squeezing-to-dripping transition for bubble formation in a microfluidic T-junction. *Chem. Eng. Sci.* **2010**, *65*, 3739–3748. <https://doi.org/10.1016/j.ces.2010.03.012>.
37. Christopher, G.F.; Noharuddin, N.N.; Taylor, J.A.; Anna, S.L. Experimental observations of the squeezing-to-dripping transition in T-shaped microfluidic junctions. *Phys. Rev. E Stat. Nonlinear Soft Matter Phys.* **2008**, *78*, 036317. <https://doi.org/10.1103/PhysRevE.78.036317>.
38. Mu, K.; Qiao, R.; Si, T.; Cheng, X.; Ding, H. Interfacial instability and transition of jetting and dripping modes in a co-flow focusing process. *Phys. Fluids* **2021**, *33*, 052118. <https://doi.org/10.1063/5.0049971>.
39. Kumar, P.; Pathak, M. Pressure Transient during Wettability-Mediated Droplet Formation in a Microfluidic T-Junction. *Ind. Eng. Chem. Res.* **2020**, *59*, 11839–11850. <https://doi.org/10.1021/acs.iecr.0c01504>.
40. Kumar, P.; Pathak, M. Influence of Capillary Number on Pressure Profile Evolution in Microfluidic T-Junction. In Proceedings of the 5th World Congress on Momentum, Heat and Mass Transfer, Virtual, 14–16 October 2020. <https://doi.org/10.11159/ic-mfht20.116>.
41. Azzini, F.; Pulvirenti, B.; Rossi, M.; Morini, G.L. Squeezing Droplet Formation in a Flow-Focusing Micro Cross-Junction. *Micromachines* **2024**, *15*, 339. <https://doi.org/10.3390/mi15030339>.
42. Chiarello, E.; Gupta, A.; Mistura, G.; Sbragaglia, M.; Pierno, M. Droplet breakup driven by shear thinning solutions in a microfluidic T-junction. *Phys. Rev. Fluids* **2017**, *2*, 123602. <https://doi.org/10.1103/PhysRevFluids.2.123602>.
43. Agnihotri, S.N.; Raveshi, M.R.; Nosrati, R.; Bhardwaj, R.; Neild, A. Droplet splitting in microfluidics: A review. *Phys. Fluids* **2025**, *37*, 051304.
44. Link, D.R.; Anna, S.L.; Weitz, D.A.; Stone, H.A. Geometrically Mediated Breakup of Drops in Microfluidic Devices. *Phys. Rev. Lett.* **2004**, *92*, 054503. <https://doi.org/10.1103/PhysRevLett.92.054503>.
45. Chen, Y.; Deng, Z. Hydrodynamics of a droplet passing through a microfluidic T-junction. *J. Fluid. Mech.* **2017**, *819*, 401–434. <https://doi.org/10.1017/jfm.2017.181>.
46. Kumar, P.; Pathak, M. Droplet generation and breakup in a ribbed microfluidic T-junction for scalable emulsification process. *Microsyst. Technol.* **2023**, *29*, 321–336. <https://doi.org/10.1007/s00542-023-05428-7>.
47. Mandal, J.; Sarkar, S. Universal correlation for droplet fragmentation in a microfluidic t-junction. *Langmuir* **2024**, *40*, 17489–17499.
48. Leshansky, M.A.; Pismen, M.L. Breakup of drops in a microfluidic T junction. *Phys. Fluids* **2009**, *21*, 023303. <https://doi.org/10.1063/1.3078515>.
49. Leshansky, A.M.; Afkhami, S.; Jullien, M.C.; Tabeling, P. Obstructed breakup of slender drops in a microfluidic T junction. *Phys. Rev. Lett.* **2012**, *108*, 264502. <https://doi.org/10.1103/PhysRevLett.108.264502>.
50. Jullien, M.C.; Ching, M.J.T.M.; Cohen, C.; Menetrier, L.; Tabeling, P. Droplet breakup in microfluidic T-junctions at small capillary numbers. *Phys. Fluids* **2009**, *21*, 072001. <https://doi.org/10.1063/1.3170983>.
51. Fu, T.; Ma, Y.; Funfschilling, D.; Li, H.Z. Dynamics of bubble breakup in a microfluidic T-junction divergence. *Chem. Eng. Sci.* **2011**, *66*, 4184–4195. <https://doi.org/10.1016/j.ces.2011.06.003>.
52. Chen, B.; Li, G.; Wang, W.; Wang, P. 3D numerical simulation of droplet passive breakup in a micro-channel T-junction using the Volume-Of-Fluid method. *Appl. Therm. Eng.* **2015**, *88*, 94–101. <https://doi.org/10.1016/j.applthermaleng.2014.11.084>.
53. Hoang, D.A.; Portela, L.M.; Kleijn, C.R.; Kreutzer, M.T.; Van Steijn, V. Dynamics of droplet breakup in a t-junction. *J. Fluid. Mech.* **2013**, *717*, R4. <https://doi.org/10.1017/jfm.2013.18>.
54. Chong, Z.Z.; Tan, S.H.; Gañán-Calvo, A.M.; Tor, S.B.; Loh, N.H.; Nguyen, N.T. Active droplet generation in microfluidics. *Lab Chip* **2016**, *16*, 35–58. <https://doi.org/10.1039/c5lc01012h>.
55. Huang, C.; Jiang, Y.; Li, Y.; Zhang, H. Droplet Detection and Sorting System in Microfluidics: A Review. *Micromachines* **2023**, *14*, 103. <https://doi.org/10.3390/mi14010103>.
56. Shen, Y.; Yalikun, Y.; Tanaka, Y. Recent advances in microfluidic cell sorting systems. *Sens. Actuators B Chem.* **2019**, *282*, 268–281. <https://doi.org/10.1016/j.snb.2018.11.025>.

57. Dobson, C.; Zielke, C.; Pan, C.W.; Feit, C.; Abbyad, P. Method for passive droplet sorting after photo-tagging. *Micromachines* **2020**, *11*, 964. <https://doi.org/10.3390/mi11110964>.
58. Gu, H.; Duits, M.H.G.; Mugele, F. Droplets formation and merging in two-phase flow microfluidics. *Int. J. Mol. Sci.* **2011**, *12*, 2572–2597. <https://doi.org/10.3390/ijms12042572>.
59. Sesen, M.; Alan, T.; Neild, A. Microfluidic on-demand droplet merging using surface acoustic waves. *Lab Chip* **2014**, *14*, 3325–3333. <https://doi.org/10.1039/c4lc00456f>.
60. Babahosseini, H.; Misteli, T.; Devoe, D.L. Microfluidic on-demand droplet generation, storage, retrieval, and merging for single-cell pairing. *Lab Chip* **2019**, *19*, 493–502. <https://doi.org/10.1039/c8lc01178h>.
61. Collignon, S.; Friend, J.; Yeo, L. Planar microfluidic drop splitting and merging. *Lab Chip* **2015**, *15*, 1942–1951. <https://doi.org/10.1039/c4lc01453g>.
62. Lee, S.; Kim, H.; Won, D.J.; Lee, J.; Kim, J. On-demand, parallel droplet merging method with non-contact droplet pairing in droplet-based microfluidics. *Microfluid. Nanofluid.* **2016**, *20*, 1. <https://doi.org/10.1007/s10404-015-1676-z>.
63. Shen, F.; Li, Y.; Liu, Z.; Li, X.J. Study of flow behaviors of droplet merging and splitting in microchannels using Micro-PIV measurement. *Microfluid. Nanofluid.* **2017**, *21*, 66. <https://doi.org/10.1007/s10404-017-1902-y>.
64. Fallah, K.; Fattahi, E. Splitting of droplet with different sizes inside a symmetric T-junction microchannel using an electric field. *Sci. Rep.* **2022**, *12*, 3226. <https://doi.org/10.1038/s41598-022-07130-6>.
65. Zhang, Y.; Liu, X.; Deng, Z.; Chen, Y. Asymmetric droplet splitting in a T-junction under pressure difference. *Int. J. Multiph. Flow* **2024**, *180*, 104967. <https://doi.org/10.1016/j.ijmultiphaseflow.2024.104967>.
66. Zhang, Y.; Li, P.; Zhou, B.; Liu, X. Investigation on asymmetric splitting behavior of droplets through T-junction with different-length branches. *Chem. Eng. Sci.* **2025**, *304*, 121075. <https://doi.org/10.1016/j.ces.2024.121075>.
67. Bijarchi, M.A.; Dizani, M.; Honarmand, M.; Shafii, M.B. Splitting dynamics of ferrofluid droplets inside a microfluidic T-junction using a pulse-width modulated magnetic field in micro-magnetofluidics. *Soft Matter* **2021**, *17*, 1317–1329. <https://doi.org/10.1039/d0sm01764g>.
68. Liu, Z.; Li, D.; Wang, X.; Pang, Y.; Ma, Y.; Li, M.; Wang, J. Breakup regimes of double emulsion droplets in a microfluidic Y-junction. *Phys. Fluids* **2021**, *33*, 102009. <https://doi.org/10.1063/5.0067032>.
69. Li, S.; Wen, L.; Wang, W. Asymmetric breakup of a single droplet through a Y-junction microchannel with non-uniform flow rate. *Phys. Fluids* **2023**, *35*, 042015. <https://doi.org/10.1063/5.0142244>.
70. Schütz, S.S.; Khor, J.W.; Tang, S.K.Y.; Schneider, T.M. Interaction and breakup of droplet pairs in a microchannel Y-junction. *Phys. Rev. Fluids* **2020**, *5*, 083605. <https://doi.org/10.1103/PhysRevFluids.5.083605>.
71. Li, H.; Wu, Y.; Wang, X.; Zhu, C.; Fu, T.; Ma, Y. Magnetofluidic control of the breakup of ferrofluid droplets in a microfluidic Y-junction. *RSC Adv.* **2015**, *6*, 778–785. <https://doi.org/10.1039/c5ra21802k>.
72. Liu, Z.; Su, P.; Pang, Y.; Liu, W.; Wang, Z.; Wang, X. Dynamic mechanism of double emulsion droplets flowing through a microfluidic T-junction. *Phys. Fluids* **2023**, *35*, 072001. <https://doi.org/10.1063/5.0155427>.
73. Naseri, P.; Seyyedi, S.M.; Hashemi-Tilehnoee, M.; Naeimi, A.S. Analysis of magnetic field-induced breakup of ferrofluid droplets in a symmetric Y-junction microchannel. *Sci. Rep.* **2024**, *14*, 23763. <https://doi.org/10.1038/s41598-024-74805-7>.
74. Jiao, B.; Chen, L.; Yan, X.; Wang, X. Bubble breakup in the microchannels with a long constriction. *Exp. Therm. Fluid. Sci.* **2026**, *172*, 111640. <https://doi.org/10.1016/j.expthermflusci.2025.111640>.
75. Wang, X.; Liu, Y.; Liu, D.; Ge, X.; Li, L.; Qiu, T. Droplet breakup in the square microchannel with a short square constriction to generate slug flow. *AIChE J.* **2022**, *68*, e17739. <https://doi.org/10.1002/aic.17739>.
76. Singla, A.; Mehul, B.; Ray, B. Droplet dynamics in a constricted microchannel. *Chem. Eng. Sci.* **2024**, *300*, 120532. <https://doi.org/10.1016/j.ces.2024.120532>.
77. Yin, Y.; Tian, X.; Zhu, X.; Liu, H.; Zhang, X.; Zhu, C.; Fu, T.; Ma, Y. Fluid dynamics of gas–liquid slug flow under the expansion effect in a microchannel. *Chem. Eng. Sci.* **2025**, *302*, 120941. <https://doi.org/10.1016/j.ces.2024.120941>.
78. Jafari, I.; Fallah, K. Drop breakup in a symmetric T-junction microchannel under electric field. *Microfluid. Nanofluid.* **2020**, *24*, 94. <https://doi.org/10.1007/s10404-020-02399-3>.
79. Xi, H.D.; Guo, W.; Leniart, M.; Chong, Z.Z.; Tan, S.H. AC electric field induced droplet deformation in a microfluidic T-junction. *Lab Chip* **2016**, *16*, 2982–2986. <https://doi.org/10.1039/c6lc00448b>.
80. Frampton, K.D.; Martin, S.E.; Minor, K. The scaling of acoustic streaming for application in micro-fluidic devices. *Appl. Acoust.* **2003**, *64*, 681–692. [https://doi.org/10.1016/S0003-682X\(03\)00005-7](https://doi.org/10.1016/S0003-682X(03)00005-7).
81. Ali, M.; Kim, W.; Khan, M.S.; Sahin, M.A.; Destgeer, G.; Park, J. Droplet acoustofluidics: Recent progress and challenges. *Biomecrofluidics* **2025**, *19*, 031502.

82. Gerlt, M.S.; Haidas, D.; Ratschat, A.; Suter, P.; Dittrich, P.S.; Dual, J. Manipulation of single cells inside nanoliter water droplets using acoustic forces. *Biomicrofluidics* **2020**, *14*, 064112. <https://doi.org/10.1063/5.0036407>.
83. Karbalaeei, A.; Kumar, R.; Cho, H.J. Thermocapillarity in microfluidics-A review. *Micromachines* **2016**, *7*, 13. <https://doi.org/10.3390/mi7010013>.
84. Mandal, J.; Sanyal, D.; Sarkar, S. Thermal Marangoni stress induced droplet mobilization in a microfluidic confinement. *Phys. Fluids* **2025**, *37*, 081704. <https://doi.org/10.1063/5.0280822>.
85. Murshed, S.M.S.; Tan, S.H.; Nguyen, N.T. Temperature dependence of interfacial properties and viscosity of nanofluids for droplet-based microfluidics. *J. Phys. D Appl. Phys.* **2008**, *41*, 085502. <https://doi.org/10.1088/0022-3727/41/8/085502>.
86. Garnier, N.; Grigoriev, R.O.; Schatz, M.F. Optical Manipulation of Microscale Fluid Flow. *Phys. Rev. Lett.* **2003**, *91*, 054501. <https://doi.org/10.1103/PhysRevLett.91.054501>.
87. Kholardi, M.D.; Farhadi, M. Understanding droplet formation in T-shaped channels with magnetic field influence: A computational investigation. *Phys. Fluids* **2024**, *36*, 053302. <https://doi.org/10.1063/5.0203322>.
88. Guilherme, A.L.; Abdo, R.F.; Cunha, L.H.P.; Siqueira, I.R.; Thompson, R.L.; Oliveira, T.F. Field-induced control of the breakup of ferrofluid droplets in planar extensional and simple shear flows. *Phys. Fluids* **2025**, *37*, 103305.
89. Wu, Y.; Fu, T.; Ma, Y.; Li, H.Z. Active control of ferrofluid droplet breakup dynamics in a microfluidic T-junction. *Microfluid. Nanofluid.* **2015**, *18*, 19–27. <https://doi.org/10.1007/s10404-014-1414-y>.
90. Zhang, C.; Xing, D. Single-molecule DNA amplification and analysis using microfluidics. *Chem. Rev.* **2010**, *110*, 4910–4947. <https://doi.org/10.1021/cr900081z>.
91. Xu, Y.; Wang, Z.; Li, C.; Tian, S.; Du, W. Droplet microfluidics: Unveiling the hidden complexity of the human microbiome. *Lab Chip* **2025**, *25*, 1128–1148.
92. Luo, X.; Wang, K.; Xue, Y.; Cao, X.; Zhou, J.; Wang, J. Digital PCR-free technologies for absolute quantitation of nucleic acids at single-molecule level. *Chin. Chem. Lett.* **2025**, *36*, 109924.
93. Hébert, M.; Courtney, M.; Ren, C.L. Semi-automated on-demand control of individual droplets with a sample application to a drug screening assay. *Lab Chip* **2019**, *19*, 1490–1501.
94. Shi, L.; Liu, S.; Li, X.; Huang, X.; Luo, H.; Bai, Q.; Li, Z.; Wang, L.; Du, X.; Jiang, C.; et al. Droplet microarray platforms for high-throughput drug screening. *Microchim. Acta* **2023**, *190*, 260. <https://doi.org/10.1007/s00604-023-05833-9>.
95. Shembekar, N.; Chaipan, C.; Utharala, R.; Merten, C.A. Droplet-based microfluidics in drug discovery, transcriptomics and high-throughput molecular genetics. *Lab Chip* **2016**, *16*, 1314–1331. <https://doi.org/10.1039/c6lc00249h>.
96. Zhai, J.; Li, C.; Li, H.; Yi, S.; Yang, N.; Miao, K.; Deng, C.; Jia, Y.; Mak, P.-I.; Martins, R.P. Cancer drug screening with an on-chip multi-drug dispenser in digital microfluidics. *Lab Chip* **2021**, *21*, 4749–4759. <https://doi.org/10.1039/d1lc00895a>.
97. Li, H.; Yang, Q.; Li, G.; Li, M.; Wang, S.; Song, Y. Splitting a droplet for femtoliter liquid patterns and single cell isolation. *ACS Appl. Mater. Interfaces* **2015**, *7*, 9060–9065. <https://doi.org/10.1021/am509177s>.
98. Joensson, H.N.; Svahn, H.A. Droplet microfluidics-A tool for single-cell analysis. *Angew. Chem. Int. Ed. Engl.* **2012**, *51*, 12176–12192. <https://doi.org/10.1002/anie.201200460>.
99. Matuła, K.; Ravello, F.; Huck, W.T.S. Single-Cell Analysis Using Droplet Microfluidics. *Adv. Biosyst.* **2019**, *4*, e1900188. <https://doi.org/10.1002/adbi.201900188>.
100. Mazutis, L.; Gilbert, J.; Ung, W.L.; Weitz, D.A.; Griffiths, A.D.; Heyman, J.A. Single-cell analysis and sorting using droplet-based microfluidics. *Nat. Protoc.* **2013**, *8*, 870–891.
101. Hochstetter, A. Lab-on-a-chip technologies for the single cell level: Separation, analysis, and diagnostics. *Micromachines* **2020**, *11*, 468. <https://doi.org/10.3390/M11050468>.
102. Kunstmann-Olsen, C.; Hanczyc, M.M.; Hoyland, J.; Rasmussen, S.; Rubahn, H.G. Uniform droplet splitting and detection using Lab-on-Chip flow cytometry on a microfluidic PDMS device. *Sens. Actuators B Chem.* **2016**, *229*, 7–13. <https://doi.org/10.1016/j.snb.2016.01.120>.
103. Dak, P.; Ebrahimi, A.; Swaminathan, V.; Duarte-Guevara, C.; Bashir, R.; Alam, M.A. Droplet-based biosensing for lab-on-a-chip, open microfluidics platforms. *Biosensors* **2016**, *6*, 14. <https://doi.org/10.3390/bios6020014>.
104. Kaminski, T.S.; Garstecki, P. Controlled droplet microfluidic systems for multistep chemical and biological assays. *Chem. Soc. Rev.* **2017**, *46*, 6210–6226. <https://doi.org/10.1039/c5cs00717h>.
105. Zhao, X.; Ou, G.; Lei, M.; Zhang, Y.; Li, L.; Ge, A.; Wang, Y.; Li, Y.; Liu, B.-F. Rapid generation of hybrid biochemical/mechanical cues in heterogeneous droplets for high-throughput screening of cellular responses. *Lab Chip* **2021**, *21*, 2691–2701. <https://doi.org/10.1039/d1lc00209k>.

106. Gach, P.C.; Iwai, K.; Kim, P.W.; Hillson, N.J.; Singh, A.K. Droplet microfluidics for synthetic biology. *Lab Chip* **2017**, *17*, 3388–3400. <https://doi.org/10.1039/c7lc00576h>.
107. Bowman, E.K.; Alper, H.S. Microdroplet-Assisted Screening of Biomolecule Production for Metabolic Engineering Applications. *Trends Biotechnol.* **2020**, *38*, 701–714. <https://doi.org/10.1016/j.tibtech.2019.11.002>.
108. Yang, L.; Lu, Q. Beyond Cutting: CRISPR-Driven Synthetic Biology Toolkit for Next-Generation Microalgal Metabolic Engineering. *Int. J. Mol. Sci.* **2025**, *26*, 7470.
109. Jenjob, R.; Phakkeeree, T.; Seidi, F.; Theerasilp, M.; Crespy, D. Emulsion Techniques for the Production of Pharmacological Nanoparticles. *Macromol. Biosci.* **2019**, *19*, e1900063. <https://doi.org/10.1002/mabi.201900063>.
110. Roy, S.; Kumar, R.; Acooli, A.; Roy, S.; Chatterjee, A.; Chattaraj, S.; Nayak, J.; Jeon, B.-H.; Basu, A.; Banerjee, S.; et al. Transforming Nanomaterial Synthesis through Advanced Microfluidic Approaches: A Review on Accessing Unrestricted Possibilities. *J. Compos. Sci.* **2024**, *8*, 386.
111. Dhand, C.; Dwivedi, N.; Loh, X.J.; Ying, A.N.J.; Verma, N.J.; Beuerman, R.W.; Lakshminarayanan, R.; Ramakrishna, S. Methods and strategies for the synthesis of diverse nanoparticles and their applications: A comprehensive overview. *RSC Adv.* **2015**, *5*, 105003–105037. <https://doi.org/10.1039/c5ra19388e>.
112. Kumar, S.; Kaushal, J.B.; Lee, H.P. Sustainable sensing with paper microfluidics: Applications in health, environment, and food safety. *Biosensors* **2024**, *14*, 300.
113. Yang, Y.; Chen, Y.; Tang, H.; Zong, N.; Jiang, X. Microfluidics for Biomedical Analysis. *Small Methods* **2020**, *4*, 1900451. <https://doi.org/10.1002/smtd.201900451>.
114. Hess, D.; Yang, T.; Stavarakis, S. Droplet-based optofluidic systems for measuring enzyme kinetics. *Anal. Bioanal. Chem.* **2020**, *412*, 3265–3283. <https://doi.org/10.1007/s00216-019-02294-z>.
115. Ding, Y.; Howes, P.D.; Demello, A.J. Recent advances in droplet microfluidics. *Anal. Chem.* **2020**, *92*, 132–149. <https://doi.org/10.1021/acs.analchem.9b05047>.
116. He, K.; Lin, Y.; Guo, X.-J.; Yuan, W.; Ge, Y.; Huang, S.-M. Phase-splitting features and polydispersity of droplet/slug flow split in a mini-T-junction: Effect of wall wettability. *Exp. Therm. Fluid. Sci.* **2022**, *133*, 110579.
117. Chang, J.; Xu, R.; Cui, J.; Song, Q.; Shen, T. Influences of liquid viscosity and relative velocity on the head-on collisions of immiscible drops. *Energies* **2022**, *15*, 8544.
118. Zhang, J.; Wang, Y.; Chen, L.; Shen, L.; Cui, H. Modelling the passive breakup of a surfactant-contaminated droplet in a T-junction microchannel. *J. Fluid. Mech.* **2024**, *986*, A23.
119. De Menech, M. Modeling of droplet breakup in a microfluidic T-shaped junction with a phase-field model. *Phys. Rev. E Stat. Nonlinear Soft Matter Phys.* **2006**, *73*, 031505. <https://doi.org/10.1103/PhysRevE.73.031505>.
120. Afkhami, S.; Leshansky, A.M.; Renardy, Y. Numerical investigation of elongated drops in a microfluidic T-junction. *Phys. Fluids* **2011**, *23*, 022002. <https://doi.org/10.1063/1.3549266>.
121. Nguyen, T.T.; Hoang, V.T.; Park, J.M. A proposed model for predicting droplet breakup dynamics in microfluidic T-junction. *J. Micromech. Microeng.* **2025**, *35*, 075005. <https://doi.org/10.1088/1361-6439/ade44b>.
122. Sun, X.; Zhu, C.; Fu, T.; Ma, Y.; Li, H.Z. Dynamics of droplet breakup and formation of satellite droplets in a microfluidic T-junction. *Chem. Eng. Sci.* **2018**, *188*, 158–169. <https://doi.org/10.1016/j.ces.2018.05.027>.
123. Zhou, J.; Ducimetière, Y.-M.; Migliozi, D.; Keiser, L.; Bertsch, A.; Gallaire, F.; Renaud, P. Breaking one into three: Surface-tension-driven droplet breakup in T-junctions. *Phys. Rev. Fluids* **2023**, *8*, 054201. <https://doi.org/10.1103/PhysRevFluids.8.054201>.
124. Deng, Z.; Wu, S.; Chen, Y. Theoretical study on sequential splitting of droplets flowing through fractal tree-shaped microchannel networks. *Int. J. Multiph. Flow* **2024**, *180*, 104953. <https://doi.org/10.1016/j.ijmultiphaseflow.2024.104953>.
125. Fan, L.-L.; Wang, W.; Ju, X.-J.; Liu, Z.; Xie, R.; Xu, J.; Luo, G.; Pan, D.-W.; Chu, L.-Y. High-throughput generation of monodisperse double emulsions via controllable symmetric splitting in Y-shaped microchannels. *Chem. Eng. J.* **2024**, *498*, 155727. <https://doi.org/10.1016/j.cej.2024.155727>.
126. Liu, Z.; Liu, W.; Pang, Y.; Li, D.; Zhang, C.; Wang, X. Experimental study on dynamics of double emulsion droplets flowing through the Y-shaped bifurcation. *Colloids Surf. A Physicochem. Eng. Asp.* **2022**, *654*, 130141. <https://doi.org/10.1016/j.colsurfa.2022.130141>.
127. Wang, X.; Sun, C.; Jia, S.; Pang, Y.; Liu, Z. Flow pattern maps of double emulsions transporting through bifurcation microchannels. *Soft Matter* **2024**, *20*, 6544–6557. <https://doi.org/10.1039/D4SM00488D>.
128. Ma, D.; Liang, D.; Zhu, C.; Fu, T.; Ma, Y.; Yuan, X.; Li, H.Z. The breakup dynamics and mechanism of viscous droplets in Y-shaped microchannels. *Chem. Eng. Sci.* **2021**, *231*, 116300. <https://doi.org/10.1016/j.ces.2020.116300>.

129. Wang, X.; Liu, Z.; Pang, Y. Asymmetric breakup of double emulsion droplets in symmetric junctions. *Exp. Therm. Fluid. Sci.* **2025**, *169*, 111542 <https://doi.org/10.1016/j.expthermflusci.2025.111542>.
130. Lemeski, A.T.; Seyyedi, S.M.; Hashemi-Tilehnoee, M.; Naeimi, A.S. Influence of triangular obstacles on droplet breakup dynamics in microfluidic systems. *Sci. Rep.* **2024**, *14*, 13324. <https://doi.org/10.1038/s41598-024-63922-y>.
131. Boruah, M.P.; Sarker, A.; Randive, P.R.; Pati, S.; Chakraborty, S. Wettability-mediated dynamics of two-phase flow in microfluidic T-junction. *Phys. Fluids* **2018**, *30*, 122106. <https://doi.org/10.1063/1.5054898>.
132. Kumar, P.; Pathak, M. Effect of velocity slip on the flow and heat transfer characteristics during droplet formation in a microfluidic T-junction. *J. Therm. Anal. Calorim.* **2023**, *148*, 2737–2747. <https://doi.org/10.1007/s10973-022-11622-y>.
133. Li, X.; He, L.; Lv, S.; Xu, C.; Qian, P.; Xie, F.; Liu, M. Effects of wall velocity slip on droplet generation in microfluidic T-junctions. *RSC Adv.* **2019**, *9*, 23229–23240. <https://doi.org/10.1039/c9ra03761f>.
134. Kumar, P.; Pathak, M. Controlling microfluidic droplet splitting in T-junction via wall slip. *Phys. Fluids* **2025**, *37*, 093350. <https://doi.org/10.1063/5.0284496>.
135. Kumar, P.; Pathak, M. Droplet formation under wall slip in a microfluidic T-junction. *J. Mol. Liq.* **2022**, *345*, 117808. <https://doi.org/10.1016/j.molliq.2021.117808>.
136. Tabeling, P. A brief introduction to slippage, droplets and mixing in microfluidic systems. *Lab Chip* **2009**, *9*, 2428–2436. <https://doi.org/10.1039/b904937c>.
137. Maali, A.; Bhushan, B. Review article: Measurement of slip length on superhydrophobic surfaces. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2012**, *370*, 2304–2320. <https://doi.org/10.1098/rsta.2011.0505>.
138. Wang, Y.; Huang, J.-J. Wetting and Spreading Behavior of Axisymmetric Compound Droplets on Curved Solid Walls Using Conservative Phase Field Lattice Boltzmann Method. *Entropy* **2024**, *26*, 172.
139. Zhu, L.; Tretheway, D.; Petzold, L.; Meinhart, C. Simulation of fluid slip at 3D hydrophobic microchannel walls by the lattice Boltzmann method. *J. Comput. Phys.* **2005**, *202*, 181–195. <https://doi.org/10.1016/j.jcp.2004.07.004>.
140. Blake, T.D. Slip between a liquid and a solid: D.M. Tolstói's (1952) theory reconsidered. *Colloids Surf.* **1990**, *47*, 135–145. [https://doi.org/10.1016/0166-6622\(90\)80068-F](https://doi.org/10.1016/0166-6622(90)80068-F).
141. Lin, J.-L.; Hsu, P.-P.; Kuo, J.-N. Magnetic beads inside droplets for agitation and splitting manipulation by utilizing a magnetically actuated platform. *Micromachines* **2023**, *14*, 1349.
142. Joseph, P.; Tabeling, P. Direct measurement of the apparent slip length. *Phys. Rev. E Stat. Nonlinear Soft Matter Phys.* **2005**, *71*, 035303. <https://doi.org/10.1103/PhysRevE.71.035303>.
143. Tretheway, D.C.; Meinhart, C.D. Apparent fluid slip at hydrophobic microchannel walls. *Phys. Fluids* **2002**, *14*, L9–L12. <https://doi.org/10.1063/1.1432696>.
144. Baudry, J.; Charlaix, E.; Tonck, A.; Mazuyer, D. Experimental evidence for a large slip effect at a nonwetting fluid-solid interface. *Langmuir* **2001**, *17*, 5232–5236. <https://doi.org/10.1021/la0009994>.
145. Link, D.R.; Grasland-Mongrain, E.; Duri, A.; Sarrazin, F.; Cheng, Z.; Cristobal, G.; Marquez, M.; Weitz, D.A. Electric control of droplets in microfluidic devices. *Angew. Chem.-Int. Ed.* **2006**, *45*, 2556–2560. <https://doi.org/10.1002/anie.200503540>.
146. Yin, S.; Huang, Y.; Wong, T.N.; Ooi, K.T. Dynamics of droplet in flow-focusing microchannel under AC electric fields. *Int. J. Multiph. Flow.* **2020**, *125*, 103212. <https://doi.org/10.1016/j.ijmultiphaseflow.2020.103212>.
147. Hatami, M.; Ramiar, A.; Ranjbar, A.A. Numerical assessment of different parameters affecting droplet production in an Electro-Hydrodynamic Flow Focusing Device. *Chem. Eng. Process.-Process Intensif.* **2018**, *131*, 190–202. <https://doi.org/10.1016/j.cep.2018.07.017>.
148. Zhu, H.; Lu, S.; Xu, X.; Lei, M.; Xu, W.; Li, Q. Numerical investigation on flow regime transition mechanism and length prediction method of droplet in T-junction by electric field. *Chem. Eng. J.* **2024**, *485*, 149874. <https://doi.org/10.1016/j.cej.2024.149874>.
149. Chetia, L.C.; Pati, S.; Randive, P.R. Role of wettability and electric field on droplet splitting dynamics in T-shaped branched microchannel. *Phys. Fluids* **2025**, *37*, 092015.
150. Das, D.; Biswas, N. A comprehensive review on electrically modulated transport of soft, multiphase systems in microflow: Perspectives on drops and vesicles. *Biomicrofluidics* **2025**, *19*, 031503. <https://doi.org/10.1063/5.0254950>.
151. Fadaei, M.; Majidi, S.; Shoeibi, H. Droplet generation in a co-flowing microchannel under the non-uniform magnetic fields produced by an electric current loop. *J. Magn. Magn. Mater.* **2024**, *612*, 172645. <https://doi.org/10.1016/j.jmmm.2024.172645>.
152. Pandey, S.P.; Sarkar, S.; Pal, D. Study of Path Selection of a Droplet in a Symmetric Y-Microchannel Using a Uniform Electric Field. In *Fluid Mechanics and Fluid Power; Lecture Notes in Mechanical Engineering*; Springer: Singapore, 2024. https://doi.org/10.1007/978-981-99-7177-0_36.

153. Singh, R.; Bahga, S.S.; Gupta, A. Electrohydrodynamic droplet formation in a T-junction microfluidic device. *J. Fluid. Mech.* **2020**, *905*, A29. <https://doi.org/10.1017/jfm.2020.749>.
154. Tan, S.H.; Nguyen, N.T.; Yobas, L.; Kang, T.G. Formation and manipulation of ferrofluid droplets at a microfluidic T-junction. *J. Micromech. Microeng.* **2010**, *20*, 045004. <https://doi.org/10.1088/0960-1317/20/4/045004>.
155. Zhu, G.-P.; Wang, Q.-Y.; Ma, Z.-K.; Wu, S.-H.; Guo, Y.-P. Droplet manipulation under a magnetic field: A review. *Biosensors* **2022**, *12*, 156.
156. Aboutalebi, M.; Adibi, O.; Bijarchi, M.A.; Shafii, M.B.; Hannani, S.K. The variations of breakup and non-breakup regions for ferrofluid microdroplets in T-junctions with a proposed correlation. *Sci. Iran.* **2025**, *32*. <https://doi.org/10.24200/sci.2024.57207.5113>.
157. Aboutalebi, M.; Bijarchi, M.A.; Shafii, M.B.; Hannani, S.K. Numerical investigation on splitting of ferrofluid microdroplets in T-junctions using an asymmetric magnetic field with proposed correlation. *J. Magn. Magn. Mater.* **2018**, *447*, 139–149. <https://doi.org/10.1016/j.jmmm.2017.09.053>.
158. Ma, R.; Fu, T.; Zhang, Q.; Zhu, C.; Ma, Y.; Li, H.Z. Breakup dynamics of ferrofluid droplet in a microfluidic T-junction. *J. Ind. Eng. Chem.* **2017**, *54*, 408–420. <https://doi.org/10.1016/j.jiec.2017.06.021>.
159. Shyam, S.; Dhapola, B.; Mondal, P.K. Magnetofluidic-based controlled droplet breakup: Effect of non-uniform force field. *J. Fluid. Mech.* **2022**, *944*, A51. <https://doi.org/10.1017/jfm.2022.504>.
160. Outokesh, M.; Amiri, H.A.; Miansari, M. Numerical insights into magnetic particle enrichment and separation in an integrated droplet microfluidic system. *Chem. Eng. Process.-Process Intensif.* **2022**, *170*, 108696. <https://doi.org/10.1016/j.cep.2021.108696>.
161. Wu, J.; Altalbawy, F.M.; Vaghela, K.; Praveen, K.R.; Kashyap, A.; Chauhan, K.; Bindu, D.; Alimova, F.; Sahu, P.K.; Faez, F.; et al. The effect of an external magnetic field on the breakup dynamics of a magnetic droplet in a micro-magneto fluidic system. *Chem. Eng. Res. Des.* **2025**, *222*, 468–485. <https://doi.org/10.1016/j.cherd.2025.09.016>.
162. Jiao, Z.; Huang, X.; Nguyen, N.T.; Abgrall, P. Thermocapillary actuation of droplet in a planar microchannel. *Microfluid. Nanofluid.* **2008**, *5*, 205–214. <https://doi.org/10.1007/s10404-007-0235-7>.
163. Khater, A.; Abdelrehim, O.; Mohammadi, M.; Mohamad, A.; Sanati-Nezhad, A. Thermal droplet microfluidics: From biology to cooling technology. *TrAC Trends Anal. Chem.* **2021**, *138*, 116234. <https://doi.org/10.1016/j.trac.2021.116234>.
164. De Mello, A.J.; Habgood, M.; Lancaster, N.L.; Welton, T.; Wootton, R.C.R. Precise temperature control in microfluidic devices using Joule heating of ionic liquids. *Lab Chip* **2004**, *4*, 417–419. <https://doi.org/10.1039/b405760k>.
165. Kondoh, J.; Shimizu, N.; Matsui, Y.; Sugimoto, M.; Shiokawa, S. Development of temperature-control system for liquid droplet using surface Acoustic wave devices. *Sens. Actuators A Phys.* **2009**, *149*, 292–297. <https://doi.org/10.1016/j.sna.2008.11.007>.
166. Murshed, S.M.S.; Tan, S.H.; Nguyen, N.T.; Wong, T.N.; Yobas, L. Microdroplet formation of water and nanofluids in heat-induced microfluidic T-junction. *Microfluid. Nanofluid.* **2009**, *6*, 253–259. <https://doi.org/10.1007/s10404-008-0323-3>.
167. Ting, T.H.; Yap, Y.F.; Nguyen, N.T.; Wong, T.N.; Chai, J.C.K.; Yobas, L. Thermally mediated breakup of drops in microchannels. *Appl. Phys. Lett.* **2006**, *89*, 234101. <https://doi.org/10.1063/1.2400200>.
168. Nguyen, N.-T.; Ting, T.-H.; Yap, Y.-F.; Wong, T.-N.; Chai, J.C.-K.; Ong, W.-L.; Zhou, J.; Tan, S.-H.; Yobas, L. Thermally mediated droplet formation in microchannels. *Appl. Phys. Lett.* **2007**, *91*, 084102. <https://doi.org/10.1063/1.2773948>.
169. Hoa, P.-C.; Yap, Y.-F.; Nguyen, N.-T.; Chai, J.C.-K. Thermally Mediated Droplet Formation at a Microfluidic T-Junction. *Micro Nanosyst.* **2011**, *3*, 65–75. <https://doi.org/10.2174/1876402911103010065>.
170. Nath, A.J.; Deka, D.K.; Pati, S. Thermally Mediated Droplet Breakup Dynamics Within a Symmetric T-Junction. *J. Fluids Eng.* **2025**, *147*, 081402. <https://doi.org/10.1115/1.4067961>.
171. Yap, Y.F.; Tan, S.H.; Nguyen, N.T.; Murshed, S.M.S.; Wong, T.N.; Yobas, L. Thermally mediated control of liquid microdroplets at a bifurcation. *J. Phys. D Appl. Phys.* **2009**, *42*, 065503. <https://doi.org/10.1088/0022-3727/42/6/065503>.
172. Park, J.; Jung, J.H.; Park, K.; Destgeer, G.; Ahmed, H.; Ahmad, R.; Sung, H.J. On-demand acoustic droplet splitting and steering in a disposable microfluidic chip. *Lab Chip* **2018**, *18*, 422–432. <https://doi.org/10.1039/C7LC01083D>.
173. Thirisangu, J.; Rajendran, V.K.; Selvakannan, S.; Jayakumar, S.; Hemachandran, E.; Subramani, K. Droplets in acoustic fields: A unified theory from migration to splitting. *Phys. Fluids* **2025**, *37*, 052012.
174. Park, J.; Destgeer, G.; Kim, H.; Cho, Y.; Sung, H.J. In-droplet microparticle washing and enrichment using surface acoustic wave-driven acoustic radiation force. *Lab Chip* **2018**, *18*, 2936–2945.
175. Jung, J.H.; Destgeer, G.; Ha, B.; Park, J.; Sung, H.J. On-demand droplet splitting using surface acoustic waves. *Lab Chip* **2016**, *16*, 3235–3243.
176. Sesen, M.; Alan, T.; Neild, A. Microfluidic plug steering using surface acoustic waves. *Lab Chip* **2015**, *15*, 3030–3038.
177. Huang, Y.; Das, P.K.; Bhethanabotla, V.R. Surface acoustic waves in biosensing applications. *Sens. Actuators Rep.* **2021**, *3*, 100041.

178. Park, K.; Park, J.; Jung, J.H.; Destgeer, G.; Ahmed, H.; Sung, H.J. In-droplet microparticle separation using travelling surface acoustic wave. *Biomicrofluidics* **2017**, *11*, 064112.
179. Leibacher, I.; Reichert, P.; Dual, J. Microfluidic droplet handling by bulk acoustic wave (BAW) acoustophoresis. *Lab Chip* **2015**, *15*, 2896–2905.
180. Fornell, A.; Ohlin, M.; Garofalo, F.; Nilsson, J.; Tenje, M. An intra-droplet particle switch for droplet microfluidics using bulk acoustic waves. *Biomicrofluidics* **2017**, *11*, 031101.
181. Xu, D.; Pei, Y.; Qiu, W. Continuous and tunable droplet splitting using standing-wave acoustofluidics. *Lab Chip* **2025**, *25*, 6442–6453.
182. Choi, J.H.; Lee, S.K.; Lim, J.M.; Yang, S.M.; Yi, G.R. Designed pneumatic valve actuators for controlled droplet breakup and generation. *Lab Chip* **2010**, *10*, 456–461. <https://doi.org/10.1039/b915596a>.
183. Agnihotri, S.N.; Raveshi, M.R.; Bhardwaj, R.; Neild, A. Microfluidic Valves for Selective on-Chip Droplet Splitting at Multiple Sites. *Langmuir* **2020**, *36*, 1138–1146. <https://doi.org/10.1021/acs.langmuir.9b03515>.
184. Agnihotri, S.N.; Raveshi, M.R.; Bhardwaj, R.; Neild, A. Microvalves for integrated selective droplet generation, splitting and merging on a chip. *Microfluid. Nanofluid.* **2021**, *25*, 88. <https://doi.org/10.1007/s10404-021-02487-y>.
185. Raveshi, M.R.; Agnihotri, S.N.; Sesen, M.; Bhardwaj, R.; Neild, A. Selective droplet splitting using single layer microfluidic valves. *Sens. Actuators B Chem.* **2019**, *292*, 233–240. <https://doi.org/10.1016/j.snb.2019.04.115>.
186. Yoon, D.H.; Ito, J.; Sekiguchi, T.; Shoji, S. Active and precise control of microdroplet division using horizontal pneumatic valves in bifurcating microchannel. *Micromachines* **2013**, *4*, 197–205. <https://doi.org/10.3390/mi4020197>.
187. Li, Z.; Li, L.; Liao, M.; He, L.; Wu, P. Multiple splitting of droplets using multi-furcating microfluidic channels. *Biomicrofluidics* **2019**, *13*, 024112. <https://doi.org/10.1063/1.5086716>.
188. Cheng, W.L.; Sadr, R.; Dai, J.; Han, A. Prediction of Microdroplet Breakup Regime in Asymmetric T-Junction Microchannels. *Biomed. Microdevices* **2018**, *20*, 72. <https://doi.org/10.1007/s10544-018-0310-8>.
189. Nie, J.; Kennedy, R.T. Sampling from nanoliter plugs via asymmetrical splitting of segmented flow. *Anal. Chem.* **2010**, *82*, 7852–7856. <https://doi.org/10.1021/ac101723x>.
190. Fu, T.; Ma, Y.; Li, H.Z. Hydrodynamic feedback on bubble breakup at a T-junction within an asymmetric loop. *AIChE J.* **2014**, *60*, 1920–1929. <https://doi.org/10.1002/aic.14377>.
191. Abate, A.R.; Weitz, D.A. High-order multiple emulsions formed in poly(dimethylsiloxane) microfluidics. *Small* **2009**, *5*, 2030–2032. <https://doi.org/10.1002/smll.200900569>.
192. Kovalev, A.; Yagodnitsyna, A.; Bartkus, G.; Bilsky, A. Control of pluf flow dynamics in microfluidics T-junction using pulsations of dispersed phase flow rate. *Int. J. Thermofluids* **2024**, *23*, 100720.
193. van Elburg, B.; Collado-Lara, G.; Bruggert, G.-W.; Segers, T.; Versluis, M.; Lajoinie, G. Feedback-controlled microbubble generator producing one million monodisperse bubbles per second. *Rev. Sci. Instrum.* **2021**, *92*, 035110.
194. Zhou, P.; He, H.; Ma, H.; Wang, S.; Hu, S. A Review of Optical Imaging Technologies for Microfluidics. *Micromachines* **2022**, *13*, 274. <https://doi.org/10.3390/mi13020274>.
195. Cao, Q.; Chen, W.; Zhong, Y.; Ma, X.; Wang, B. Biomedical Applications of Deformable Hydrogel Microrobots. *Micromachines* **2023**, *14*, 1824. <https://doi.org/10.3390/mi14101824>.
196. Wang, J.; Yang, L.; Wang, H.; Wang, L. Application of Microfluidic Chips in the Detection of Airborne Microorganisms. *Micromachines* **2022**, *13*, 1576. <https://doi.org/10.3390/mi13101576>.
197. Zhou, J.; Ellis, A.V.; Voelcker, N.H. Recent developments in PDMS surface modification for microfluidic devices. *Electrophoresis* **2010**, *31*, 2–16. <https://doi.org/10.1002/elps.200900475>.
198. Shakeri, A.; Khan, S.; Didar, T.F. Conventional and emerging strategies for the fabrication and functionalization of PDMS-based microfluidic devices. *Lab Chip* **2021**, *21*, 3053–3075. <https://doi.org/10.1039/d1lc00288k>.
199. Kumar, A.; Kumar, P.; Pathak, M. Spreading and migration characteristics of impacting droplets on hybrid-wettability surfaces. *Phys. Fluids* **2024**, *36*, 052106.
200. Kovach, K.M.; Capadona, J.R.; Gupta, A.S.; Potkay, J.A. The effects of PEG-based surface modification of PDMS microchannels on long-term hemocompatibility. *J. Biomed. Mater. Res. A* **2014**, *102*, 4195–4205. <https://doi.org/10.1002/jbm.a.35090>.
201. Sasaki, H.; Onoe, H.; Osaki, T.; Kawano, R.; Takeuchi, S. Parylene-coating in PDMS microfluidic channels prevents the absorption of fluorescent dyes. *Sens. Actuators B Chem.* **2010**, *150*, 478–482. <https://doi.org/10.1016/j.snb.2010.07.021>.
202. Tsao, C.W. Polymer microfluidics: Simple, low-cost fabrication process bridging academic lab research to commercialized production. *Micromachines* **2016**, *7*, 225. <https://doi.org/10.3390/mi7120225>.

203. Lee, J.; Kim, M. Polymeric Microfluidic Devices Fabricated Using Epoxy Resin for Chemically Demanding and Day-Long Experiments. *Biosensors* **2022**, *12*, 838. <https://doi.org/10.3390/bios12100838>.
204. McDonald, J.C.; Whitesides, G.M. Poly(dimethylsiloxane) as a material for fabricating microfluidic devices. *Acc. Chem. Res.* **2002**, *35*, 491–499. <https://doi.org/10.1021/ar010110q>.
205. Regehr, K.J.; Domenech, M.; Koepsel, J.T.; Carver, K.C.; Ellison-Zelski, S.J.; Murphy, W.L.; Schuler, L.A.; Alarid, E.T.; Beebe, D.J. Biological implications of polydimethylsiloxane-based microfluidic cell culture. *Lab Chip* **2009**, *9*, 2132–2139. <https://doi.org/10.1039/b903043c>.
206. Liu, K.; Xiang, J.; Ai, Z.; Zhang, S.; Fang, Y.; Chen, T.; Zhou, Q.; Li, S.; Wang, S.; Zhang, N. PMMA microfluidic chip fabrication using laser ablation and low temperature bonding with OCA film and LOCA. *Microsyst. Technol.* **2017**, *23*, 1937–1942. <https://doi.org/10.1007/s00542-016-2924-1>.
207. Ma, X.; Li, R.; Jin, Z.; Fan, Y.; Zhou, X.; Zhang, Y. Injection molding and characterization of PMMA-based microfluidic devices. *Microsyst. Technol.* **2020**, *26*, 1317–1324. <https://doi.org/10.1007/s00542-019-04662-2>.
208. Keller, N.; Nargang, T.M.; Runck, M.; Kotz, F.; Striegel, A.; Sachsenheimer, K.; Klemm, D.; Länge, K.; Worgull, M.; Richter, C.; et al. Tacky cyclic olefin copolymer: A biocompatible bonding technique for the fabrication of microfluidic channels in COC. *Lab Chip* **2016**, *16*, 1561–1564. <https://doi.org/10.1039/c5lc01498k>.
209. Agha, A.; Waheed, W.; Alamoodi, N.; Mathew, B.; Alnaimat, F.; Abu-Nada, E.; Abderrahmane, A.; Alazzam, A. A Review of Cyclic Olefin Copolymer Applications in Microfluidics and Microdevices. *Macromol. Mater. Eng.* **2022**, *307*, 2200053. <https://doi.org/10.1002/mame.202200053>.
210. Alsharhan, A.T.; Acevedo, R.; Warren, R.; Sochol, R.D. 3D microfluidics: Via cyclic olefin polymer-based in situ direct laser writing. *Lab. Chip* **2019**, *19*, 2799–2810. <https://doi.org/10.1039/c9lc00542k>.
211. Bruijns, B.; Veciana, A.; Tiggelaar, R.; Gardeniers, H. Cyclic olefin copolymer microfluidic devices for forensic applications. *Biosensors* **2019**, *9*, 85. <https://doi.org/10.3390/bios9030085>.
212. Rodrigues, R.G.; Condelipes, P.G.M.; Rosa, R.R.; Chu, V.; Conde, J.P. Scalable Processing of Cyclic Olefin Copolymer (COC) Microfluidic Biochips. *Micromachines* **2023**, *14*, 1837. <https://doi.org/10.3390/mi14101837>.
213. Giri, K.; Tsao, C.W. Recent Advances in Thermoplastic Microfluidic Bonding. *Micromachines* **2022**, *13*, 486. <https://doi.org/10.3390/mi13030486>.
214. Shakeri, A.; Khan, S.; Jarad, N.A.; Didar, T.F. The Fabrication and Bonding of Thermoplastic Microfluidics: A Review. *Materials* **2022**, *15*, 6478. <https://doi.org/10.3390/ma15186478>.
215. Su, S.; Jing, G.; Zhang, M.; Liu, B.; Zhu, X.; Wang, B.; Fu, M.; Zhu, L.; Cheng, J.; Guo, Y. One-step bonding and hydrophobic surface modification method for rapid fabrication of polycarbonate-based droplet microfluidic chips. *Sens. Actuators B Chem.* **2019**, *282*, 60–68. <https://doi.org/10.1016/j.snb.2018.11.035>.
216. Priest, C.; Gruner, P.J.; Szili, E.J.; Al-Bataineh, S.A.; Bradley, J.W.; Ralston, J.; Steele, D.A.; Short, R.D. Microplasma patterning of bonded microchannels using high-precision ‘injected’ electrodes. *Lab Chip* **2011**, *11*, 541–544. <https://doi.org/10.1039/c0lc00339e>.
217. Li, H.; Zhao, M.; Liu, W.; Chu, W.; Guo, Y. Polydimethylsiloxane microfluidic chemiluminescence immunodevice with the signal amplification strategy for sensitive detection of human immunoglobulin G. *Talanta* **2016**, *147*, 430–436. <https://doi.org/10.1016/j.talanta.2015.10.018>.
218. Kim, H.J.; Huh, D.; Hamilton, G.; Ingber, D.E. Human gut-on-a-chip inhabited by microbial flora that experiences intestinal peristalsis-like motions and flow. *Lab Chip* **2012**, *12*, 2165–2174. <https://doi.org/10.1039/c2lc40074j>.
219. Koh, K.S.; Chin, J.; Chia, J.; Chiang, C.L. Quantitative studies on PDMS-PDMS interface bonding with piranha solution and its swelling effect. *Micromachines* **2012**, *3*, 427–441. <https://doi.org/10.3390/mi3020427>.
220. Siddique, A.; Meckel, T.; Stark, R.W.; Narayan, S. Improved cell adhesion under shear stress in PDMS microfluidic devices. *Colloids Surf. B Biointerfaces* **2017**, *150*, 456–464. <https://doi.org/10.1016/j.colsurfb.2016.11.011>.
221. Li, C.-W.; Zhu, Y.; Zhan, J.; Ma, J.; Gu, L.; Fang, Y.; Yi, C. Separation of polystyrene nanoparticles in polydimethylsiloxane microfluidic devices with a combined titania and sodium dodecyl sulfate inner coating. *Microchim. Acta* **2017**, *184*, 2227–2239. <https://doi.org/10.1007/s00604-017-2202-7>.
222. Shay, T.; Dickey, M.D.; Velev, O.D. Hydrogel-enabled osmotic pumping for microfluidics: Towards wearable human-device interfaces. *Lab Chip* **2017**, *17*, 710–716. <https://doi.org/10.1039/C6LC01486K>.
223. Ma, X.; Guo, G.; Wu, X.; Wu, Q.; Liu, F.; Zhang, H.; Shi, N.; Guan, Y. Advances in Integration, Wearable Applications, and Artificial Intelligence of Biomedical Microfluidics Systems. *Micromachines* **2023**, *14*, 972. <https://doi.org/10.3390/mi14050972>.

224. Nunes, P.S.; Ohlsson, P.D.; Ordeig, O.; Kutter, J.P. Cyclic olefin polymers: Emerging materials for lab-on-a-chip applications. *Microfluid. Nanofluid.* **2010**, *9*, 145–161. <https://doi.org/10.1007/s10404-010-0605-4>.
225. Perozziello, G.; Simone, G.; Malara, N.; La Rocca, R.; Talerico, R.; Catalano, R.; Pardeo, F.; Candeloro, P.; Cuda, G.; Carbone, E.; et al. Microfluidic biofunctionalisation protocols to form multi-valent interactions for cell rolling and phenotype modification investigations. *Electrophoresis* **2013**, *34*, 1845–1851. <https://doi.org/10.1002/elps.201300106>.
226. Sui, G.; Wang, J.; Lee, C.-C.; Lu, W.; Lee, S.P.; Leyton, J.V.; Wu, A.M.; Tseng, H.-R. Solution-phase surface modification in intact poly(dimethylsiloxane) microfluidic channels. *Anal. Chem.* **2006**, *78*, 5543–5551. <https://doi.org/10.1021/ac060605z>.
227. Greiner, A.M.; Hoffmann, P.; Bruellhoff, K.; Jungbauer, S.; Spatz, J.P.; Moeller, M.; Kemkemer, R.; Groll, J. Stable biochemically micro-patterned hydrogel layers control specific cell adhesion and allow long term cyclic tensile strain experiments. *Macromol. Biosci.* **2014**, *14*, 1547–1555. <https://doi.org/10.1002/mabi.201400261>.
228. Vu, T.T.; Fouet, M.; Gue, A.M.; Sudor, J. A new and easy surface functionalization technology for monitoring wettability in heterogeneous nano- and microfluidic devices. *Sens. Actuators B Chem.* **2014**, *196*, 64–70. <https://doi.org/10.1016/j.snb.2014.01.085>.
229. Toepke, M.W.; Beebe, D.J. PDMS absorption of small molecules and consequences in microfluidic applications. *Lab Chip* **2006**, *6*, 1484–1486. <https://doi.org/10.1039/b612140c>.
230. Min, K.; Lim, J.; Lim, J.H.; Hwang, E.; Kim, Y.; Lee, H.; Lee, H.; Hong, S. Fabrication of perforated PDMS microchannel by successive laser pyrolysis. *Materials* **2021**, *14*, 7275. <https://doi.org/10.3390/ma14237275>.
231. Mora, A.E.M.; de Lima, S.M.M. Taylor droplet breakup in T-type microchannels: A detailed flow analysis. *Results Eng.* **2024**, *23*, 102513.
232. Brackbill, J.U.; Kothe, D.B.; Zemach, C. A continuum method for modeling surface tension. *J. Comput. Phys.* **1992**, *100*, 335–354. [https://doi.org/10.1016/0021-9991\(92\)90240-Y](https://doi.org/10.1016/0021-9991(92)90240-Y).
233. Sussman, M.; Puckett, E.G. A Coupled Level Set and Volume-of-Fluid Method for Computing 3D and Axisymmetric Incompressible Two-Phase Flows. *J. Comput. Phys.* **2000**, *162*, 301–337. <https://doi.org/10.1006/jcph.2000.6537>.
234. Xiao, F.; Dianat, M.; McGuirk, J.J. A robust interface method for drop formation and breakup simulation at high density ratio using an extrapolated liquid velocity. *Comput. Fluids* **2016**, *136*, 402–420. <https://doi.org/10.1016/j.compfluid.2016.06.021>.
235. da Silva, F.S.P.; Lisboa-Filho, P.N. Volume of Fluid (VOF) Method as a Suitable Method for Studying Droplet Formation in a Microchannel. *Micromachines* **2025**, *16*, 757.
236. Nekouei, M.; Vanapalli, S.A. Volume-of-fluid simulations in microfluidic T-junction devices: Influence of viscosity ratio on droplet size. *Phys. Fluids* **2017**, *29*, 032007. <https://doi.org/10.1063/1.4978801>.
237. Said, M.; Bouda, N.N.; Harmand, S. A Comparative Study of Two Numerical Methods Applied for 3D Liquid-Liquid Taylor Flow in a Microchannel. *J. Appl. Fluid. Mech.* **2024**, *17*, 1–18. <https://doi.org/10.47176/jafm.17.1.2157>.
238. Hoseinpour, B.; Sarreshtehdari, A. Lattice Boltzmann simulation of droplets manipulation generated in lab-on-chip (LOC) microfluidic T-junction. *J. Mol. Liq.* **2020**, *297*, 111736.
239. Hoseinpour, B.; Ashorynejad, H.R.; Sarreshtehdari, A. Investigation of droplet generation through Lab-On-Disk microfluidic system using Lattice Boltzmann Method. *J. Mol. Liq.* **2021**, *325*, 114961.
240. Liu, H.; Ba, Y.; Wu, L.; Li, Z.; Xi, G.; Zhang, Y. A hybrid lattice Boltzmann and finite difference method for droplet dynamics with insoluble surfactants. *J. Fluid. Mech.* **2018**, *837*, 381–412.
241. Liu, H.; Nan, L.; Chen, F.; Zhao, Y.; Zhao, Y. Functions and applications of artificial intelligence in droplet microfluidics. *Lab Chip* **2023**, *23*, 2497–2513. <https://doi.org/10.1039/d3lc00224a>.
242. Barnes, C.; Sonwane, A.R.; Sonnenschein, E.C.; Del Giudice, F. Machine learning enhanced droplet microfluidics. *Phys. Fluids* **2023**, *35*, 092003. <https://doi.org/10.1063/5.0163806>.
243. Dong, H.; Lin, J.; Tao, Y.; Jia, Y.; Sun, L.; Li, W.J.; Sun, H. AI-enhanced biomedical micro/nanorobots in microfluidics. *Lab Chip* **2024**, *24*, 1419–1440. <https://doi.org/10.1039/d3lc00909b>.
244. Wang, J.X.; Yu, W.; Wu, Z.; Liu, X.; Chen, Y. Physics-based statistical learning perspectives on droplet formation characteristics in microfluidic cross-junctions. *Appl. Phys. Lett.* **2022**, *120*, 204101. <https://doi.org/10.1063/5.0086933>.
245. Raissi, M.; Perdikaris, P.; Karniadakis, G.E. Physics-informed neural networks: A deep learning framework for solving forward and inverse problems involving nonlinear partial differential equations. *J. Comput. Phys.* **2019**, *378*, 686–707. <https://doi.org/10.1016/j.jcp.2018.10.045>.
246. Jin, X.; Cai, S.; Li, H.; Karniadakis, G.E. NSFnets (Navier-Stokes flow nets): Physics-informed neural networks for the incompressible Navier-Stokes equations. *J. Comput. Phys.* **2021**, *426*, 109951. <https://doi.org/10.1016/j.jcp.2020.109951>.
247. Zhang, Z.; Gu, G.X. Physics-informed deep learning for digital materials. *Theor. Appl. Mech. Lett.* **2021**, *11*, 100220. <https://doi.org/10.1016/j.taml.2021.100220>.

248. Kissas, G.; Yang, Y.; Hwuang, E.; Witschey, W.R.; Detre, J.A.; Perdikaris, P. Machine learning in cardiovascular flows modeling: Predicting arterial blood pressure from non-invasive 4D flow MRI data using physics-informed neural networks. *Comput. Methods Appl. Mech. Eng.* **2020**, *358*, 112623. <https://doi.org/10.1016/j.cma.2019.112623>.
249. Wang, Y.; Han, X.; Chang, C.-Y.; Zha, D.; Braga-Neto, U.; Hu, X. Auto-PINN: Understanding and Optimizing Physics-Informed Neural Architecture. *arXiv* **2023**, arXiv:2205.13748. <https://doi.org/10.48550/arXiv.2205.13748>.
250. Hinderink, E.; Bera, B.; Schinkel, C.; van Steijn, V. Coalescence of concentrated emulsions in microfluidic constrictions through avalanches. *Sci. Rep.* **2025**, *15*, 5720. <https://doi.org/10.1038/s41598-025-87291-2>.
251. Mazutis, L.; Baret, J.-C.; Treacy, P.; Skhiri, Y.; Araghi, A.F.; Ryckelynck, M.; Taly, V.; Griffiths, A.D. Multi-step microfluidic droplet processing: Kinetic analysis of an in vitro translated enzyme. *Lab Chip* **2009**, *9*, 2902–2908. <https://doi.org/10.1039/B907753G>.
252. Biniwale, R.B.; Ichikawa, M. Thermal imaging of catalyst surface during catalytic dehydrogenation of cyclohexane under spray-pulsed conditions. *Chem. Eng. Sci.* **2007**, *62*, 7370–7377.
253. Constante-Amores, C.; Batchvarov, A.; Kahouadji, L.; Shin, S.; Chergui, J.; Juric, D.; Matar, O. Role of surfactant-induced Marangoni stresses in drop-interface coalescence. *J. Fluid. Mech.* **2021**, *925*, A15.
254. Papamatthaiou, S.; Menelaou, P.; El Achab Oussallam, B.; Moschou, D. Recent advances in bio-microsystem integration and Lab-on-PCB technology. *Microsyst. Nanoeng.* **2025**, *11*, 78.
255. Rondot, N.; Yan, S.; Mager, D.; Kulinsky, L. A low-cost printed circuit board-based centrifugal microfluidic platform for dielectrophoresis. *Microsyst. Nanoeng.* **2025**, *11*, 23.
256. Volgin, V.M.; Kabanova, T.B.; Davydov, A.D. Modeling of local maskless electrochemical deposition of metal microcolumns. *Chem. Eng. Sci.* **2018**, *183*, 123–135. <https://doi.org/10.1016/j.ces.2018.03.019>.
257. Arratia, P.E.; Gollub, J.P.; Durian, D.J. Polymeric filament thinning and breakup in microchannels. *Phys. Rev. E—Stat. Nonlinear Soft Matter Phys.* **2008**, *77*, 036309.
258. Hindson, B.J.; Ness, K.D.; Masquelier, D.A.; Belgrader, P.; Heredia, N.J.; Makarewicz, A.J.; Bright, I.J.; Lucero, M.Y.; Hiddessen, A.L.; Legler, T.C.; et al. High-Throughput Droplet Digital PCR System for Absolute Quantitation of DNA Copy Number. *Anal. Chem.* **2011**, *83*, 8604–8610. <https://doi.org/10.1021/ac202028g>.
259. Fallah-Araghi, A.; Baret, J.-C.; Ryckelynck, M.; Griffiths, A.D. A completely in vitro ultrahigh-throughput droplet-based microfluidic screening system for protein engineering and directed evolution. *Lab Chip* **2012**, *12*, 882–891. <https://doi.org/10.1039/C2LC21035E>.
260. Guo, M.T.; Rotem, A.; Heyman, J.A.; Weitz, D.A. Droplet microfluidics for high-throughput biological assays. *Lab Chip* **2012**, *12*, 2146–2155. <https://doi.org/10.1039/C2LC21147E>.

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