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Acoustics in additive manufacturing: A path toward contactless, scalable, and high-precision manufacturing

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ABSTRACT

Acoustic techniques have emerged as a transformative approach in additive manufacturing, enabling contactless, high-precision manipulation of particles, droplets, and cells through acoustic wavefields. While acoustic patterning has demonstrated remarkable control over microscale spatial configurations, its scalability into three-dimensional (3D) fabrication has remained constrained by challenges in bonding limitations and vertical stacking. To solve this challenge, hybrid acoustic-assisted 3D printing integrates acoustophoresis with established methods, such as direct ink writing and stereolithography, enhancing material deposition accuracy, microstructure alignment, and porous structuring of 3D printed products. However, these hybrid systems remain tethered to layer-by-layer architectures, limiting the full potential of acoustic techniques. Recent breakthroughs in standalone acoustic 3D fabrication, leveraging levitation, focusing, and ejection, have unlocked potential in contactless, layerless, and flexible multi-material assembly. Acoustic levitation systems enable mid-air construction on non-planar surfaces, and focused ultrasound techniques facilitate deep-penetration polymerization and acoustic droplet ejection advances nozzle-free droplet-based bioprinting. This review systematically evaluates the evolution of acoustics in additive manufacturing, addressing critical challenges in material compatibility, resolution, and scalability, while outlining the future of acoustics in additive manufacturing technology.

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I. INTRODUCTION

Additive manufacturing, commonly known as 3D printing, has revolutionized modern manufacturing by enabling the precise fabrication of complex, customized structures across industries such as healthcare,[1,2] electronics,[3,4] and robotics,[5,6] offering unprecedented customization and rapid prototyping capabilities.[7] Multiple 3D printing techniques, including fused deposition modeling (FDM),[8–10] direct ink writing (DIW),[11–13] stereolithography (SLA),[14–16] selective laser sintering (SLS),[17–19] and inkjet 3D printing,[6,20] have advanced significantly, offering high precision and customization.[21–23] However, these methods struggle to precisely create microstructures with diverse materials, including solid particles, liquid droplets, and cells due to limited control over spatial arrangement, difficulty in handling delicate components, and seamless integration of multiple materials.[24]

Acoustic techniques have emerged as a compelling alternative and a complementary approach to conventional 3D printing, offering a contactless, non-invasive, and precise means of manipulating materials at the microscale.[25–28] Unlike traditional 3D printing methods limited by mechanical constraints, acoustics-based approaches enable precise, dynamic positioning, assembly, and patterning of particles, droplets, and cells. These methods primarily utilize acoustophoresis, a non-contact and label-free technique that employs controlled ultrasound to manipulate particles or droplets using acoustic forces within fluid mediums, such as water or air.[29–31] The label-free advantage preserves the native state of biological samples by eliminating the need for chemical modifications, fluorescent tagging, or magnetic labeling, minimizing interference with cellular function and fluid properties. This material-agnostic and non-invasive approach enables the precise control of solid or liquid materials in these environments, making it highly versatile for applications in biomedical engineering, materials science, and additive manufacturing.[32–36]

Acoustic manipulation relies on spatially structured acoustic fields that generate radiation forces to trap and position particles or droplets without contact. The acoustic trap size d_{trap} is typically half of the acoustic wavelength λ, which is inversely related to the driving frequency f[37,38]

$$d_{\text{trap}} \sim \frac{\lambda}{2} = \frac{c}{2f}, \tag{1}$$

where c is the speed of sound in the medium. The acoustic intensity $I(z)$ decays with depth[39]

$$I(z) = I_0 e^{-2\alpha(f)z}, \tag{2}$$

where z is the distance from the source, I_0 is the initial intensity, and $\alpha(f)$ is the attenuation coefficient, which increases with frequency. These principles apply broadly across acoustic trapping systems and define the resolution and effective range.

Acoustic patterning utilizes acoustic forces to arrange particles into precise spatial configurations within a liquid medium and has been widely used for applications such as tissue engineering and microstructure assembly due to its precision and versatility.[40–42] This technique enables rapid assembly of particles into arbitrary shapes but remains largely limited to 2D and quasi-3D configurations. Scaling acoustic patterning into true 3D volumetric fabrication remains a major challenge. This requires advances in acoustic field manipulation, material stabilization, and *in situ* curing techniques.

To overcome these limitations, researchers have integrated acoustics with existing 3D printing techniques, giving rise to acoustic-assisted 3D printing. This hybrid approach enhanced material precision, deposition control, and microstructural organization, by combining acoustic forces with established additive manufacturing methods. For instance, acoustophoretic printing leverages ultrasound waves to facilitate ejection and placement of droplets.[43] Acoustic patterning has been integrated with traditional 3D printing to fabricate intricate microstructures within printed objects. This approach has enabled the patterning of materials, such as glass fibers,[44] conductive elements,[45] polymer microparticles,[42] and living cells[46,47] within 3D printed products. This expands applications in bioprinting, electronics, and composite material fabrication.[45,48–50] While the integration of acoustics has enhanced conventional 3D printing techniques, these approaches remain constrained by the inheriting mechanisms including layer-by-layer deposition and substrate reliance from conventional methods. This partially undermines the contactless potential of acoustics, delicate material processing and multi-material integration.

Recent advances have demonstrated standalone acoustic 3D fabrication, where sound waves act as the sole structuring force, enabling contact-free, multi-material assembly without mechanical deposition or substrate support. These approaches include acoustic levitation, focusing, and ejection and offer new possibilities for volumetric structuring, adaptive *in situ* fabrication, and processing of delicate or multi-phase materials. Acoustic levitation enables contactless mid-air assembly of objects with complex geometries,[51] while omnidirectional levitation extends fabrication to non-planar and dynamic surfaces.[52] Acoustic focusing uses high-intensity ultrasound fields to structure or solidify materials directly, offering layerless fabrication suitable for soft materials and bioprinting.[53,54] Additionally, acoustic ejection enables contact-free droplet deposition, overcoming nozzle clogging and shear-induced damage risks inherent in extrusion-based methods.[55,56] Collectively, these advances establish acoustics as an emerging platform that expands the capabilities of additive manufacturing beyond conventional methods.

Recent reviews highlight the potential of acoustic particle manipulation for micro/nanoparticle structuring,[57] biomedical acoustics for biofabrication and organoid assembly,[58] and acoustic holography for contactless, high-precision fabrication.[59,60] However, a comprehensive framework for acoustics in additive manufacturing remains lacking. This review systematically classifies acoustic patterning, assisted 3D printing, and standalone acoustic fabrication, evaluating their scalability, integration with conventional methods, and potential as independent fabrication approaches. The summary of these studies is listed in Table I. This review connects fundamental acoustic principles with recent innovations, offering a comprehensive view of non-contact, high-resolution material assembly and positioning acoustics as a powerful tool in advanced manufacturing. It also highlights key challenges, such as material compatibility, resolution, and scalability, and outlines the roadmap to improve acoustic-based fabrication in areas, including precision, efficiency, and practical applications.

II. ACOUSTIC PATTERNING

Acoustic patterning is an innovative technique leveraging the precision of acoustophoresis to manipulate and arrange particles or cells in predetermined spatial configurations (i.e., patterns).[31] Utilizing customized acoustic fields, such as standing waves, materials can be guided based on their acoustic contrast, which is a function of the ratios of the mechanical compressibility and densities of the medium and the particle, respectively.[68] Depending on the nature of the material and the acoustic contrast, objects can experience forces toward or away from zones of high pressure.[42,68]

In general, objects, which have higher density and lower compressibility relative to the surrounding medium, migrate to the pressure nodes. Conversely, objects with lower density and higher compressibility than that of the medium migrate toward the pressure antinode.[42] This process enables precise control over the spatial distribution of materials through strategic positioning of nodes and antinodes throughout a build volume, paving the way for advanced fabrication techniques. One of the most versatile approaches in acoustic patterning is ultrasound-directed self-assembly (UDSA), which employs the acoustic radiation force associated with a standing ultrasound wave to manipulate particles into user-specified patterns within

TABLE I. Summary of materials, mediums, structural patterns, and applications of acoustics in additive manufacturing.

Material(s)	Medium	Structure/pattern	Application(s)	Reference
HCT-116 human colon cancer cells	Collagen type I hydrogel	Complex 2D/3D cell patterns	Tissue engineering	Ma *et al.*[46]
Coacervate droplets	Aqueous medium	2D	Micro-droplet spatial organization	Tian *et al.*[61]
PDMS-DMPA particles	Aqueous solution	2D	Acoustic assembly and fabrication	Melde *et al.*[42]
Solid particles, biological cells, and hydrogel beads	Hydrogel	3D	Tissue engineering and additive manufacturing	Melde *et al.*[41]
Hydrogels, honey, and liquid metals	Air	2D or limited 3D droplet patterns	Multi-material droplet-based printing	Foresti *et al.*[43]
Biocompatiable hydrogels	Air-liquid meniscus	3D	Volumetric printing and spatial patterning	Vidler *et al.*[62]
Glass, polystyrene, and metal	Resin	3D composite structure	Volumetric printing, tissue engineering and drug screening	Agrawal *et al.*[50]
Silver particles and carbon nanofibers	PEGDA matrix	3D composite structure	Multi-layer polymer composite	Wang *et al.*[45]
Nickel-coated carbon fibers	Polymer matrix	3D composite structure	Macroscale engineered materials fabrication	Greenhall and Raeymaekers[63]
Gelatin-based hydrogels	Liquid–air surface	Porous structure	Multi-layer food constructs	Chen *et al.*[64]
Poly(aspartic acid) (PASP) based fibrous hydrogels	Extracellular matrix	3D fibrous structure	Tissue engineering	Pázmány *et al.*[65]
Hydrogels (cell embedded), polymer organic solutions, and particles	Air	Complex 3D structures on arbitrary surfaces	Multi-material in situ (bio) printing	Chen *et al.*[66]
UV glue droplets, wooden sticks, spherical beads	Air	3D	Contactless additive manufacturing	Ezcurdia *et al.*[51]
Polydimethylsiloxane (PDMS)	PDMS	3D transparent and opaque (porous) structure	Additive manufacturing	Habibi *et al.*[67]
PDMS	PDMS	3D transparent and opaque (porous) structure	Additive manufacturing	Derayatifar *et al.*[53]
Gelatin methacryloyl (GelMA)	Hydrogel	3D hydrogel constructs	Tissue engineering, tumor microenvironments	Chen *et al.*[56]
Pluronic, Matrigel	Hydrogel	3D cell-laden hydrogel structures	Multiscale 3D bioprinting, regenerative medicine	Jentsch *et al.*[55]

a fluid medium.[69–72] By adjusting ultrasound parameters—such as frequency, amplitude, and phase, researchers can precisely control particle location, orientation, and pattern fidelity.[73,74] UDSA enables assembly of micro- to millimeter-scale structures with high throughput and has demonstrated compatibility with various particle materials, sizes, and shapes, provided they exhibit density or compressibility contrast with the surrounding fluid.[71]

Applications of acoustic patterning include droplet and particle manipulation, cell patterning, and self-assembly, each leveraging acoustic waves to impose order at the microscale. These methods have demonstrated high resolution and biocompatibility, making them particularly attractive for biomedical engineering, electronics, and materials science. Sections II A–II C explore key applications of acoustic patterning in greater detail.

A. Droplet and particle patterning

By leveraging standing wave pressure fields, acoustic holograms, or UDSA, acoustic patterning techniques enables precise, contact-free manipulation of liquid droplets or solid particles for applications in material assembly, biofabrication, and microfluidics in diverse fields.

In 2016, Tian *et al.*[61] applied acoustic standing wave pressure fields for spontaneous assembly of chemically encoded two-dimensional coacervate droplet arrays [Fig. 1(a)]. The study employs a custom-built acoustic trapping device with four piezoelectric transducers arranged around a square chamber to generate orthogonal acoustic standing waves. This setup facilitates the spontaneous assembly of polydiallyldimethylammonium chloride (PDDA)/adenosine triphosphate (ATP) coacervate droplets into defect-free two-dimensional arrays by trapping them at acoustic pressure nodes. The method relies

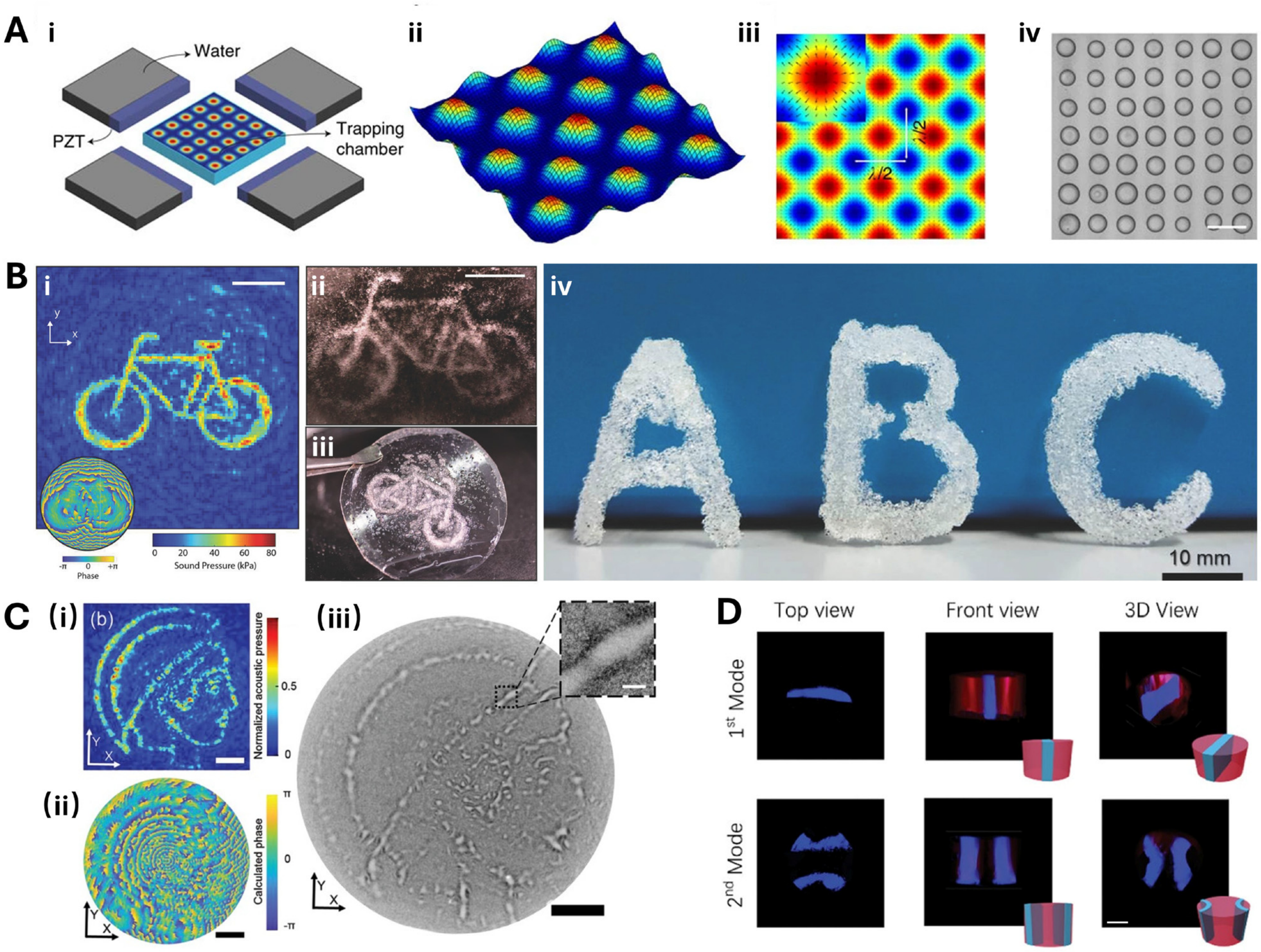

FIG. 1. Acoustic patterning of droplets, particles and cells. (a) Acoustic patterning of droplets. (i) Schematics of the acoustic trapping device with four piezoelectric transducer (PZT) elements generating a periodic acoustic standing wave pressure field. (ii) A simulation of the acoustic pressure distribution shows high-pressure (red) and low-pressure (blue) regions traping the droplets in low-pressure nodes (iii) A simulation of the Gor'kov potential revealing node spacing as half the acoustic wavelength (λ). (iv) Optical microscopy images of acoustically patterned PDDA/ATP droplets (the scale bar is $\lambda/2$ in a length of 110 μm). Tian *et al.* Nat. Commun. **7**, 13068 (2016). Copyright 2016 Authors, licensed under a Creative Commons Attribution (CC BY). (b) Acoustic patterning and assembly of silicone particles. (i) The pressure field for assembling silicone particles into a bicycle shape (scale bar of 10 mm). (ii) Assembled silicone particles after 20 s of ultrasound exposure (scale bar of 10 mm). (iii) A fixed structure after 40 s of ultrasound exposure and post-curing. (iv) Models of the letters A, B, and C fabricated using the same technique.[42] Reproduced with permission from Melde *et al.*, Adv. Mater. **30**(3), 1704507 (2018). Copyright 2018 John Wiley and Sons. (c) Acoustic holographic cell Patterning. (i) Measured acoustic pressure map replicating a complex image (scale bar of 5 mm). (ii) Calculated phase distribution of the hologram (scale bar of 5 mm). (iii) Bright-field image of the patterned cells embedded in hydrogel; inset shows dense cell assembly. All scale bars are 5 mm except the inset (500 μm).[46] Ma *et al.*, Adv. Mater. **32**(4), 1904181 (2019). Copyright 2019 Authors, licensed under a Creative Commons Attribution (CC BY). (d) Acoustic patterning of 293T cells within hydrogel fibers and tubules under different resonance modes. Fluorescence images show top, front, and 3D views of the cured hydrogel structures (red) with patterned cell distribution (blue) and corresponding schematic models. (i) In the first mode, cells are focused into a single central band along the fiber/tubule axis. (ii) In the second mode, cells form two radially separated bands. Scale bar: 500 μm. Reproduced with permission from Yin *et al.*, Adv. Sci. **11**, 2308396 (2024). Copyright 2024 Authors, licensed under a Creative Commons Attribution (CC BY).

on *in situ* complex coacervation to create water-rich, molecularly crowded droplets that coalesce or remain clustered based on acoustic frequency modulation. The results demonstrate precise control over droplet size, spacing, and attachment properties, with single-droplet arrays forming at specific wavelengths.

Subsequently in 2022, Shapiro *et al.*[75] introduced a new technique, sonolithography, an in-air acoustic patterning technique that employs ultrasonic standing waves to direct aerosolized droplets and solid particulates into predefined spatial arrangements. This method enables non-contact, rapid, and scalable deposition across centimeter-scale surfaces, utilizing commercially available 40 kHz ultrasonic transducers arranged in an octagonal array to generate controlled acoustic pressure fields. By manipulating nodes and antinodes, particles—including water droplets (1–5 μm), collagen solutions, conductive inks, polymer microspheres, and sand grains (0.5–1 mm) —are patterned based on size-dependent acoustophoresis. The system allows for size-based segregation, demonstrated through the patterning of bioactive molecules for tissue engineering, conductive coatings for electronics, and composite materials with hierarchical structuring. For biofabrication applications, collagen I was nebulized and acoustically patterned onto Petri dishes, enabling spatially guided endothelial cell adhesion. Direct cell patterning was achieved using a droplet-on-demand dispenser (80 μm nozzle), ensuring cell viability while forming engineered tissue-like structures.

Melde *et al.*[42] applied acoustic fields to arrange PDMS microspheres in arbitrary 2D designs and then instantly bind them to create a permanent object [Fig. 1(b)]. The PDMS microspheres were synthesized via emulsion polymerization and subsequently functionalized with a UV-sensitive photoinitiator. These particles were dispersed in a poly(ethylene glycol)-dimethacrylate solution, which served as the cross-linking medium. The acoustic patterning process involves placing a 3D-printed acoustic hologram in front of an ultrasound transducer, generating a high-resolution sound pressure field that directs microspheres into specific positions through acoustic radiation forces. Once the particles assemble into the desired shape, they are crosslinked via UV exposure, permanently fixing the structure while reusing the bulk suspension. This contact-free and maskless technique enables rapid formation of 2D shapes, with the potential for 3D assembly through complex hologram designs.

The study by Presley *et al.*[72] presents a multi-frequency ultrasound-directed self-assembly (UDSA) method that advances traditional single-frequency acoustic patterning by enabling the formation of complex, non-periodic particle arrangements with fewer transducers. The study establishes a theoretical framework to optimize ultrasound parameters—frequency, amplitude, and phase—for precise particle control. Experimental validation demonstrated the method's ability to assemble intricate patterns with sub-100 μm precision, surpassing the structural complexity achievable with single-frequency UDSA. Results showed that multi-frequency excitation allows for higher pattern reconfigurability and improved spatial accuracy while maintaining assembly efficiency. Compared to acoustic holography, this technique achieves adaptive and scalable patterning without requiring custom hardware. The findings suggest that multi-frequency UDSA can be leveraged for manufacturing functional composite materials with tailored mechanical, electrical, and thermal properties, expanding its potential in materials engineering and biomedical fabrication.

In summary, acoustic patterning techniques, including standing wavefields, acoustic holography, and ultrasound-directed self-assembly (UDSA), provide precise spatial control over droplets and particles, enabling intricate 2D and quasi-3D configurations. On the other hand, integrating 3D structures into a stable, fused construct remains challenging due to the lack of inherent bonding mechanisms, material instability after patterning, and limited control over vertical stacking.

B. Cell patterning

As acoustic manipulation is contactless and biocompatible, it has emerged as an innovative technique for patterning cells in biomedical applications. It uses acoustic waves to apply radiation or hydrodynamic forces on cells to manipulate and pattern them within liquid or hydrogel.[76–80] It has demonstrated compatibility with a variety of hydrogel precursors and the potential to produce micro cellular structures with precise cell distribution and physiologically relevant cell density enabled by its high resolution.[77,80] Collins *et al.*[81] applied surface acoustic waves for cell and particle patterning with single-cell resolution in 2D. Applications mainly involve cell study at single cell level, including long-term capture and observation for drug discovery, and cellular response to effector molecules.

Ma *et al.*[46] utilized acoustic holograms and acoustophoresis to enable a rapid, biocompatible method for creating both regular and arbitrary cell patterns using acoustic holography [Fig. 1(c)]. By leveraging localized acoustic focusing and streaming, cells can be arranged into customized patterns within collagen hydrogel. HCT-116 colon cancer cells were suspended in a pre-gel collagen solution, and a 5 MHz ultrasound field formed complex cell assemblies, which were immobilized by hydrogel gelatin. The results showed high-fidelity patterns with excellent cell viability and proliferation over seven days, confirmed by fluorescence imaging. This rapid, scalable approach enables biomimetic 3D tissue structures, offering applications in tissue engineering, regenerative medicine, and mechanobiology.

Yin *et al.*[82] developed an acoustofluidic system for producing structured, cell-laden hydrogel fibers and tubules with tunable cell patterning driven by acoustic resonance [Fig. 1(d)]. The method utilizes acoustic radiation forces (ARF) inside a capillary to arrange cells or particles into radial patterns before UV cross-linking solidifies the structure. By adjusting acoustic frequencies, the team demonstrated controllable patterns, such as 2-, 4-, and 6-petal radial cell assemblies in both hydrogel fibers and tubules. The process enabled continuous production while preserving high cell viability over 72 h, confirmed by viability assays and live/dead staining showing minimal cytotoxicity. Patterned cells remained intact and proliferative in 3D hydrogels. This approach provides a biocompatible, contact-free method for fabricating biomimetic structures that mimic native tissue architectures, offering great potential for tissue engineering and biofabrication applications requiring precise cell alignment.

Acoustic patterning techniques enable precise and contactless arrangement of cells within liquid or hydrogel environments while maintaining cell viability, making them valuable for tissue engineering and regenerative medicine. However, integrating 3D cell assemblies into cohesive, functional structures remains challenging due to the lack of inherent cell–cell or matrix adhesion post-patterning and limitations in controlling vertical layering.

C. Discussion

Acoustic patterning has emerged as a powerful tool for precisely organizing materials at the microscale, with applications spanning biomedical engineering, electronics, and composite fabrication. Techniques, such as standing wavefields, acoustic holography, and ultrasound-directed self-assembly (UDSA), allow for high-precision spatial control over droplets, particles, and cells. However, while these methods enable intricate 2D and quasi-3D configurations, fully integrating 3D assemblies into cohesive structures remains a challenge. A primary limitation is the lack of inherent bonding mechanisms within acoustically assembled structures. Unlike conventional additive manufacturing, which relies on thermal fusion, cross-linking, or curing, acoustic patterning primarily focuses on spatial positioning rather than material integration. Even when particles or cells are arranged in 3D, they often remain loosely packed and require additional stabilization strategies. Once the acoustic field is removed, assembled materials may become unstable, dispersing due to surface tension, gravitational effects, or Brownian motion. Although some advancements, like particle cross-linking via UV exposure,[42] provide partial solutions, they still fall short of achieving true 3D fabrication. Additionally, controlling vertical stacking along the Z-axis at scale remains challenging, as acoustic forces that enable precise in-plane positioning struggle to maintain alignment and cohesion in multi-layered structures.

Future developments in acoustic patterning must address these limitations by integrating real-time bonding strategies, adaptive acoustic fields, and multi-frequency control mechanisms. Additionally, combining acoustic patterning with advanced manufacturing processes, such as additive manufacturing and biofabrication may transform proof-of-concept demonstrations into scalable, functional technologies. By overcoming these hurdles, acoustic patterning has the potential to revolutionize material assembly, enabling the creation of complex, multi-material structures with unprecedented precision.

III. ACOUSTICS-ASSISTED 3D PRINTING

Acoustic techniques have demonstrated remarkable precision and versatility in patterning and manipulating materials, making them invaluable tools for applications requiring non-contact and high-resolution control. However, acoustic patterning has an inherent limitation in scalability, particularly along the Z-axis for constructing fully three-dimensional structures. To overcome these limitations, acoustic systems have been increasingly integrated with existing 3D printing techniques such as DIW,[83] inkjet 3D printing,[84] and SLA.[85,86] In these hybrid systems, manipulation by acoustic waves serves as a complementary tool to enhance material deposition, improve structural integrity, or enable intricate patterning that would be difficult or impossible to achieve using conventional methods. This synergy has not only enhanced the capabilities of traditional 3D printing techniques but also has paved the way for more versatile and efficient fabrication processes, particularly in applications like bioprinting, electronics, and soft robotics. By leveraging the precision of acoustic forces alongside the scalability of traditional 3D printing methods, acoustics-assisted printing represents a possible bridging of the gap between highly controlled material structuring and large-scale fabrication, setting the stage for further innovations in acoustics-driven manufacturing.

A. Material deposition and curing

Acoustic waves can facilitate precise control over material deposition, distribution, and curing processes for 3D printing, enhancing the versatility and resolution of printed structures. Foresti *et al.*[43] presents acoustophoretic printing, a contact-free, drop-on-demand technique utilizing acoustic waves to enhance droplet ejection and precision [Fig. 2(a)]. Using a Fabry–Pérot resonator, localized acoustic forces were generated to facilitate overcoming capillary forces and ejecting droplets of a wider range of materials than inkjet printing. By decoupling droplet detachment from fluid flow, acoustics enables the controlled ejection of materials with viscosities ranging from 0.5 to 25 000 mPa s and Z number, the inverse Ohnesorge number, from 0.001 to 1000, compared to 1–15 for inkjet printing.[87] The study demonstrated the printing of cell-laden hydrogels, yield-stress fluids, optical adhesives, and liquid metals. This approach enhances printing versatility, allowing the creation of monodisperse droplets and complex 3D structures while maintaining the viability of sensitive materials, such as cell-laden hydrogels.

In addition to soft materials, acoustics has also been used to direct metal powder deposition for laser-based metal 3D printing. Martinez-Marchese *et al.*[88] presented ultrasound particle lensing (UPL) for controlling powder streams in laser-directed energy deposition with powder feed. UPL uses a 150-element ultrasound array to generate acoustic radiation forces that focus metal powder streams (Ti6Al4V, avg. 88 μm) in-flight, independent of particle size or speed. The system achieved up to 111% increase in track cross-sectional area and catchment efficiency, with the most significant improvements at 900 W laser power and 10 V ultrasound voltage. Lower laser powers (700 and 800 W) also showed 92% and 53% efficiency gains, respectively. The focused powder stream enabled better material utilization, increased track height by 72%, and consistent track geometry without widening the deposited tracks. This solid-state, digitally tunable method allows dynamic control of the powder stream, addressing common directed energy deposition challenges, such as poor deposition efficiency and limited resolution. The study demonstrates the potential of acoustics to enhance metal additive manufacturing.

Acoustics has also been used to enhance resin distribution and curing processes. Vidler *et al.*[62] introduced dynamic interface printing (DIP), a novel acoustically modulated 3D printing approach that leverages a constrained air−liquid meniscus as the fabrication interface [Fig. 2(b)]. The system uses adjustable acoustic vibrations to dynamically control the shape and position of the meniscus, aligning it precisely with the projected light patterns for polymerization. The technique supports a wide range of materials, including biologically relevant hydrogels like PEGDA and GelMA, achieving print speeds over 700 μm/s and maintaining high cell viability (93%) in cell-laden constructs. Acoustic waves generated at the interface improve mixing, reduce sedimentation of suspended cells or particles, and allow 3D particle patterning. Notably, DIP enables printing through opaque bioinks, demonstrated by fabricating a tricuspid valve from opaque alginate and performing *in situ* overprinting of multi-material structures like a ball-and-socket joint. The system's scalability was shown by parallel printing with a 3×3 array of print heads, highlighting DIP's potential for high-throughput biofabrication and rapid prototyping. These capabilities make DIP a versatile and transformative tool for high-speed, high-resolution additive manufacturing and bioengineering applications.

Debbi *et al.*[89] has introduced ultrasound-mediated polymerization as a noninvasive alternative to traditional photo-cross-linking methods for hydrogel fabrication in biomedical applications. By harnessing ultrasound-induced cavitation, this technique initiates the polymerization of acousto-sensitive materials like PEGDA and PVA-MA without the need for photoinitiators, enabling deep tissue cross-linking through up to 3 cm of muscle or brain tissue. The mechanical properties of the resulting hydrogels, including Young's modulus tunable from 10 to 80 kPa, were adjustable by ultrasound exposure time, allowing tailoring to target tissue properties. It also allows protective encapsulation of cells, which reached viability over 85%, significantly higher than that without protective encapsulation. The functional human iPSC-derived cardiomyocytes also retained contractility post-polymerization. Additionally, ultrasound-mediated polymerization enabled sustained drug release with tunable profiles based on ultrasound parameters. Overall, ultrasound-mediated polymerization provides a versatile, deep-penetrating alternative to photo-cross-linking,

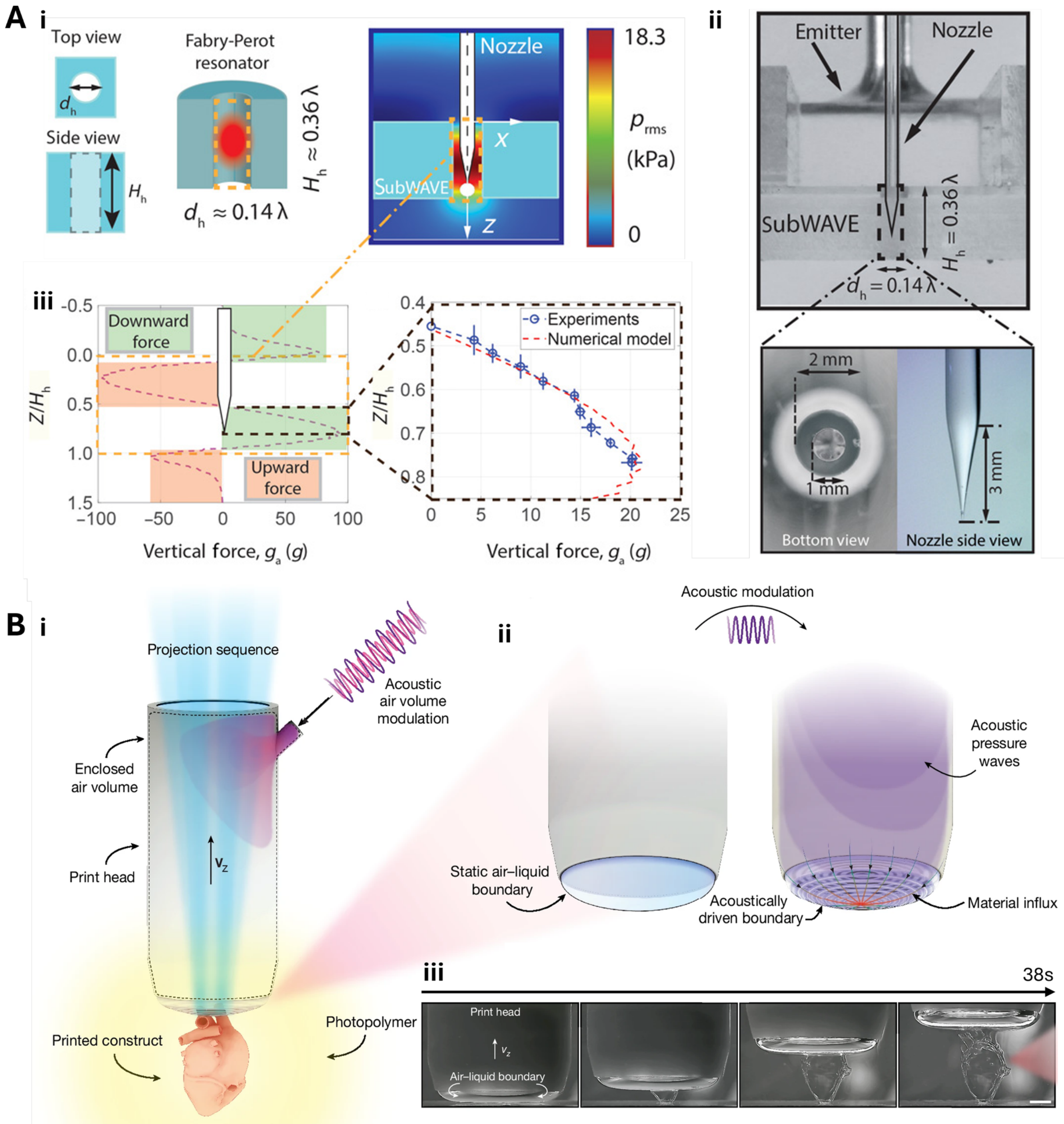

FIG. 2. Acoustics-assisted material deposition and curing. (a) Acoustophoretic printing using acoustophoretic force to facilitate droplet ejection. (i) The device consists of a tapered glass nozzle in a cavity. An emitter induces a subwavelength Fabry–Pérot resonance in the cavity, generating localized acoustic forces that facilitate droplet ejection. (ii) Side view of the setup and close-up view of the tapered nozzle. (iii) Finite element modeling and experimental results of the acoustophoretic force along the Z axis.[43] Reproduced with permission from Foresti *et al.* Sci. Adv. **4**(8), eaat1659 (2018). Copyright 2018 Authors, licensed under a Creative Commons Attribution-NonCommercial (CC BY-NC). (b) Dynamic interface printing, an acoustically modulated 3D printing technique using a constrained air–liquid meniscus as the fabrication interface. (i) Schematics of the print head. An air–liquid boundary forms at the base of the print head submerged in a liquid photopolymer. A meniscus at the air–liquid interface serves as the printing surface where 405 nm light initiates polymerization, solidifying the liquid into structured forms. (ii) Acoustic modulation of the interface, generating capillary-gravity waves enabling high-resolution patterned projections and rapid centimeter-scale fabrication. This enhances material transport and resin uniformity. (iii) Rapid printing a model of a human heart structure in 38 s.[62] Reproduced with permission from Vidler *et al.* Nature **634**(8036), 1096–1102 (2024). Copyright 2024 Authors, licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives (CC BY-NC-ND).

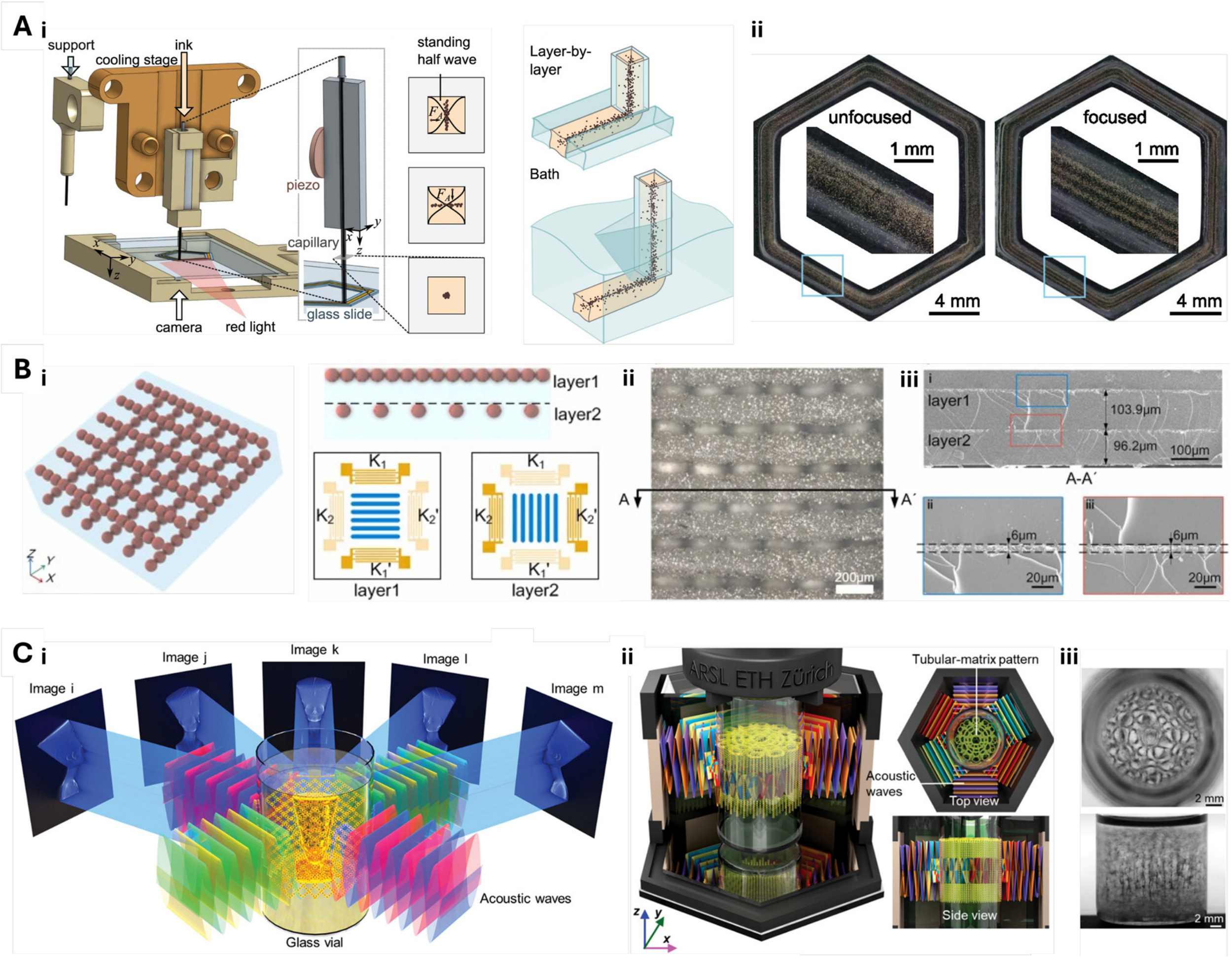

FIG. 3. Acoustics in micro-structure aligning for 3D printed products. (a) Acoustic-assisted DIW. (i) Schematic of an acoustic-assisted DIW system with a piezoelectric transducer generating standing wave fields for particle alignment. Both layer-by-layer and bath support printing methods can be conducted. (ii) Printed filaments with and without acoustic focusing, showing enhanced particle alignment and structural uniformity in the focused condition.[83] Reproduced with permission from Friedrich and Begley, ACS Appl. Polym. Mater. **2**(7), 2528–2540. Copyright 2020 American Chemical Society. (b) Sonolithographic patterning. (i) Schematic of sonolithographic patterning: Microparticles aligned using acoustic standing waves in a layer-by-layer manner, with interdigital transducers generating acoustic fields for precise particle positioning. (ii) Optical microscopy image of multi-layered particle structure, showing controlled spatial arrangement. (iii) SEM images of the cross section (A–A´) of the patterned layers, revealing well-defined particle distributions and high-resolution close-ups (ii) and (iii) of individual layers with microscale alignment.[92] Reproduced with permission from Wang *et al.*, Addit. Manuf. **60**, 103247 (2022). Copyright 2022 Elsevier. (c) SonoPrint, an acoustically assisted volumetric 3D printing system. (i) Schematics of the experimental setup. The PZTs generate bulk acoustic waves, which transmit through a glass vial containing microparticles suspended in photopolymerizable resin. Projections produced by volumetric software at different angles and times cure the resin in the vial to fabricate complex geometries, with the patterned particles. (ii) Bulk acoustic waves are generated by PZTs surrounding the glass vial and positioned orthogonally in the xz-plane producing a tubular-matrix pattern. (iii) top and side view of the resulting patterned microspheres of this tubular matrix.[50] Reproduced with permission from Agrawal *et al.*, Adv. Mater. **36**(40), 2408374 (2024). Copyright 2024 Authors, licensed under a Creative Commons Attribution-NonCommercial (CC BY-NC).

overcoming light-based limitations for *in situ* tissue engineering, drug delivery, and additive manufacturing.

B. Micro-structure aligning

The alignment of microstructures within 3D-printed composites is critical for optimizing mechanical, electrical, and thermal properties. Acoustic-assisted techniques leverage standing waves and acoustic focusing to precisely position filler particles, fibers, and conductive materials within printed objects.[44,63,90] The alignment of fillers has resulted in the enhancement of the electrical, mechanical, thermal, and optical properties of the composites.[69,91]

Friedrich and Begley[83] explored the role of acoustophoretic manipulation in DIW to precisely control particle distribution within 3D-printed filaments [Fig. 3(a)]. By utilizing standing acoustic waves within the print nozzle, microparticles—including metallic, ceramic, and polymer-based fillers—are aligned into structured patterns before deposition. This acoustic field guides particle movement toward nodes or antinodes depending on density and compressibility, enabling the fabrication of functionally graded composites and structured conductive pathways. The study also highlights that post-extrusion flow effects, such as plastic flow, disturbed zone dynamics, and capillary spreading, influence particle alignment, potentially altering the final microstructure. In addition, layer-by-layer support has shown to improve positional accuracy, whereas bath-based support generates more uniform distributions. The work emphasizes the importance of *in situ* curing strategies to lock-in acoustically induced particle patterns, preserving tunable electrical, mechanical, and biofunctional properties. By integrating acoustic focusing into DIW, this study advances additive manufacturing techniques for high-performance electronics, tissue engineering scaffolds, and multi-functional composites.

Wang *et al.*[92] demonstrated the use of standing surface acoustic waves for microparticle alignment integrated with stereolithography 3D printing [Fig. 3(b)]. This enables the fabrication of functional polymer composites with tailored microstructures and properties. Materials, including silver particles and carbon nanofibers, were patterned within a photocurable poly(ethylene glycol) diacrylate matrix using a surface acoustic wave device. The acoustic fields, generated by pairs of interdigital transducers, created pressure nodes that aligned particles into stripe-like, net-like, or dot-like patterns based on excitation strategies. Once the patterns were formed, ultraviolet (UV) curing solidified the resin, preserving the particle arrangements. High-resolution patterning with uniform particle distribution was achieved, yielding anisotropic conductive polymer films with electrical conductivity up to 827 S/m. The study demonstrates the potential of standing surface acoustic waves to produce multifunctional composites for applications in electronics, soft robotics, and advanced manufacturing.

Agrawal *et al.*[50] developed SonoPrint, an acoustically assisted volumetric 3D printing system that simultaneously patterns and prints reinforcement microparticles within composite structures [Fig. 3(c)]. The system utilizes piezoelectric transducers to generate standing wave fields, which align microparticles (e.g., glass, polystyrene, and metals) into complex motifs (e.g., radial lines, hexagons, and polygons) directly within a photosensitive resin. Unlike traditional reinforcement techniques, which are often constrained by material properties and alignment limitations, SonoPrint's acoustic manipulation is independent of particle size, geometry, and charge, offering flexibility in composite fabrication. By integrating volumetric printing with acoustic alignment, the system overcomes challenges associated with layer-by-layer methods, where acoustic scattering between polymerized and unpolymerized regions disrupts pattern formation. Mechanical testing demonstrates that SonoPrint-produced composites achieve up to 46% and 13% increases in tensile and compressive strengths, respectively, compared to randomly distributed particle composites. This rapid, scalable approach enables the fabrication of highly tunable structures in mere minutes, with potential applications spanning biohybrid robotics, tissue engineering, and high-performance composite manufacturing. This study marks an advance in the integration of acoustics and additive manufacturing.

Greenhall and Raeymaekers[63] combined ultrasound-directed self-assembly with stereolithography to fabricate composites with patterned particles. During printing, ultrasound-assisted assembly was applied at each layer to organize particles within the resin before curing. Nickel-coated carbon fibers were aligned in a single direction within single-layer structures to enhance conductivity, while in multilayer structures, they formed Bouligand microstructures for multifunctional applications. This approach enables the fabrication of multimaterial, macroscale 3D composite structures with tailored microstructural fillers for diverse applications.

Melchert *et al.*[90] used DIW to 3D print flexible resin composites with carbon and silver-coated glass fibers, employing acoustophoresis to align fibers and form percolated conductive networks. This approach significantly improved conductivity while preserving flexibility, achieving up to 48% of bulk silver's conductivity at just 2.6 vol. % filler loading—an order of magnitude higher than conventional composites. The patterned structures endured over 500 bending cycles with minimal conductivity loss. By tuning the acoustic field, electrical anisotropy can be controlled, making the ink either 2D conductive (allowing current to flow across a plane for flexible circuits and touch sensors), 1D conductive (guiding current in one direction for interconnects), or insulating. With 97% fiber utilization compared to less than 5% in traditional composites, this method offers a versatile route for integrating functional particles into soft electronics, flexible sensors, and wearable devices.

Acoustic-assisted alignment techniques, such as standing wave integration in 3D printing techniques (e.g., DIW and sonolithography), can precisely position filler particles (e.g., carbon fibers, silver nanoparticles) in composites enhancing conductivity, strength, or thermal performance.[44,63,69,90,91] However, post-extrusion flow (e.g., capillary spreading) can disrupt alignment, necessitating *in situ* curing. Additionally, acoustic scattering between cured and uncured regions limits resolution in layer-by-layer processes, highlighting dependence on conventional printing frameworks. Addressing these limitations will expand the scalability and material versatility of acoustic-assisted alignment for next-generation additive manufacturing.

C. Porous structure generation

The creation of porous structures is a crucial aspect of advanced manufacturing, particularly in applications, such as tissue engineering, filtration, and lightweight composites. Traditional 3D printing methods, such as FDM and SLA, often struggle to achieve precise control over pore size, distribution, and structural integrity. However, acoustic-assisted techniques, such as acoustic focusing, offer significant advantages in generating porous materials with high precision and scalability. By leveraging the unique properties of acoustic waves, these techniques enable the controlled formation of pores through energy concentration, allowing for the creation of complex, highly customizable porous structures.

Pázmány *et al.*[65] demonstrated how ultrasound-induced cavitation enhances the porosity of poly(aspartic acid)-based fibrous hydrogel scaffolds, facilitating improved cell infiltration [Fig. 4(a)]. Ultrasonication creates microscopic cavitation bubbles through high-frequency oscillations, generating controlled bubble formation and collapse within the polymer structure. This action increases scaffold porosity and enables deeper cell integration. The ultrasonically treated scaffolds demonstrate improved mechanical properties, including a specific load capacity of $0.11 \pm 0.01\ \mathrm{N\,m^2/g}$ after rehydration and a nearly twofold increase in elongation at break, indicating greater flexibility and mechanical resilience. Importantly, ultrasonication was confirmed to be cytocompatible, reinforcing its potential in scaffold fabrication for tissue engineering applications.

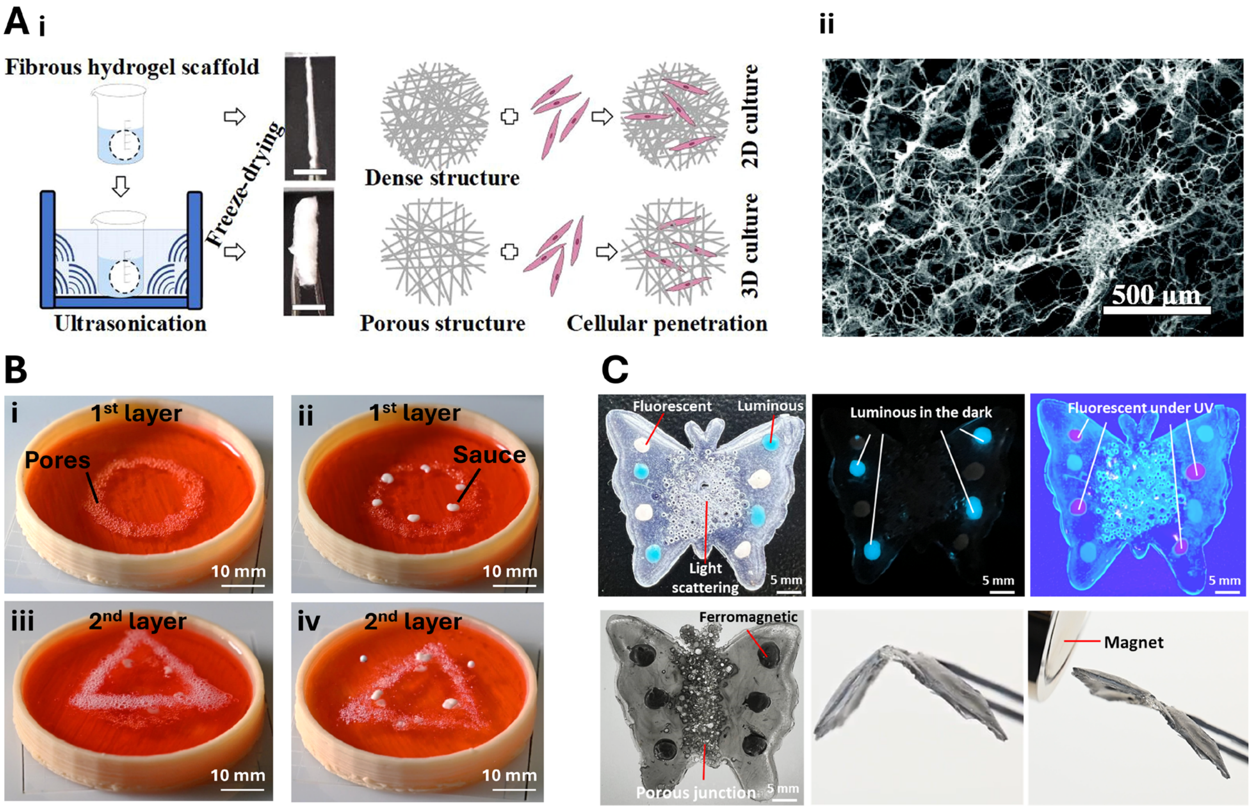

FIG. 4. Creation of porous structures using directed ultrasound. (a) Acoustics-driven porosity enhancement in fibrous hydrogel scaffolds. (i) Schematic of ultrasound-induced porosity enhancement in poly(aspartic acid)-based fibrous hydrogel scaffolds. Cavitation bubbles generated by ultrasonication exert localized mechanical forces, expanding the scaffold structure and increasing porosity. This transformation shifts the scaffold from a dense, 2D-supporting structure to a porous network, facilitating enhanced 3D cell infiltration. (ii) Scanning electron microscopic image of the ultrasonicated scaffold, revealing a highly porous structure.[65] Reproduced with permission from Pázmány *et al.*, Mol. Liq. **359**, 119243 (2022). Copyright 2022 Authors, licensed under a Creative Commons Attribution (CC-BY). (b) Multi-layered tart with customized porous structures (i) In the first step, a red gelatin layer was first deposited into a 3D-printed chocolate container, where circular pores were introduced via acoustic focusing. (ii) White sauce was then deposited using acoustic levitation. (iii) A second transparent gelatin layer with a triangular porous pattern was added, followed by additional sauce and sprinkles (iv). (c) Multi-material light-manoeuvring butterfly-shaped device with porous structures. Its porous structure enhances light scattering, while functional fillers embedded in the wings produce blue luminescence in darkness and red fluorescence under UV light. A butterfly-shaped soft actuator where the porous junction allows flexible movement of rising wings when exposed to a magnetic field. Figures (b) and (c) are reproduced with permission from Chen *et al.*, **10** (2024). Copyright 2024 Authors, licensed under a Creative Commons Attribution (CC-BY).

Chen *et al.*[64] leveraged acoustic focusing to fabricate precise porous structures using an unltrasound phased array of transducers (PAT). By dynamically controlling focal points on liquid surfaces, the system induces bubble formation to pattern porosity with high precision. This approach enabled the creation of tailored porous designs in gelatin-based hydrogels and multi-layered food constructs. As demonstrated in Fig. 4(b), this technique was applied to fabricate bi-layered food structures, where acoustic focusing induced porous patterns within gelatin layers, altering texture, appearance, and flexibility. Beyond food engineering, Fig. 4(c) illustrates the integration of the PAT with stereolithographic printing, where acoustic focusing is used to create porous structures within UV-cured resin layers, enhancing material functionality. This integration enabled the fabrication of light-maneuvering devices with porous-induced light-scattering effects and magnetic soft actuators with porous junctions for flexible motion control. Unlike traditional methods that require chemical porogens or sacrificial templates, this ultrasound-based system dynamically generates porosity without contact, making it highly applicable to food engineering, soft robotics, and functional composites. Acoustic focusing and ultrasound-induced cavitation create tunable porous architectures in fabricated hydrogels and composites, enhancing cell infiltration in tissue scaffolds and functional gradients in soft robotics.[64,65] On the other hand, the resolution and uniformity are hindered by acoustic field attenuation and thermal diffusion variability. In addition, the pore generation is limited to materials with specific properties (e.g., viscosity), which limits universal application.

D. Discussion

Acoustic-assisted 3D printing enhances conventional additive manufacturing by integrating acoustic forces with established additive manufacturing techniques, such as FDM, DIW, and SLA. The acoustic fields allow for dynamic, precise, and contactless manipulation of materials, including conductive fibers, cells, and porous architectures in printed products. This expands applications in electronics, soft robotics, and bioprinting. Additionally, acoustic fields allow for dynamic, real-time control of material alignment, improving structural organization within printed constructs. The contactless approach of acoustics minimize cross-contamination, making it particularly valuable for biomedical applications, such as tissue engineering, organ-on-a-chip technologies, and biofabrication. Despite these benefits, acoustic-assisted printing remains constrained by its dependence on traditional 3D printing architectures. This reliance inherently limits the full potential of acoustic manipulation, as it is still bound by layer-by-layer deposition and substrate constraints dictated by most conventional printing methods. While acoustics enhances material handling and deposition precision, it does not eliminate the fundamental limitations of these base techniques. Furthermore, since most hybrid systems still require mechanical extrusion, vat photopolymerization, or nozzle-based deposition, they partially undermine the fully contactless potential of acoustic techniques, particularly in applications where delicate materials or multi-material integration are critical. Overcoming these challenges has driven interest in fully acoustic-driven fabrication, where sound waves serve as the primary mechanism for material structuring and assembly, offering a pathway to truly contact-free and volumetric additive manufacturing.

IV. ACOUSTIC 3D FABRICATION

Standalone acoustic 3D fabrication is an emerging manufacturing approach that uses sound waves as the primary mechanism for material manipulation, structuring, and assembly. Leveraging acoustic levitation,[34,51,52,93,94] acoustic focusing,[67,95,96] and acoustic ejection techniques,[55,56] acoustic 3D fabrication offers unique advantages in material handling, compatibility, and contact-free assembly, distinguishing it from traditional and hybrid additive manufacturing approaches. Its material versatility—acoustic forces can manipulate solids and soft matter, allowing for the precise structuring of diverse materials, including bioinks, fragile biological cells, nanoparticles, and functional composites. Acoustic-driven approaches enable the simultaneous structuring of diverse materials without mechanical extrusion constraints. This surpasses conventional 3D printing, which faces challenges in multi-material integration due to viscosity mismatches, adhesion issues, or curing incompatibilities depending on the mechanisms of each technique. In addition, the contactless nature of acoustics can eliminate risks like nozzle clogging, shear-induced damage, or cross-contamination for material integration, making them particularly advantageous for bioprinting and soft material processing. Furthermore, acoustic fabrication allows nondestructive handling of delicate composites and operation in inaccessible environments, demonstrating the exciting potential of fabrication directly on or inside biological tissues (*in situ* and *in vivo* bioprinting). Sections IV A–IV C explores these emerging standalone acoustic fabrication techniques, evaluating their current capabilities, limitations, and future prospects in achieving true 3D, contactless, and scalable additive manufacturing.

A. Acoustic levitation

Acoustic levitation is a contactless technique that uses sound waves to suspend and manipulate objects in mid-air by controlled acoustic pressure fields.[34,97,98] This allows precise positioning and assembly of materials such as droplets, beads, and elongated objects without physical contact. Recent advancements have expanded its capabilities, enabling the mid-air construction of complex 3D structures on nonplanar or irregular surfaces. Innovations like omnidirectional levitation on irregular surfaces and robotic integration have further enhanced its versatility, making it a powerful tool for multi-material, *in situ* printing in applications ranging from bioprinting and soft robotics to functional material engineering.[51,52]

Ezcurdia *et al.*[51] introduced LeviPrint, an innovative system that combines acoustic levitation with robotic manipulation for contactless 3D printing and assembly of complex structures using beads, sticks, and droplets [Fig. 5(a)]. The system employs ultrasonic PATs to create highly controlled acoustic fields that can trap and orient elongated objects with precision. By integrating two-sided PATs with a robotic arm that controls the positioning of the arrays, LeviPrint positions materials, such as UV glue droplets, lightweight wooden sticks, and spherical beads within the array to construct joints, bridges, and intricate geometries, demonstrating its versatility.

Chen *et al.*[52] developed an advanced acoustophoretic printing system, which combines a PAT and advanced control algorithms allowing omnidirectional and multi-material *in situ* 3D printing using acoustic levitation [Fig. 5(b)]. This printing system utilizes the OpenMPD platform (multimodal particle-based displays)[99] and BEM (boundary element method)[100] algorithms to enable the formation of multiple acoustic traps in proximity to large sound-scattering surfaces. The BEM algorithm dynamically calculates and updates the positions of multiple acoustic tweezers by changing the phases of the ultrasound transducers, allowing control over the levitation and omnidirectional movement of multiple droplets of bioinks in mid-air. The BEM algorithm simulates acoustic wave interactions with large, scattering surfaces in real-time, predicting, and mitigating potential distortions in the acoustic field. This allows levitation, transportation, and *in situ* deposition of bioinks onto irregular surfaces of diverse orientations, including a human hand. This system is capable of printing diverse soft materials within a wide range of viscosity (1–5 000 000 mPa s) including biopolymers and composite hydrogels and bioinks. The embedded cells in the hydrogels also demonstrated high viability post-printing. Its contactless nature minimizes risks of cross-contamination, damage and mechanical wear on the substrate. It eliminates reliance on robotic arms and enables levitation at proximity or on large sound scattering surfaces, greatly contributing to the versatility of the fabrication device.

B. Acoustic focusing

Acoustic focusing leverages concentrated acoustic energy to induce localized effects, such as cavitation and sonochemical reactions, enabling precise structuring of materials at the microscale. Compared to light, ultrasound waves (<10 MHz) can penetrate optically scattering materials over 100 times deeper, making them promising for energy deposition to initiate polymerization at greater depths.[101] By focusing sound waves, this technique facilitates the direct[101] polymerization and layerless fabrication of complex geometries.[53,54,67]

Habibi *et al.*[67] proposed direct sound printing (DSP), utilizing focused ultrasound to induce cavitation and create localized high-temperature and high-pressure zones in heat-curing polymers like PDMS for 3D fabrication [Fig. 6(a)]. This process uses a spherical transducer to focus acoustic energy, forming "ultra-active microreactor" regions where cavitation bubbles oscillate and collapse, triggering rapid sonochemical polymerization. By precisely controlling the focus,

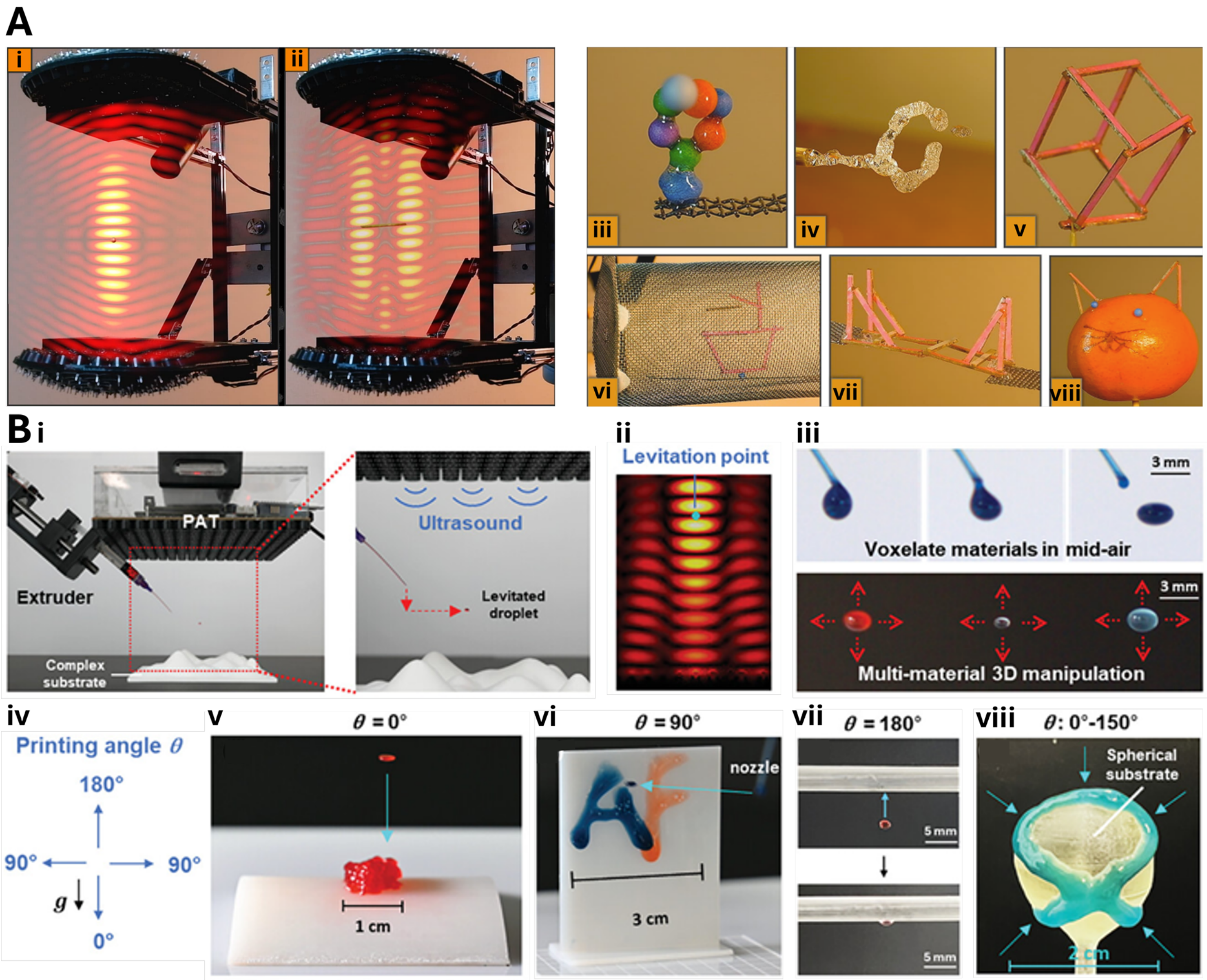

FIG. 5. 3D printing using acoustic levitation. (a) Mid-air assembly of beads, sticks and droplets. Pressure fields generated by a fixed-levitator showing an acoustic trap for holding a single sub-wavelength particle (i) and a double acoustic trap where half the emitters are driven with an inverse polarity signal capable of fully trapping elongated objects like sticks (ii) in mid-air. Particles (iii) and glue droplets (iv) can be joined to build a loop (v) 12 orthogonally placed sticks joined via L-joints to form a cube. (vi) a stick being levitated inside an acoustically transparent container. (vii) Fifteen sticks are joined using butt joints, L-joints, and miter butt joints to form a bridge. (viii) Assembly of multiple primitives at various angles to form a solid spherical object (cat face).[51] (b) Omnidirectional and multi-material *in situ* printing using acoustic levitation. (i) The AcoustoFab system, where the PAT generates the sound field for controlled levitation and transportation of materials introduced into the working space by extruders. (ii) The acoustic pressure distribution of a levitation trap. (iii) The system voxelizes extruded materials into droplets in mid-air and moves them omnidirectionally (iv). This allows deposition at varying angles: 0° on a horizontal surface (v), 90° on a vertical surface (vi), and 180° upward on a horizontal cylinder (vii). (viii) The printing angle can be dynamically adjusted for each voxel, facilitating printing on a spherical surface.[52] Reproduced with permission from Chen *et al.*, Adv. Mater. Technol. **10**, 2401792 (2024). Copyright 2024 Authors, licensed under a Creative Commons Attribution (CC BY).

DSP enables the direct, additive-free solidification of complex geometries with tunable porosity and transparency.

Derayatifar *et al.*[53] introduced holographic DSP that builds on the principles of DSP and further improved it by introducing acoustic holography for greater precision and scalability [Fig. 6(b)]. Unlike DSP, which relies on a single acoustic focal point, holographic DSP utilizes pre-patterned acoustic wavefronts stored in holograms to project entire cross-sectional images, enabling simultaneous polymerization across multiple regions. This method achieves one order of magnitude faster printing speeds compared to conventional DSP and produces layerless, high-resolution structures. The process operates with a stationary hologram and a robotic arm-controlled printing platform, facilitating complex trajectory planning and multi-material printing. Experimental validation using sono-chemiluminescence and high-speed imaging confirmed precise cavitation control, allowing for the fabrication of intricate geometries, including multi-object and remote in-body printing. Additionally, these DSP approaches support porosity tuning, making it highly applicable to biomedical, soft robotics, and advanced composite fabrication. By integrating acoustic holography into 3D printing, holographic DSP presents a scalable, energy-efficient

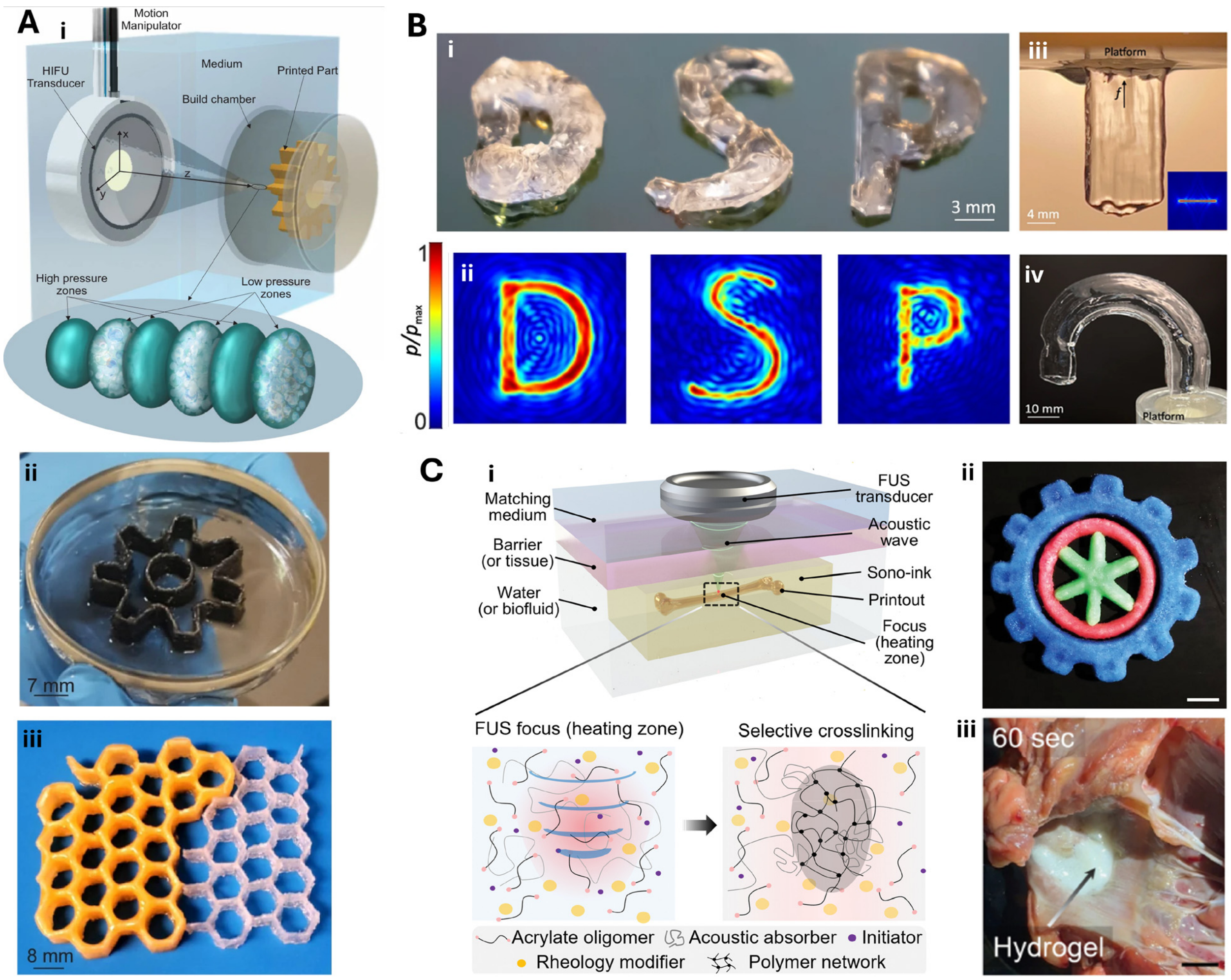

FIG. 6. 3D printing using focused sound waves. (a) Direct Sound Printing (DSP) utilizes focused ultrasound to induce cavitation and fabricate 3D structures within a liquid resin or monomer-curing agent. (i) A monolithic spherical transducer generates an ultrasonic field, forming a localized microreactor where cavitation bubbles collapse, triggering polymerization. This enables layer-by-layer fabrication with tunable porosity, including colored gears (ii) and honeycomb structures (iii).[67] Reproduced with permission from Habibi *et al.* Nat. Commun. **13**(1), 1800 (2022). Copyright 2022 Authors, licensed under a Creative Commons Attribution (CC BY). (b) Holographic DSP improves the printing speed and energy efficiency of direct sound printing, demonstrated by printed "DSP" letters (i), simulated pressure patterns (ii), a transparent printed wall (iii), and a self-supported U-shaped structure (iv).[53] Reproduced with permission from Derayatifar *et al.*, Nat. Commun. **15**(1), 6691 (2024). Copyright 2024 Authors, licensed under a Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND). (c) Acoustic volumetric 3D printing that enables deep-penetration digital fabrication and selectively cures sono-ink via sonothermal polymerization. The sono-ink formulation enhances acoustic absorption while minimizing streaming effects, enabling multi-material structures such as a three-part wheel (ii) and minimally invasive medical applications, including scaffold printing on biological tissues (iii).[54] Reproduced with permission from Kuang *et al.*, Science, **382**(6675), 1148–1155. Copyright 2023 The American Association for the Advancement of Science.

method for remote and volumetric polymerization, marking a significant leap in ultrasound-based additive manufacturing.

Kuang *et al.*[54] introduced Deep-Penetration Acoustic Volumetric Printing (DAVP), an innovative 3D printing technique that uses focused ultrasound (FUS) and self-enhancing sono-inks to enable contactless, volumetric fabrication of complex structures, even inside the body [Fig. 6(c)]. Unlike light-based methods, which are limited by light attenuation, DAVP leverages ultrasound waves that penetrate deep into optically scattering materials, such as biological tissues, making it ideal for minimally invasive medical applications. The sono-inks, composed of p hase-transitioning polymers like poly(N-isopropyl acrylamide), suppress acoustic streaming while enabling rapid sonothermal polymerization at the FUS focus, allowing precise, high-resolution printing. DAVP achieves centimeter-scale penetration depths, enabling the fabrication of intricate hydrogel constructs, nanocomposites, and drug-eluting scaffolds through thick tissues. This breakthrough paves the way for *in situ* bioprinting, tissue reconstruction, and targeted drug delivery, offering a versatile platform for advanced biomedical engineering and minimally invasive therapies.

C. Acoustic droplet ejection

Acoustic droplet ejection (ADE) is a technique that utilizes focused acoustic energy to transfer or eject liquid droplets in a nozzle-free

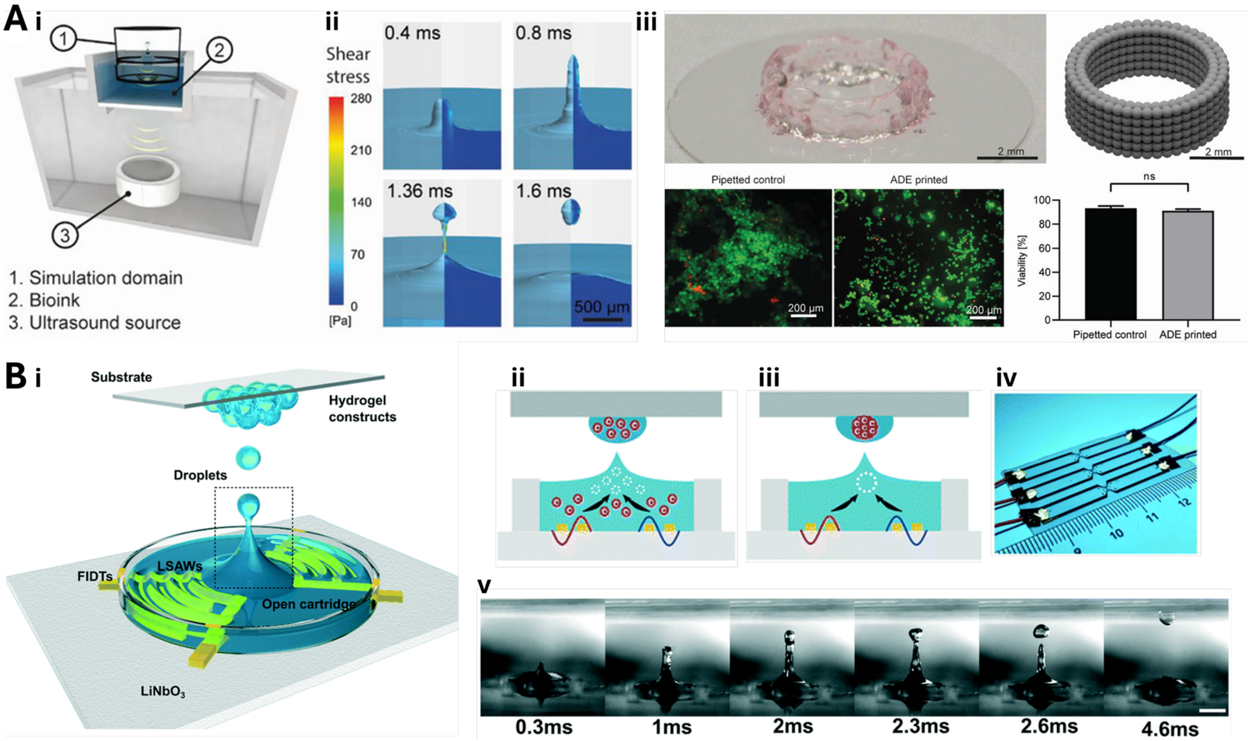

FIG. 7. Acoustic ejection in 3D printing. (a) Acoustic droplet ejection method for nozzle-free 3D bioprinting. (i) The setup and simulation domain illustrate the induced shear stress at different time points (ii). (iii) A 96-droplet-per-layer cylinder bioprinted using acoustic ejection with fluorescence imaging confirming high post-printing cell viability.[55] Reproduced with permission from Jentsch *et al.*, Small Methods **5**(6), 2000971 (2021). Copyright 2021 Authors, licensed under a Creative Commons Attribution-NonCommercial (CC BY-NC). (b) Another nozzle-free acoustic droplet printing method. (i) The system consists of focused interdigital transducers on a piezoelectric lithium niobate substrate with an open cartridge. (ii) This enables precise deposition of high-concentration cell suspensions or (iii) single-cell spheroids into 3D hydrogel constructs after pulsed RF signal input. (iv) A real image of the system. (v) Time-lapsed high-speed imaging captures the ejection process, highlighting its ability to generate droplets across three scale levels by adjusting ultrasound frequency reducing shear stress and clogging.[56] Reproduced with permission from Chen *et al.*, Lab Chip **21**(8), 1604–1612. Copyright 2021 Royal Society of Chemistry.

manner.[102] Unlike traditional inkjet- or extrusion-based printing methods, ADE-based liquid handing enables precise, contact-free deposition of liquid materials and has emerged as a promising approach for bioprinting.

In 2021, Chen *et al.*[56] demonstrated the printing method that utilizes surface acoustic waves for precise ejecting and depositing the high-concentration cells and single-cell spheroid to fabricate 3D native-like tissues [Fig. 7(a)]. At the system bottom, the sinusoidal radio frequency signal is applied to the focused interdigital transducers, which create surface acoustic waves that converge acoustic pressure and raise the liquid–air interface into a stretched jet. At the top of the system, a substrate receives the ejected droplets at the targeted deposit position. This work presented different constructs like dot arrays, crossroads, and pyramids and resulted in high cell viability (>94%) and controllability of low-concentration materials.

Jentsch *et al.*[55] investigated multi-scale 3D bioprinting based on the acoustic droplet ejection method that built 3D cell-laden structures from large cell aggregates to individual cells [Fig. 7(b)]. In this work, high-intensity focused ultrasound acts on the bioink reservoir and generates acoustic streaming and a surface flow with a dome on the liquid. A portion of the liquid can be ejected and collected from the dome's peak when ultrasound pressure and kinetic flow energy exceed the liquid's interface energy. This method enables variable ejected droplet sizes over three scale levels through changing ultrasound frequency. It minimizes shear stresses and clogging during printing and represents great potential in the field of tissue engineering, regenerative medicine, and mechanobiology.

D. Discussion

We have examined the emergence of acoustic 3D fabrication as a standalone manufacturing approach, breaking away from hybrid methods that rely on conventional 3D printing techniques. Unlike acoustics-assisted 3D printing, which enhances existing additive manufacturing processes, acoustic 3D fabrication employs sound waves as the primary mechanism for material manipulation, enabling contactless assembly and precise spatial control. Techniques, such as acoustic levitation, acoustic focusing, and acoustic droplet ejection, have demonstrated the ability to construct intricate, multi-material architectures without the need for extrusion-based or photopolymerization-dependent processes. Acoustic levitation, in particular, has shown promise in assembling lightweight structures in mid-air, while acoustic focusing has facilitated the formation of microscale patterns and porous architectures with exceptional resolution. These advancements not only introduce new design possibilities but also overcome many of the substrate and material limitations inherent in traditional 3D printing. Despite their transformative potential, acoustic fabrication methods still face bottlenecks in scalability, material diversity, and process stability. As research continues to refine acoustic manipulation strategies, the potential for fully autonomous, high-resolution, and material-agnostic fabrication remains a compelling avenue for exploration.

V. CHALLENGES AND FUTURE PERSPECTIVES

While recent advancements in acoustic 3D fabrication have demonstrated remarkable progress, such as multi-material printing[52] and high-resolution patterning of diverse materials,[42] bottlenecks persist due to the inherent physics of sound−matter interactions and system design constraints.[103]

Acoustic 3D fabrication faces persistent challenges related to both material properties and the fundamental physics of sound–matter interaction. Levitating and manipulating materials with high density, viscosity, or surface tension is particularly difficult in air, where acoustic radiation forces are weaker and less stable.[43,52] Increasing acoustic power to overcome these limitations often introduces heat, which can compromise resolution and damage temperature-sensitive materials. Furthermore, the effectiveness of acoustic levitation and structuring depends strongly on acoustic contrast, the ratio of mechanical compressibility to density between the material and the surrounding medium.[68] Materials with low contrast are harder to manipulate reliably, and high-viscosity fluids such as bioinks are especially susceptible to acoustic streaming. This introduces uncontrolled flow and shear stress, distorting structures, and degrading pattern fidelity.[68] Maintaining resolution in these conditions typically requires intense, focused fields or impedance-matching strategies to stabilize the interface.[104] Multi-material printing adds further complexity, as acoustic impedance mismatches between materials can generate non-uniform forces, leading to unstable integration.[52]

These challenges are governed by wavelength-dependent tradeoffs in acoustic-based fabrication. Acoustic trap size and intensity distribution are fundamentally determined by the acoustic wavelength λ, as described in Eqs. (1) and (2). Acoustic trap size typically defines both the minimum spacing between independently controlled objects and the upper limit of particle sizes that can be stably manipulated.[68,105,106] In acoustic focusing techniques, the focal spot size, which defines the resolution, is fundamentally limited by diffraction and typically cannot be smaller than approximately $\frac{\lambda}{2}$.[54,107,108] Increasing the acoustic frequency decreases λ, thereby reducing the trap size and focal point and enabling finer spatial confinement and higher resolution. However, this also lowers the maximum size of building blocks, potentially limiting the scalability of the printed object. Higher frequency also increases the attenuation coefficient, resulting in lower energy penetration and diminished acoustic radiation force further from the transducer. Although higher frequencies can theoretically enhance focal point pressure and trap strength by increasing pressure amplitude, these benefits are constrained by practical limitations. As frequency rises, piezoelectric materials exhibit greater dielectric and mechanical losses, and transducers experience higher electrical impedance, which reduces electromechanical coupling, energy transfer efficiency, and overall acoustic output.[109–111] Additionally, distortions caused by pressure gradients, acoustic interference, and transducer misalignment can disrupt field uniformity,[54,97,112] while absorption and scattering from previously deposited materials further degrade patterning accuracy in deeper layers. While strategies such as parallel polymerization via acoustic focusing have improved throughput,[53,54,67] maintaining consistent, high-resolution fields across large build volumes remains a significant technical challenge.

Overcoming current limitations in acoustic 3D fabrication will require coordinated progress in materials, system design, and real-time control. Developing materials with tailored acoustic properties, such as tunable impedance or enhanced contrast, can improve force transmission and enable more consistent manipulation of viscous or low-contrast media. At the device level, adaptive transducer arrays and real-time monitoring systems can dynamically maintain field uniformity and compensate for wave interference, misalignment, or attenuation, reducing structural defects in large-scale or multilayer printing. Bridging microscale precision with macroscale fabrication requires advanced acoustic field strategies. The simultaneous use of acoustic waves of multiple frequencies can enable control over both fine features and broader structural alignment. Similarly, superimposed acoustic fields, created by overlaying multiple waveforms, allow dynamic tuning of trap strength, spacing, or geometry within a single patterning zone. In more complex setups, hierarchical field designs, which combine coarse, large-scale fields with localized high-resolution regions, help distribute energy across spatial scales, supporting consistent patterning from single cells to centimeter-scale constructs.

Recent advances in computational acoustics have greatly enhanced the control of acoustics.[99,100,113,114] However, real-world acoustic fabrication can introduce a broader range of dynamic conditions that can affect the sound field, such as time-dependent changes in material properties (e.g., curing), local temperature variations, dynamic substrate geometries, and acoustic interference from previously deposited layers. To address these challenges, systems must move beyond static field designs and adopt real-time acoustic field shaping, where acoustic parameters—including phase, amplitude, frequency, and transducer timing—are dynamically adjusted during operation to maintain target field distributions. Within this framework, feedback-driven manipulation becomes essential. Real-time data from embedded acoustic sensors, optical imaging, or motion tracking systems can monitor field behavior, droplet trajectories, and structure formation, allowing the system to actively correct for disruptions. For example, in a closed-loop acoustic levitation setup for 3D printing, optical tracking of droplet position can be used to continuously adjust the driving phases of a phased transducer array. This dynamic control is key to ensuring pattern fidelity and process stability in complex or large-scale acoustic fabrication scenarios.

To support this adaptivity, machine learning–guided acoustic field calibration offers a powerful tool for managing complex, nonlinear, and dynamic behaviors during fabrication. Machine learning (ML) models can learn how factors, such as material properties, environmental conditions, and device-specific variations, affect acoustic field performance. This enables predictive tuning of actuation parameters to maintain field stability and target accuracy over time. In particular, reinforcement learning can be used to iteratively optimize multi-frequency excitation schemes by maximizing field uniformity or trap stability based on real-time feedback. ML can also aid in adaptive error correction, identifying and compensating for field distortions caused by material transitions or prior deposition layers. By integrating these AI-driven capabilities, including dynamic field shaping, closed-loop feedback, and data-driven calibration, future acoustic manufacturing platforms can achieve greater robustness, precision, and scalability. This will be essential for enabling consistent, high-resolution fabrication in biomedical applications, tissue engineering, and large-scale structural assembly.

Beyond solving current challenges, acoustic techniques in 3D printing present exciting opportunities for expanding the applications of numerous fields, including bioprinting, drug delivery, and food engineering. Conventional 3D bioprinting faces challenges such as geometric mismatches, mechanical damage during handling, and contamination risks, while acoustic methods offer a contactless and highly precise approach to assembling biological structures directly within clinical or biological environments.[115–119]

One promising avenue is acoustic-assisted *in situ* bioprinting, where cell-embedded bioinks can be precisely deposited onto human tissues without direct mechanical contact. This technique is particularly valuable for fragile or irregular surfaces, such as wound sites, organ interfaces, or vascular structures, where traditional extrusion or inkjet-based bioprinting methods struggle. Additionally, omnidirectional acoustic patterning enables fabrication on non-planar and dynamic substrates, facilitating applications in complex reconstructive surgeries, tissue grafts, and minimally invasive therapeutic interventions.[52,120]

Beyond levitation-based assembly, focused ultrasound enables noninvasive fabrication of biomaterials within living organisms by localized polymerization through mechanisms such as sonothermal effects and acoustic cavitation,.[53,54,67] Unlike light-based photopolymerization, which is limited by optical penetration depth and tissue transparency, acoustic techniques can penetrate deeper through optically opaque biological structures, paving the way for layerless, volumetric *in vivo* printing.[54,101] This holds promise for next-generation tissue engineering, regenerative medicine, and implantable biomaterial designs, offering new pathways for precision-guided reconstruction of damaged tissues and biohybrid implants. Future research can expand the acoustic-responsive bioinks optimized for both acoustic manipulation and biological compatibility, as well as explore strategies to ensure vascularization, innervation, and immune compatibility of bioprinted structures.

In pharmaceutical manufacturing, precise formulation, encapsulation, and deposition of active ingredients are critical to ensuring dosage accuracy and controlled release.[121–124] Acoustic techniques, such as acoustic ejection and levitation, can precisely dispense and structure pharmaceutical compounds without mechanical stress, preserving the integrity of bioactive molecules. Furthermore, acoustic focusing could enable the layerless printing of drug-loaded hydrogels and nanostructured drug carriers, allowing for the customized fabrication of patient-specific drug formulations. Future research could investigate the integration of acoustic 3D printing with pharmaceutical microfluidics, developing tailored drug delivery systems with enhanced bioavailability and precise spatial control.

In addition to biomedical applications, acoustic 3D fabrication shows considerable potential in the field of food engineering. By enabling the contactless assembly of food-grade materials, this technology can create customized textures and structures without compromising nutritional content.[64,125–127] For example, acoustic methods could precisely position and pattern plant-based proteins, enhancing the texture and mouthfeel of meat substitutes. Furthermore, the ability to construct scaffold-free cultured meat through acoustic assembly could advance sustainable food production. The noninvasive nature of acoustic techniques ensures that delicate nutrients and bioactive compounds remain intact during fabrication, potentially leading to functional foods with enhanced health benefits. Future work can focus on formulating food materials suitable for acoustic processing and establishing protocols that maintain nutrient integrity and safety.

VI. CONCLUSIONS

Recent advancements in acoustic 3D fabrication have significantly expanded the capabilities of additive manufacturing, demonstrating precision, versatility, and scalability. Early studies on acoustic patterning showcased exceptional control over particles, droplets, and cells but were limited by scalability and integration with established fabrication methods. The incorporation of acoustics into conventional techniques, such as DIW, inkjet printing, and SLA, improved material deposition, porous structure customization, and intricate particle alignment, yet these approaches primarily enhanced existing methods rather than enabling fully autonomous, scalable acoustic-driven fabrication.

Recent breakthroughs have addressed these limitations by demonstrating standalone, scalable acoustic fabrication methods. For instance, omnidirectional multi-material *in situ* printing has been achieved using acoustic levitation, focused ultrasound-driven polymerization enables volumetric structuring and layerless printing of soft materials, and acoustic ejection transfers and assembles liquid droplets in a nozzle-free manner.

Despite these advancements, challenges remain in material compatibility, scalability, and process control. The acoustic contrast of different materials, particularly high-density metals and ultra-viscous fluids, limits precise manipulation, while achieving microscale resolution in macroscale fabrication remains a hurdle. Exciting future work includes multi-frequency acoustic coupling, hierarchical field design, and AI-driven real-time adjustments to improve control, precision, and efficiency. Additionally, expanding applications in biomedicine, *in situ* bioprinting, and food engineering could unlock new frontiers in personalized medicine, regenerative therapies, and sustainable food production.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Hongyi Chen: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (lead). **James Hardwick:** Conceptualization (supporting); Data curation (supporting); Formal analysis (supporting); Visualization (supporting); Writing – original draft (supporting); Writing – review & editing (supporting). **Lei Gao:**

Data curation (supporting); Formal analysis (supporting); Visualization (supporting); Writing – review & editing (supporting). **Diego Martinez Plasencia:** Formal analysis (supporting); Writing – review & editing (supporting). **Sriram Subramanian:** Conceptualization (supporting); Funding acquisition (equal); Project administration (supporting); Supervision (supporting); Writing – review & editing (supporting). **Ryuji Hirayama:** Conceptualization (supporting); Data curation (supporting); Formal analysis (supporting); Funding acquisition (lead); Project administration (lead); Supervision (lead); Writing – original draft (supporting); Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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