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Review article

Inkjet printing quality improvement research progress: A review☆

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ABSTRACT

Inkjet printing is a prevalent printing technology that finds extensive applications in diverse fields, including mechanical manufacturing and flexible electronics. Enhancing the quality of inkjet printing has consistently piqued significant interest, with the goal of attaining superior printing resolution, precise color reproduction, and finer image details. This article begins with an overview of the current advancements in inkjet printing, elaborating on four key principles and technologies of inkjet printing. Subsequently, the article delves into the application and research progress related to enhancing inkjet printing quality across various fields. This exploration is structured around four perspectives: printing equipment, substrates, ink properties, and emerging printing technologies. Significant enhancements in inkjet printing quality, resulting in improved image details and color reproduction effects, can be attained by optimizing ink formulations, refining inkjet head design, and selecting suitable substrates and surface treatment methods. To conclude, this article addresses and summarizes future technological advancements aimed at enhancing inkjet printing quality.

1. Introduction

With the evolution of digital and computer technologies, digital printing has transformed into a novel printing method and is poised to exert an increasing influence on societal development. Inkjet printing, with its advantages in high efficiency and lower costs, has emerged as the predominant printing method in today's market. As digital technology continues to progress, inkjet printing technology is gradually maturing, leading to heightened expectations for the quality of inkjet printing. Consequently, enhancing the quality of inkjet printing products holds paramount significance. This chapter provides a comprehensive overview of the developmental trajectory of inkjet printing, elucidating the importance of inkjet printing technology. It also introduces the printing principles and parameters associated with inkjet printing technology.

1.1. The development history of inkjet printing

As technology has advanced, scholars have delved deeper into the study of fluids, leading to the gradual maturation of inkjet printing technology, which has evolved from its inception to its current state. In 1752, the German physicist Euler formulated the equations of motion for ideal fluids, drawing upon the principles of fluid dynamics [1]. In 1833, French scholar Savart published the findings of his droplet break-up experiment, thereby establishing the theoretical groundwork for the implementation of inkjet printing

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[2]. In 1858, British physicist William Thomson, also known as Lord Kelvin, invented a telegraphic information recording device that operated on principles similar to inkjet printing. In 1878, Lord Rayleigh referred to the principle of a single stream of fluid breaking up into small droplets in his relevant research [3]. In 1951, through relentless research efforts, Siemens Elmqvist of Sweden developed an inkjet device based on the Rayleigh droplet separation principle, marking the creation of the first inkjet printing device capable of printing text. In 1963, Dr. Richard Sweet of Stanford University in the United States conducted research on continuous inkjet printing technology, building upon Elmqvist's earlier inkjet device [4]. In 1972, Clevite company became the first to commercialize piezoelectric on-demand inkjet technology [5]. In 1980, Hewlett-Packard (HP) in the United States introduced the first commercial printer, and in 1984, HP pioneered thermal inkjet printing technology. Canon, a company known for its research and development prowess, also developed products based on thermal inkjet printing technology [6]. After years of evolution, inkjet printing technology has emerged as a pivotal technique in the field of printing.

1.2. Inkjet printing technology

Inkjet printing stands out as a genuinely plateless printing technology. Tiny ink droplets are precisely expelled from the inkjet printhead onto the substrate's surface through various methods, creating the desired text and graphics with remarkable precision. In accordance with different inkjet techniques, it can be categorized into two distinct groups: Continuous Inkjet Technology (CIJ) and Drop-on-Demand Inkjet Technology (DOD). Fig. 1 illustrates the classification of inkjet printing technology.

1.2.1. Continuous inkjet printing technology

Continuous inkjet technology produces an uninterrupted stream of ink droplets by applying high-frequency pulses to the printhead. The droplets pass through a charging zone to acquire a charge before entering a deflection electrode area for redirection. Ink droplets that have carried text and graphics information are deposited onto the substrate, while the remaining droplets in the deflection electrode area are redirected, recovered, and recycled by an ink recovery device. Fig. 2 provides a schematic diagram illustrating the principle and structure. Continuous inkjet systems feature a more intricate structure, but they may not achieve very high droplet control precision. They are typically employed in scenarios where exacting printing precision is not a prerequisite, and large-scale production is the focus.

Continuous inkjet technology encompasses three categories: Sweet inkjet, Hertz inkjet, and Microdroplet inkjet. Sweet inkjet can be further categorized into deflected and non-deflected types. Deflected Sweet inkjet can be classified into binary deflection and multi-state deflection control [7].

1.2.2. On-demand inkjet printing technology

When inkjet printing is applied to a region with graphic information, on-demand inkjet technology eliminates the need for charging or controlling the deflection of ink droplets.It features a straightforward structure without the necessity for an ink droplet recovery device and achieves high precision in control. With technological advancements, on-demand inkjet technology has gradually become the primary method in inkjet printing. This technology is categorized based on different driving principles, including piezoelectric component drive, heating element drive, and electric power drive. Among these, piezoelectric component drive includes piezoelectric inkjet technology and the acoustic wave type; heating element drive encompasses thermal bubble inkjet technology; electric power drive includes electrostatic and electrophoretic printing technologies. Notably, piezoelectric inkjet and thermal bubble inkjet technologies are widely applied. The classification of on-demand inkjet printing technology is depicted in Fig. 3.

Piezoelectric inkjet technology operates by pulsing the piezoelectric element, inducing volume changes. This, in turn, generates positive or negative pressure within the ink chamber, thereby controlling the ejection and retraction of ink droplets. Piezoelectric ceramics are frequently employed as piezoelectric materials due to their malleability in shaping and robust piezoelectric properties. In piezoelectric inkjet technology, lead zirconate titanate (PZT) is a commonly employed material for the piezoelectric element. Due to the varying directions of deformation of piezoelectric elements under different external electric fields, piezoelectric inkjet technology can be classified into four modes: squeezing (Fig. 4a), bending (Fig. 4b), pushing (Fig. 4c), and shearing (Fig. 4d), each suitable for distinct applications [8]. Fig. 4 provides a schematic diagram illustrating the principle and structure.

Thermal bubble inkjet technology utilizes an electric current to heat a component in the ink chamber, creating bubbles in the ink.

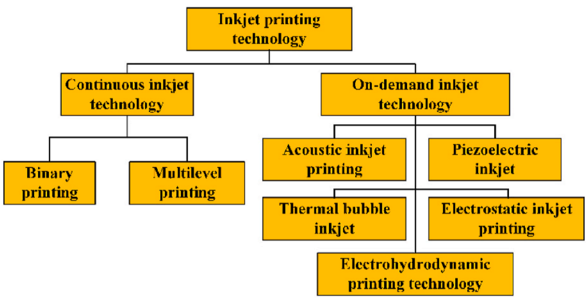

Fig. 1. Inkjet printing technology classification.

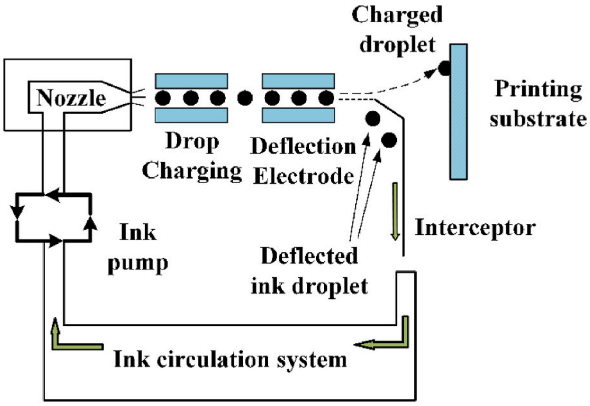

Fig. 2. Continuous inkjet technology principle and structure diagram.

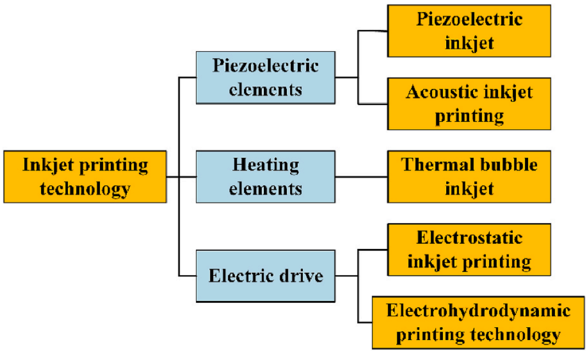

Fig. 3. Classification of on-demand inkjet printing technologies.

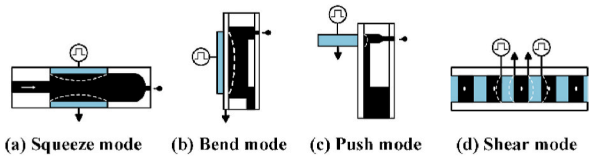

Fig. 4. When subjected to an electric field, piezoelectric crystals exhibit various deformation modes for ink extrusion: a) utilizing two piezoelectric crystals for ink extrusion, b) employing a single piece of piezoelectric crystal bending to expel ink, c) using a single piece of piezoelectric crystal for ink expulsion via pushing, d) employing multiple piezoelectric crystals for ink expulsion through shear deformation.

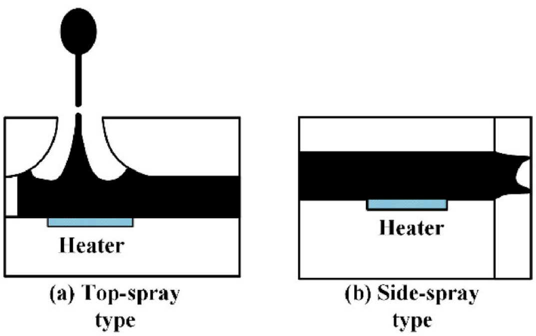

Fig. 5. Two types of thermal bubble structures: (a) top-jet printing (b) side-jet printing.

The expansion and contraction of these bubbles create positive or negative pressure within the ink chamber, thereby controlling the ejection and retraction of ink droplets. Thermal bubble inkjet technology has higher ink demands due to the need for heating to generate bubbles [9]. Simultaneously, controlling the size and direction of the bubbles generated by heating is challenging and can impact printing precision. Thermal bubble inkjet technology consumes more energy and has slower printing speeds when compared to piezoelectric inkjet technology. Thermal bubble inkjet technology can be categorized into top-jet types (Fig. 5a) and side-jet types (Fig. 5b) based on the heating element's position relative to the nozzle [10]. Fig. 5 provides a schematic diagram illustrating the structure and principle.

The principle of electrostatic inkjet entails applying pulse voltage to an electrode, generating an adhesive force between the electrode and a vibrating plate. This deformation of the plate enables ink to flow into the ink chamber. When the adhesive force vanishes, the vibrating plate returns to its original state, expelling the ink [11]. In electrostatic inkjet technology, a ground connection is typically necessary to mitigate the impact of static electricity.

Acoustic inkjet technology uses vibrations to focus waves at a single point, where the wave's energy displaces the ink from the ink chamber [12]. Acoustic inkjet technology demands higher ink stability, necessitating the use of specialized ink formulations to ensure dependable and high-quality inkjet printing. Acoustic inkjet technology involves relatively high equipment costs, encompassing the expense of the printhead and control electronics. As a result, it is less frequently employed in large-scale inkjet printing applications.

Electrohydrodynamic inkjet printing technology is an innovative printing method rooted in the principles of electro-hydrodynamic (EHD) dynamics [13]. Electrohydrodynamic inkjet printing technology involves the application of voltage between the substrate and the printhead. Under the electric field's influence, ink accumulates charge on the liquid's surface. When the electric field force surpasses the liquid's surface tension, it pulls ink droplets from the nozzle, forming a conical meniscus, as depicted in Fig. 6 [14]. EHD jets typically have a diameter ranging from 0.01 to 0.2 times that of their nozzles, enabling sub-micron resolution accuracy and, consequently, high-resolution inkjet printing [15]. EHD inkjet systems feature various printhead types, including coreless single nozzles, needle-point single nozzles, and multi-nozzle configurations [16].

Scholars have significantly contributed to the rapid advancement of inkjet printing through research in fluid dynamics, experimentation, and the invention and commercialization of various technologies. With the widespread adoption of inkjet printing technology, researchers have conducted extensive studies aimed at enhancing the quality of inkjet printing in multiple facets.

2. Factors affecting the quality of inkjet printing

The entire process, from the ejection of ink from the printing equipment to its spreading on the substrate, can impact the final printing result. Enhancing printing quality involves improving print resolution, increasing inkjet stability, and minimizing the occurrence of coffee rings and satellite droplets during printing. This chapter delves deeper into the significance of enhancing printing quality across four aspects: printing equipment, ink, substrate, and printing technology.

2.1. Printing equipment

As manufacturing technology rapidly advances, inkjet printing technology continues to mature. Printing speed and resolution have seen rapid advancements, with printhead resolutions reaching 600 dpi, and some even achieving 1200 dpi [17]. Resolution is a key metric for evaluating printing equipment, and the resolution of printing devices is determined by their overall system structure. Decreasing the nozzle size directly can result in a finer resolution, but as the nozzle diameter decreases, there is an increased risk of nozzle clogging. Grayscale printing technology, developed on the basis of traditional inkjet printing, enables variable droplet size printing [18]. Grayscale printing technology, while capable of achieving higher resolution, also requires greater precision in printhead control. Transitioning from just two printing states to variable droplet size printing results in increased complexity for the entire printing control system. Hence, efficient printhead control is essential for grayscale printing technology. Apart from improving print quality through increased resolution, enhancing the stability of inkjet printing can be achieved by refining the drive control system of the equipment to ensure consistent printing results. A stable and reliable drive control system is crucial for maintaining a steady ink ejection. Scholars have conducted extensive research on print heads and ink chambers to address this aspect. In 2004, Wei Dazhong et al. conducted a simplified simulation of liquid flow within chambers, establishing the mathematical foundation for microdroplet ejection, and introduced a design method for cylindrical bent-type piezoelectric inkjet printhead chambers [19]. Zhang Wenhuan et al.

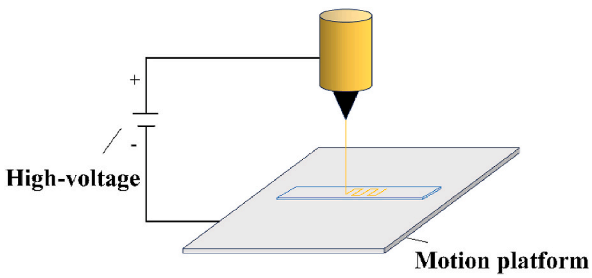

Fig. 6. Electric fluid principle structural diagram. Reproduced from ref. 106 with permission from Progress in Chemistry, copyright 2022.

improved the piezoelectric driver of the printhead, resulting in enhanced jetting speed and accuracy [20]. In their fluid analysis of piezoelectric printheads, Dong-Youn Shin et al. utilized a 1D Finite Difference Method (FDM) model and introduced uncertainty factors and a window model. This approach struck a balance between computational efficiency and a certain degree of model simplification when conducting fluid analysis on piezoelectric printheads. Compared to more detailed 2D models, the 1D model exhibited faster calculation speeds. In their research on piezoelectric inkjet printheads [21]. Herman Wijshoff et al. mentioned that simultaneous excitation of multiple channels can induce resonance in the printhead structure, affecting printing performance [22]. Therefore, when improving printheads, attention should be paid to whether the printhead structure is prone to resonance with other control systems. In 2007, Silverbrook introduced Memjet inkjet technology, utilizing MEMS technology in Memjet printheads. This technology achieved a printing precision of 1600 dpi [23], demonstrating that improvements in printheads can enhance printing accuracy. Besides ensuring the stable operation of the drive system, reducing system failures is equally important. Frits Dijksman et al., through the analysis of the trajectories of a large number of ejected droplets, found that a failure occurred approximately every 21,000 average droplet ejections. They emphasized the necessity of a fully automated printhead maintenance system compared to manual repairs [24]. Therefore, in addition to stable inkjet performance, printing equipment can reduce system failure rates by incorporating an automatic maintenance system.

Based on these analyses, it is evident that the continual improvement of printheads and drive technologies is paramount for enhancing print quality and resolution. The evolution of grayscale printing technology, in particular, imposes greater demands on printhead control accuracy. The increasing need for print quality is steering printing technology towards higher precision printing.

2.2. Ink

Ink, as the primary component of inkjet printing, is intricately linked to printing quality. The electrical conductivity, pH value, viscosity, surface tension, and other characteristics of ink all influence the entire process, from droplet generation to spreading on the substrate [25]. Due to the operating principle of inkjet printing, the fluid dynamic properties of ink have the most substantial impact on printing outcomes. Viscosity is a property that hinders the internal flow of liquid, describing the thickness or fluidity of the liquid. The viscosity of different liquids depends on the strength and arrangement of molecular interactions. The method for calculating viscosity is as presented in Eq. (1):

$$\eta = \frac{\tau}{D} \tag{1}$$

where η, τ, and D are the viscosity, shear stress acting on the fluid, and shear rate of the ink.

Surface tension is the energy per unit length on the surface of a liquid, a characteristic that leads the liquid surface to minimize its area, resulting in droplets taking a spherical shape. Various factors, including the type of liquid, temperature, and the nature of the surface in contact with the liquid, can impact the surface tension of droplets. The calculation method for surface tension is as presented in Eq. (2):

$$\sigma = \frac{F}{l_0} \tag{2}$$

where σ, F, and l_0 are the surface tension, force acting on the liquid surface, and length over which the force is applied.

In fluid dynamics, three pivotal parameters—Reynolds number (Re), Weber number (We), and Ohnesorge number (Oh)—define the boundary states of liquid droplet ejection. The calculation formulas for the three parameters and their interrelationships are as presented by Eqs. (3)–(5):

$$Re = \frac{\rho v a}{\eta} \tag{3}$$

$$We = \frac{\rho v^2 a}{\sigma} \tag{4}$$

$$Z = \frac{1}{Oh} = \frac{Re}{\sqrt{We}} \tag{5}$$

where ρ represents the density of the droplet, v is the ejection velocity of the droplet, a is the nozzle aperture, σ is the surface tension of the droplet, and η is the viscosity of the droplet. Through the aforementioned Eqs. (3)–(5), it's evident that the parameter Z is closely linked to the surface tension and viscosity of ink, commonly employed to depict the formation characteristics of ink droplets [22].

The fundamental characteristics of ink are crucial parameters for studying the ejection process of ink droplets. Precisely describing the motion interface between gas and liquid is critical for investigating inkjet processes. Among the current methods for motion interface tracking, the Volume of Fluid (VOF) method, first proposed by Hirt and Nichols in 1981, stands out as one of the most important approaches [26]. By setting characteristic parameters such as droplet density (ρ), viscosity (η), surface tension (σ), the VOF equation is solved to track the motion interface. Building on the analysis of droplet technology, scholars have conducted more in-depth studies on droplet flight and spreading. Due to the Rayleigh instability during the droplet's descent, satellite droplets significantly smaller than the main droplet can appear behind the main droplet [27]. These satellite droplets can cause splashing on the substrate, leading to a reduction in printing quality. Avoiding the occurrence of satellite droplets or minimizing their impact on printing has become a focus of research for many scholars. Kye-Si Kwon et al. investigated the generation principle of satellite droplets, exploring the threshold and generation curve for inhibiting satellite droplets [28,29]. Adding surfactants, polymers, and other substances to the ink can alter the surface tension and viscosity of the droplets, thus suppressing the generation of satellite droplets [30–33]. After leaving the printhead, in addition to the potential generation of satellite droplets, during the spreading process on the substrate, the droplet may exhibit the "coffee ring" effect due to capillary flow within the droplet. Deegan et al. proposed that the "coffee ring" effect is caused by the higher evaporation rate at the droplet's edge compared to the central evaporation rate, resulting in an outward capillary flow inside the droplet that carries suspended particles to the droplet's edge, forming a ring. In their study on eliminating the coffee ring effect [34]. Soltman et al. found that larger contact angles (close to but not exceeding 90°) are less likely to produce the "coffee ring" effect, while smaller contact angles are more prone to forming it [35]. Hence, by enhancing the properties of ink to mitigate or even diminish the occurrence of coffee rings and satellite droplets, we aim to ensure the optimal spreading of droplets on the substrate after ejection. This strategy is designed to minimize printing errors and uphold the overall print quality.

2.3. Substrate

The behavior of ink spreading varies on different substrates, and in inkjet printing, a diverse range of inks and substrates are utilized. The pH value, structure, and ink-absorbing characteristics of the substrate can all have an impact on printing quality [36]. The limitation of ink droplet spreading and the achievement of high-resolution printing can be realized by modifying the chemical properties or physical structure of the substrate [37]. In the investigation of droplet spreading characteristics, Cui Xinyu observed that the roughness of the substrate predominantly influences the retraction degree and spreading speed of liquid droplets after spreading [38]. While measuring the dynamic characteristics of inkjet-printed Ag thin films on flexible substrates, Kim D et al. discovered that the substrate influences the thickness and surface roughness of Ag films during the sintering process [39]. Iftimi L. D et al. observed that when printing pharmaceuticals, using edible solid foam as a substrate led to improved printing results [40]. Modifying the surface structure of the substrate also contributes to improving resolution. Sirringhaus et al. directed the flow of ink droplets by patterning the substrate's surface, printing channels with a width of 5 μm [41]. Hendriks et al. guided droplet spreading and deposition within channels by heat-pressing channels with a width of 15 μm onto the substrate [42]. Therefore, surface patterning of the substrate can aid in achieving higher printing resolutions. Grüßer et al. determined that the advancement of wetting substrates can reduce the expenses related to ink and substrates [43]. Rui Jie et al. conducted a comparative analysis of four paper types concerning three-dimensional color gamut, whiteness, glossiness, smoothness, and ink absorption. Their findings indicated that paper with higher smoothness and glossiness demonstrated enhanced color rendering capabilities and a broader color gamut range [44]. Therefore, modifying the physical structure and surface characteristics of the substrate can further ensure the correct spreading of ink droplets on the substrate, thereby guaranteeing printing quality.

2.4. Electrohydrodynamic jet printing technology

As technology continues to advance, the adoption of emerging printing technologies can further enhance the quality of inkjet printing. Electrohydrodynamic jet printing technology, as an emerging inkjet printing technology, excels primarily in its high-resolution printing capabilities. In 1914, Zeleny et al. proposed conducting arc discharge experiments using electrohydrodynamic to measure the electrical strength on the surface of conductive objects. They observed the formation of a conical fluid shape at the tip of the nozzle, which was commonly referred to as the 'Taylor cone' [28]. In 1980, Lai et al. uncovered that electrohydrodynamic jetting technology was not limited to industrial spray painting but also found application in fluid atomization and particle deposition for mass spectrometry analysis [45]. In 2004, Li D et al. pioneered the electrospinning process by generating fine fluid filaments through the stable electrohydrodynamic jetting mode [46]. In 2010, Mishra S et al. found that electrohydrodynamic jetting technology was capable of high-speed printing on flat substrates, reaching speeds of up to 10 KHz [47]. In 2015, Onses M. S et al. discovered that inkjet printing technology using electrohydrodynamic could achieve resolutions below 100 nm, demonstrating significant development potential in fields such as electronic printing [48]. Through the above discussion, it is evident that, besides improvements in printing equipment, ink, and substrates, the application of higher-precision printing technology can not only enhance the quality of inkjet printing but also drive its broader adoption across various industries.

In summary, it is evident that there are numerous factors influencing print quality, with aspects ranging from printing equipment to printing technology closely associated with print quality. To delve further into the impact of various improvement measures on the quality of inkjet printing, Chapter Three will discuss methods to enhance print quality from the four perspectives mentioned above.

3. Inkjet printing quality optimization

Quality inspection standards for inkjet printing products encompass ISO/TS 15311, ISO/TS 24790 (jointly developed by the International Organization for Standardization and the International Electrotechnical Commission), and GB/T 36598 (developed by the National Printing Standardization Technical Committee) [49]. Quality inspection encompasses both objective and subjective evaluations of various characteristics, including color accuracy, clarity, color saturation, uniformity, paper quality, and other relevant data associated with printed materials. These evaluations collectively lead to an overall assessment of the print product's quality. Enhancing inkjet printing quality extends beyond meeting standardized inspection requirements [50,51]. It primarily focuses on consistently delivering high-quality printed materials while perpetually propelling technological innovation.

This article explores various facets contributing to the enhancement of inkjet printing quality. When considering the resolution and stability of inkjet printing, achieving smaller ink droplet sizes becomes essential for enhancing resolution. Simultaneously, minimizing satellite droplets and the 'coffee ring' effect is crucial to bolster stability. Improvements in printing quality are reflected in equipment, ink, substrates, and emerging technologies. Optimizing printing equipment, which encompasses print heads and ink supply systems, fine-tuning piezoelectric pulse control, and enhancing jetting accuracy and efficiency, contributes to overall quality enhancement. Additionally, improving ink performance, bolstering droplet accuracy, and mitigating issues like the 'coffee ring' and satellite droplets further elevate print quality. Optimizing substrate surface treatment and material selection is crucial to improve ink absorption and transfer, minimize bleed-through and blurring, and enhance image clarity. Employing electrofluidic printing technology for electric field-controlled ejection, thereby enhancing accuracy, speed, print quality, and reducing resource consumption. These measures synergize to comprehensively improve printing accuracy, clarity, and stability, catalyzing technological innovation.

3.1. Improvements in inkjet equipment

3.1.1. Optimization of piezoelectric inkjet drive pulses

The formation of ink droplets is voltage-pulse-dependent, and the duty cycle of the pulses plays a crucial role.Lin et al. proposed that the rise time t_r and fall time t_f of the pulses should adhere to $V/t_r \leq 15, V/t_f \leq 15$ to ensure complete expansion and contraction of the PZT tube [52]. Bogy et al. developed an optimal pulse width calculation method to ensure that two consecutive droplets do not coalesce, ensuring that the center-to-center distance between them remains greater than the droplet diameter [53]. Xiaojian Li et al. discovered that at a constant pulse of 300 v and 250 H_z, the size of the droplet progressively expands with the expansion of the duty cycle of pulse [54]. Moreover, when the pulse duty cycle is below 12 %, droplets cannot be ejected. Additionally, the pulse frequency also plays a significant role. Zejian Hu et al. noted that, with an ink flow rate of 30 ml/h, increasing the pulse frequency from 10 kHz to 30 kHz caused previously split satellite droplets to merge with the main droplet. When the frequency reached 30 kHz, the droplets appeared as uniformly sized single droplets [55]. When the pulse frequency is 40 kHz, the ink droplets have irregular sizes. Applying disturbances in the direction of droplet formation can help eliminate satellite droplets. Runze et al. performed experiments with a 50 % glycerol-water solution and observed that applying longitudinal disturbances at a frequency of 84Hz induced asymmetry in the droplet's shape, resulting in oscillations and distortion. However, during the entire process, only one breakage occurred, and no satellite droplets were generated [56]. Oke Oktavianty et al. conducted a comparison between the basic waveform, W-shaped pulses, and enhanced W-shaped pulse waveforms. They discovered that reducing the trailing edge by 40 % in the W-shaped pulse effectively diminishes post-jetting residual vibrations and eliminates satellite droplets [57].

3.1.2. Improvements in printheads

Since the 1990s, inkjet printing technology has progressively matured, with thermal bubble jet and piezoelectric inkjet technologies emerging as the most commonly employed methods [58]. The shape and structure of the printhead impact both print quality and ink droplet flow rate and velocity [59]. To enable high-frequency printing in thermal bubble inkjet, Xi Shun Peng proposed a semi-spherical cavity thermal inkjet printhead, as depicted in Fig. 7. This design achieves a notable high-frequency printing capability at 30 kHz and boasts the most significant volume ratio between droplets and the cavity, reaching 14.9 % [60]. Such a structural configuration lowers costs for printing systems that require high-frequency printing without necessitating high printing precision. Piezoelectric inkjet technology, while capable of achieving high printing precision and frequency, imposes stringent sealing requirements for the ink chamber. Ali Rehmani et al. observed that the subcutaneous printhead can eject a larger ink volume compared to the columnar printhead. Under a flow rate of 40 μ_l/h, the subcutaneous printhead achieves a printing line width of 65 μm, while the columnar printhead achieves a printing line width of 47 μm [61]. It is evident that, at the same ink flow rate, the columnar printhead can achieve finer printing results with higher resolution.

Lai et al. discovered that the curvature of the print head exerts a certain influence on droplet formation. Print heads with linear curvature ejected droplets with a volume of 0.01 pL at a consistent frequency of 100 kHz, while print heads with parabolic and third-order curvatures produced droplets with volumes exceeding 0.04 pL. Print heads with linear curvature achieved a higher ejection

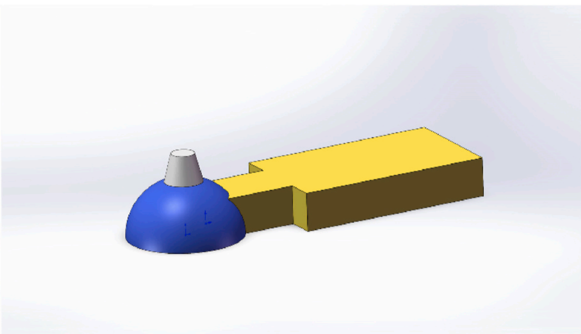

Fig. 7. Structure diagram of hemispherical cavity thermal inkjet printhead.

speed, reaching 100 m/s at a consistent 100 kHz frequency, whereas print heads with parabolic and third-order curvatures had ejection speeds below 40 m/s [62].

Qiang Yang et al. proposed a novel design concept involving the development of a superhydrophobic, low-adhesion inkjet printhead. This printhead design was implemented in piezoelectric inkjet printing, eliminating constraints on ink properties while effectively suppressing the generation of satellite droplets [63]. The distinct behavior of various printheads with Rayleigh instability filament breakup is illustrated in Fig. 8a–d. As the ink droplets do not wet the superhydrophobic surface, the ink does not wet the outer surface of the superhydrophobic nozzle. Consequently, the ejected ink droplets do not accumulate near the nozzle, preventing the formation of satellite droplets. The critical breakup length of the ink filament used is 434.2 μm. Among these four printheads, only the superhydrophobic nozzle has an ink filament length smaller than the critical breakup length, making it less prone to rupture and the formation of satellite droplets.

In summary, typically, the nozzle diameter plays a crucial role in determining the size of ejected ink droplets. A larger nozzle diameter results in larger droplet diameters, leading to lower achievable resolutions. The roundness of the nozzle influences the ink flow rate, with greater roundness corresponding to higher ink flow. Moreover, nozzles with different curvatures can impact the inkjet velocity. In addition to enhancements in nozzle structure, the utilization of excessively thick nozzles requires the assembly of complete resolutions through interleaved rows of nozzles when aiming for higher resolutions. This not only enlarges the overall spatial dimensions of the printing system but also diminishes the system's fault tolerance [64].

3.1.3. *Improvement of ink supply system*

As the application scope of inkjet printing technology continues to expand, the requirements for ink characteristics in the print heads have become increasingly stringent.Maintaining the stability of ink properties within the ink supply system is a prerequisite for ensuring the proper functioning of print heads and print quality [65]. A typical ink supply system consists of a primary ink tank, secondary ink tanks, ink pumps, filters, and a feedback control system. The ink supply system is responsible for providing a stable ink flow to the print heads. However, despite filtration, ink may retain air bubbles, which have the potential to impact print head performance and may even result in nozzle clogging [66]. Therefore, a better-designed ink supply system with improved degassing efficiency ensures not only the normal functioning of inkjet printing but also helps prevent nozzle clogging. Wen Xiaohui et al. devised an ink supply system featuring a recirculation ink and degassing module, as depicted in Fig. 9. In this system, the degassing module efficiently removes gases from the ink, minimizing the formation of particulate precipitates during ink flow. Furthermore, they conducted a comparison of three different degassing modules and discovered that after the Cobbett degassing process, the gas concentration in the liquid was only half of that observed after the MC14971 degassing process [67].

In addition to changes in the ink supply system's structure, ink supply pressure can also affect the performance of the printhead. In a simulated experiment conducted by San Kim et al. on the ejection characteristics and curved meniscus motion of an on-demand inkjet system, they observed that reducing the ink supply pressure resulted in decreased velocity and volume of ink droplets. Without pressure control, residual vibrations persisted for 292 us, but with a pressure of -3 kP_a, the termination time was reduced to 200 us [61]. By controlling the pressure, the time of residual vibrations was reduced by 31.5 %. Therefore, when using different ink supply systems and inks, adjusting to the appropriate ink supply pressure is also crucial. The lifespan of electromagnetic pumps in the ink supply system limits the operating duration of the system [68]. Therefore, designing electromagnetic pumps more suitable for inkjet printing to enhance their lifespan ensures the long-term stable operation of the ink supply system.

3.1.4. *Nozzle cleaning system*

As printing equipment operates, toner and paper dust generated become airborne.When these impurities settle on the printhead or its surroundings, they can impact the size of ink droplets and their ejection direction [69]. At present, China lacks domestically developed inkjet printhead technology with mature independent intellectual property. Consequently, a significant portion of equipment relies on imports, leading to higher costs. Frequent printhead replacements impose a significant financial burden on businesses [70]. Therefore, regular printhead cleaning not only ensures printing quality but also helps extend the printhead's lifespan to some extent.

Most inkjet devices require manual printhead cleaning, resulting in high costs and the need for skilled labor. Automatic printhead cleaning not only saves costs but also allows cleaning to be performed as needed based on the printhead's condition, enhancing the

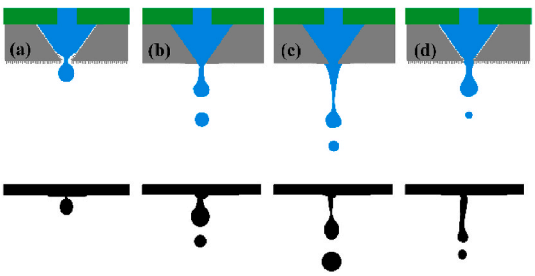

Fig. 8. Four types of nozzle inkjet effects: (a) superhydrophobic nozzle (b) hydrophobic nozzle (c) hydrophilic nozzle (d) highly adhesive superhydrophobic nozzle. Reproduced from ref. 64 with permission from American Chemical Society, copyright 2017.

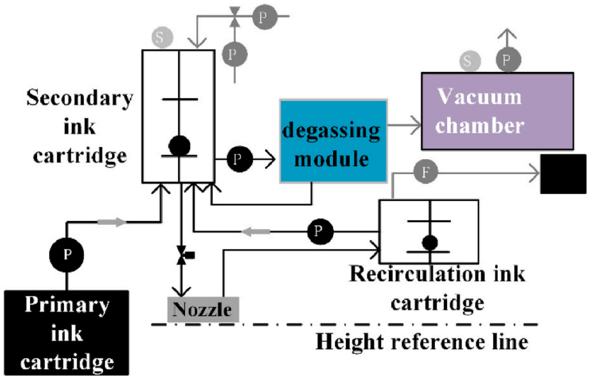

Fig. 9. Ink supply system schematic diagram.

production efficiency of the printing equipment. There are two common cleaning methods for print heads: contact and non-contact. Non-contact cleaning typically involves suctioning or extracting impurities from the print head, while contact cleaning is done by wiping with a roller along the print head [71]. Yang Guiyong et al. invented an ultrasonic cleaning system for ceramic printer heads [72]. Yuanhua Li et al. conducted research on the influence of nanoparticles in ink on the performance of piezoelectric inkjet printing. They discovered that hydrophobic cationic nanoparticles in the ink tend to clog the printhead, and the particles adhering to the printhead are challenging to fully clean, potentially resulting in secondary clogging [73]. Zhou Jingfu designed an automatic maintenance device for the printhead, incorporating a humidifying box. This innovation reduces the risk of printhead damage due to human factors and ensures that the printhead is not affected by airborne impurities when idle [74].

In summary, inkjet printing technology continues to advance. Throughout the inkjet printing process, eliminating satellite droplets can be achieved by optimizing the driving equipment or improving nozzle design. Additionally, to attain higher printing resolutions, designing smaller nozzles may necessitate the addition of a cleaning system to mitigate nozzle clogging associated with the reduction in nozzle size. Furthermore, designing a stable and durable ink supply system is crucial to ensuring the stable operation of printing.

3.2. Improvement of ink performance

The quality of inkjet printing is intricately tied to the ink. Factors like ink spreading and penetration have a direct impact on printing quality. Moreover, ink properties, including surface tension, conductivity, pH, and viscosity, also play a significant role in determining the overall printing quality [75]. Therefore, for different working scenarios, inks are categorized accordingly.

The main classifications of inks are summarized in Table 1.

The viscosity of printing ink is typically in the range of 2–10 $mP_{a.s}$, the surface tension of printing ink is generally between 25 and 50 mN/m, the calculation methods for viscosity and surface tension are as represented by Eq. (1) and Eq. (2), and to prevent corrosion of the print head, the pH value is usually in the range of 7–10.5. The particle size of ink is typically less than 500 nm [76–78].

Ink, while meeting the basic requirements for printing, can also enhance print quality through appropriate improvements. The addition of polymers and surfactants to the ink can improve the stability of droplets on the substrate. Jooho Moon et al. incorporated high-boiling, low-surface-tension ethylene glycol into droplets. Due to the differential evaporation rates, with water evaporating faster at the droplet's edge than in the center and ethylene glycol evaporating more slowly, the concentration of ethylene glycol gradually becomes higher at the edge compared to the center as evaporation progresses [79,80]. Manos Anyfantakis et al. discovered that the addition of polymers to increase ink viscosity or surfactants to restrict outward capillary flow can effectively suppress the 'coffee ring' effect [81,82]. Eral et al. determined that electrowetting aids in mitigating the pinning of the three-phase contact line of droplets, thereby inhibiting the 'coffee ring' effect [83]. The variation in surface tension between the margin and center of the droplet induces Marangoni flow, effectively mitigating the 'coffee ring' effect. Kun Zhang et al. proposed using Hydroxypropyl Methyl Cellulose (HPMC) as a replacement for Diethylene Glycol (DEG) to improve ink surface activity and flowability. Merely 0.6 wt% of HPMC is required to sustain stable droplet formation without satellite droplets, whereas DEG necessitates the addition of 50 wt% to achieve the same effect. HPMC not only enhances the jetting performance of dye ink but also contributes to reduced chemical usage and lower carbon emissions [84]. Zhiyuan et al. found that when the concentration of PEG400 in PEG-S465 dye ink reached 30 % or higher, no satellite droplets were produced during the droplet descent process [85]. However, higher ink concentrations lead to slower droplet

Table 1
Classification of commonly used inks.

Classification Method	Ink type
Functionality	Color ink, Functional ink
Coloration method	Pigment ink, Dye ink, Reactive ink, Coating ink
Applied industry	Publication ink, Packaging ink, Label ink, Textile ink, Ceramic ink, PCB ink
Ink base method	Textile ink, Ceramic ink, PCB ink

speeds, which are unfavorable for high-speed printing. Therefore, improving print stability by adding surfactants and polymers to the ink provides an innovative solution for environmentally friendly printing. However, it is crucial to consider the impact of polymers on droplet speed, droplet spreading, and other factors. In addition to enhancing print quality by adding polymers to the ink, the development of new conductive inks can improve print resolution, enabling the fabrication of smaller-sized flexible electronic products. In inkjet printing for wearable electronics and electronic displays, Marina Galliani et al. proposed a conductive PEDOT:PSS formulation for inkjet printing on wearable devices. The formulation achieved an average print resolution of 27.5 ± 4.5 *um* at room temperature (19–22 °C) with a droplet speed of 10 m/s [86]. Marco Cinquino et al., in experiments with PSS ink, found that OLEDs manufactured with PSS electrodes exhibited a maximum quantum efficiency of 5.5 % and a maximum current efficiency of 15 cd/A at 8V, proposing a suitable PSS ink ratio for OLEDs [87].

In summary, the development of new inks can enhance print resolution to achieve higher printing quality and is also applicable in the fabrication of smaller-sized flexible electronic products. The addition of polymers to ink helps eliminate the "coffee ring" effect and satellite droplets during printing, ensuring print stability.

3.3. Optimization of substrate

3.3.1. Wettability and structure of substrates

Surface wettability of the substrate is crucial, as the substrate's hydrophilic or hydrophobic nature determines the final resolution and quality of the printed pattern. On a hydrophilic substrate, water-based droplets tend to spread upon deposition, leading to a final size larger than the original design [88]. Veasna Soum et al. developed a substrate with a dual-layer pore structure using Polyethersulfone (PES), achieving a print line width and droplet size of 50 *um* [89]. Fig. 10 illustrates printed patterns on six different substrates: Polyethylene naphthalate (PEN), Polyethylene terephthalate (PET), copy paper, Polyimide (PI), PES, and photo paper. Notably, the fifth substrate demonstrates superior printing stability and resolution. It is evident that substrates with porous structures contribute to faster ink absorption while concurrently restricting droplet spreading on the substrate, thereby enhancing print resolution. Therefore, the design of more substrates with porous structures or the application of such structures to other substrates can significantly improve both printing stability and resolution.

The surface chemistry and energy distribution of the substrate affect the spreading of droplets on its surface [90]. Sameer Khandekar et al. discovered that introducing nano-pores to aluminum oxide can expedite the evaporation rate of droplets on its surface. The evaporation time on a standard aluminum oxide plate is roughly four times longer than on an aluminum plate with nano-pores [91]. Hence, adding pores to the substrate accelerates the evaporation speed of ink droplets. Haihua Zhou et al. applied polymer droplets, commonly used in ink, onto porous aluminum oxide with one end sealed. They observed that increasing both the pore radius and depth can effectively ameliorate the 'coffee ring' effect [92]. In addition, modifying the substrate with Perfluorodecyltrimethoxysilane ($C13H13F17O3Si$, FAS) restricted the spreading of ink droplets on the substrate, thereby improving the resolution of inkjet printing.

3.3.2. Coating of paper surfaces

Paper is a commonly used substrate in inkjet printing, and coated paper and art paper are commonly used substrates for roll-to-roll inkjet printing [93]. Coating, surface treatment, and calendering are common methods used to modify paper properties and improve print quality, with current research primarily focused on paper coating [94]. Natércia C.T et al. modified paper with chitosan (CH) or trimethyl chitosan (TMC) by gel coating the paper with the respective polymers. They found that coated paper had a maximum absorption of ink droplets at 415 nm, reduced from the original 423 nm [95]. In the study conducted by Song Ci et al., they prepared an OCNF/CTS composite adhesive for surface coating on packaging paper. Through experiments with different mass ratios, they found that when OCNF was at 0.5 %, the grease resistance index reached 12, indicating excellent barrier performance. They also found that this composite adhesive demonstrated a broader color gamut and superior tone reproduction performance in inkjet printing, suggesting promising applications in the fields of personalized packaging materials and labels for coated paper [96].

Juraj Gigac et al. applied silica pigments in coatings, which improved the color gamut area, print clarity, and smoothness. As a

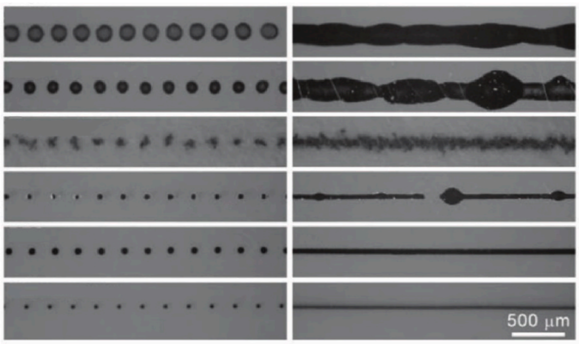

Fig. 10. Printing effects of AgNP ink on six different printing substrates: PEN, PET, copy paper, PI, PES, and photo paper. Reproduced from ref. 91 with permission from John Wiley and Sons, copyright 2023.

result, the paper's roughness decreased by 10 %, and ink penetration on paper coated with silica required only 0.5 s [97]. Arif Ozcan et al. studied the impact of different coating pigments on the printability of water-based ink paper in screen printing, but there is limited research on the printability for inkjet printing [98]. Jae Y. Shin et al. found that a mixture of GCC 90 and coating adhesive in a 3:1 wt ratio is the optimal combination for the dual-purpose coated paper studied. This results in the best overall performance for roll paper offset coated paper [99]. Sajedi-Moghaddam et al. prepared micro-supercapacitors (MSCs) using A4 paper as the substrate. They deposited a large number of graphene nanosheets on the surface of the A4 paper to make it smoother. Subsequently, they deposited AG nanowires on the surface to ensure the conductivity of the capacitors [100]. Modifying the surface of the paper not only improves printing performance but also provides more options for selecting substrates in the fabrication of flexible electronics.

In summary, modifying the substrate and altering its structure can not only enhance printing but also contribute to suppressing the "coffee ring" effect, thereby improving print quality. The uniformity of the substrate and its permeability to ink both influence the clarity of patterns presented after ink drying. Coating the paper surface can reduce the impact of ink penetration on the paper, but uneven coating may decrease the clarity of patterns.

3.4. Electrohydrodynamic jet printing technology

In recent years, electrohydrodynamic jet (E-Jet) printing technology has emerged as a promising inkjet printing technique, lauded for its high resolution, adaptability to a wide range of ink viscosities, and its capability to effortlessly produce micro and nano-scale dots or lines. Electrohydrodynamic jet (E-Jet) printing technology finds widespread use in the fabrication of transistors, micro/nano sensors, flexible electronic devices, biomaterials, and various other applications [101–103]. Due to the flexible and stretchable requirements of substrates for flexible electronic devices, traditional manufacturing technologies such as photolithography, nanoimprint lithography, transfer printing, and conventional inkjet printing are limited in the fabrication of flexible electronic devices. Electrohydrodynamic (EHD) jet printing technology is a micro/nano additive manufacturing technique that can directly print conductive circuits onto flexible substrates [104]. However, after the droplets are ejected from the nozzle, the trajectory of charged droplets is easily influenced by the electric field distribution. Jun Chen et al. proposed adding a high-voltage electrostatic focusing lens under the nozzle to focus the charged jet under the action of electric field forces [105]. With a working voltage of 2 ***kv***, the average line width of the printed lines decreased from 593.78 ***um*** to 149.57 ***um***. It is evident that the EHD printing method based on the high-voltage electrostatic focusing lens significantly improves the resolution of printed patterns under the same printing conditions. Xiaojian Li et al. proposed a Double-Ring Electrostatically Focused Electrospray Jet (DEFEJ) by adding a conductive double-ring structure under the nozzle to create an integrated focusing electric field, as shown in Fig. 11 [54]. They found that when the printing distance increased from 1.25 ***mm*** to 4 ***mm***, the electric field strength at the micro-nozzle tip and the excitation voltage of the jet did not change significantly. In contrast, the electric field strength of the conventional electrospray printing nozzle decreased by 46.2 % as the height increased, while the driving voltage increased by 58.3 %.

Huatan Chen et al. found that replacing the pulse voltage with alternating current (AC) voltage effectively suppressed the intense oscillations caused by charge accumulation in droplets. Furthermore, as the frequency of the AC voltage increased, the diameter of the ejected droplets significantly decreased from 195 ***um*** to 104 ***um***. This reduction in the required current for droplet ejection allowed for rapid startup of the nozzle [106]. Jingxuan Ma and their team used COMSOL simulation software to numerically simulate the electrospray process and electric field distribution at the nozzle of the electric fluid Taylor cone. They found that the maximum electric field strength is located at the tip of the Taylor cone and increases with the applied voltage. At the same time, the ejection speed of droplets also increases with the voltage. A decrease in printing distance also leads to increased ejection speed and electric field strength [107]. As the printing speed increased from 0.1 to 1.6 ***mm/s***, the line width gradually decreased from 37.52 $\pm$ 2.66 ***um*** to 8.84 $\pm$ 0.98 ***um***. Printing speed plays a crucial role in print uniformity and process stability. The driving pulse frequency for electric fluidic printheads can be divided into two modes: low-frequency and high-frequency [108]. Under low-frequency conditions, the droplets are

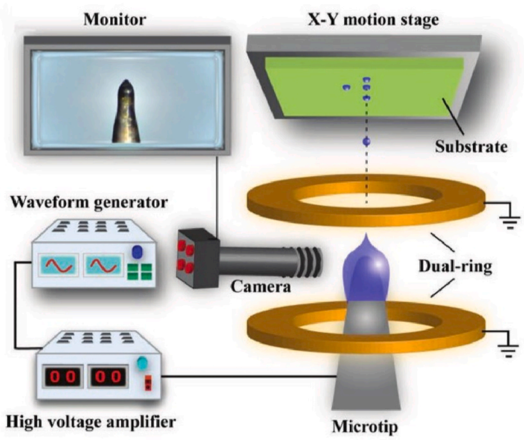

Fig. 11. Schematic diagram of DEFEJ technique. Reproduced from ref. 55 with permission from John Wiley and Sons, copyright 2023.

unstable. Xu et al. studied the jetting frequency in the low-frequency pulsation mode and found that the jetting frequency is in a 1: N ratio with the voltage frequency [109]. Choi et al. proposed a relationship between jetting frequency (f), voltage potential (v), and working height (h) [110]. Yin Guan et al. compared six different pulse waveforms and found that the trapezoidal waveform with gradual rise and fall produced more stable ink droplets with fewer satellite droplets [111].

Overall, while electrofluidic printing technology excels in achieving high resolution, its operational principle constrains the variety of printable substrates. It requires a more demanding operational environment for the equipment and, in contrast to piezoelectric inkjet technology, entails higher equipment and material costs. The printing speed is affected by factors like material flow and equipment precision.

4. Conclusion and outlook

With the continuous advancement of technology and the ongoing development of inkjet printing, inkjet printing has become an integral part of the modern printing industry. Its flexibility, high-quality output, and the ability to meet personalized demands have made inkjet printing widely applicable in various fields. However, as the demand for print quality and efficiency continues to rise, people are constantly seeking innovative ways to further enhance the performance of inkjet printing. The article focuses on four key aspects: improvements in printing equipment, ink enhancements, substrate improvements, and the application of new technologies. These areas are explored to uncover the potential and development directions for the future of inkjet printing.

As the most crucial component in the entire printing system, the quality of the printhead is closely related to printing quality. Designing printheads with smaller apertures to achieve higher resolution makes them more suitable for intricate details and high-precision printing. However, excessively small printheads are prone to clogging. Designing an ink supply system with effective degassing and stability can reduce the likelihood of printhead blockages. Regarding the inkjet system itself, the lifespan of electromagnetic pumps, to some extent, limits the overall operational duration of the ink supply system. Developing electromagnetic pumps with longer lifespans can further ensure the prolonged and stable operation of the ink supply system. In addition to improvements in the ink supply system, a well-designed automatic printhead cleaning system can also prevent issues such as printhead blockages. Currently, most inkjet printing devices use piezoelectric technology. Apart from enhancing components like printheads to reduce the occurrence of satellite droplets and the “coffee ring” effect, stability in droplet ejection can also be improved by optimizing the driving pulses.

The performance of ink is a crucial factor affecting print quality and durability. By optimizing ink performance, such as adding polymers and surfactants, and adjusting parameters like surface tension, conductivity, pH value, and viscosity, it is possible to reduce the occurrence of the “coffee ring” effect, satellite droplets, and enhance droplet stability. Currently, there is limited research directly conducted with ink in experimental studies. Most studies utilize polymers similar to ink, and the outcomes may differ from those obtained with actual ink. Therefore, direct exploration of droplet performance is crucial for understanding ink behavior.

The substrate serves as the foundation for printing materials, significantly influencing print quality and suitability. The exploration of substrates with heightened adaptability to meet diverse application requirements involves enhancing surface smoothness, durability, and color reproduction. Although modifying the chemical properties and physical structure of the substrate can improve print resolution and stability, this approach is more applicable to pliable substrates like metals. Achieving alterations in the physical structure of paper presents challenges. Therefore, analyzing the effects of different coatings on various types of paper and subsequently improving the printing performance of printing paper is crucial.

The commonly used inkjet printing technology aims to enhance print resolution by reducing the nozzle size. However, smaller nozzles are more prone to clogging. In contrast, electrodynamic fluidic (EDH) printing technology is not constrained by nozzle size, making it a potentially efficient and cost-effective high-resolution additive nanomanufacturing technique. EDH printing is currently the highest-resolution inkjet printing method available. Therefore, in scenarios where conventional inkjet technologies struggle to achieve higher resolutions, EDH printing technology can be applied. However, as electrodynamic fluidic printing controls droplet ejection by adjusting the strength of electric field forces, closely arranged nozzles may interfere with each other. Therefore, suppressing the interactions between nozzles will further enhance printing stability.

In the past few decades, inkjet printing technology has witnessed remarkable development, establishing itself as a pivotal field within the printing industry. Recent breakthroughs in inkjet printing technology have significantly improved aspects such as print quality, printing speed, and the range of printable materials. The future demands for inkjet printing technology are expected to increase steadily. In the future, endeavors will be directed towards enhancing and optimizing existing printing technologies to meet the escalating demands for print quality in production. Research will prioritize the development of printing inks characterized by heightened stability and enhanced adaptability to cater to diverse printing requirements across different substrates, while concurrently elevating print quality. Exploring a spectrum of materials as substrates will enable the application of printed products across myriad scenarios. Furthermore, the integration of emerging technologies into inkjet printing will be pursued to realize high-quality printing across an expanded array of fields. Improving inkjet printing quality holds paramount significance in meeting user demands, enhancing competitiveness, expanding application domains, and optimizing efficiency while minimizing waste.

Data availability statement

Data included in article/supplementary material/referenced in article.
No additional information is available for this paper.

CRediT authorship contribution statement

Tianle Cao: Writing – original draft, Investigation. **Zijing Yang:** Writing – review & editing, Supervision. **Hao Zhang:** Writing – original draft, Conceptualization. **Yiming Wang:** Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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