**Printed Intelligence – A Paradigm Shift**

Current Status and Future Trend

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**Abstract:**

Printed intelligence is an emerging interdisciplinary field of technology and materials science, poised to revolutionize various industries, from electronics and healthcare to energy and consumer goods. This paradigm shift leverages the convergence of printed electronics, materials science, and artificial intelligence to fabricate functional electronic devices, sensors, and circuits using printing techniques on a wide range of flexible substrates.

The fundamental premise of Printed Intelligence is to transform ordinary materials into intelligent, interactive surfaces by embedding electronic functionality directly into them. This innovation has opened doors to a multitude of applications, such as flexible displays, wearable devices, IoT devices, and even smart packaging. The ability to seamlessly integrate electronics into everyday objects has the potential to enhance user experiences, improve product efficiency, and reduce manufacturing costs.

Key components of Printed Intelligence include conductive inks, flexible substrates, and printable semiconductors. These materials enable the deposition of electronic components like transistors, diodes, and sensors onto various surfaces, including paper, plastic, and fabric. This versatility not only fosters creativity in design but also sustainability by minimizing electronic waste and reducing the environmental footprint of electronics manufacturing.

One of the most exciting aspects of Printed Intelligence is its adaptability to diverse applications. For instance, it can enable the development of wearable health monitors that conform to the body's shape, delivering real-time health data. In the automotive industry, it can revolutionize dashboard displays and sensors, enhancing safety and user interfaces. Moreover, it has the potential to enable cost-effective solar cells, making renewable energy more accessible.

However, Printed Intelligence also poses challenges, such as optimizing the performance and reliability of printed devices and developing new printing techniques to accommodate ever-evolving electronic requirements. Moreover, ethical considerations related to data privacy and security in smart, interconnected environments need careful consideration.

Printed Intelligence represents a transformative shift in how we perceive and utilize electronic devices. By harnessing the power of printing technologies, this field paves the way for innovative, flexible, and sustainable solutions across various domains. As research and development continue to advance, Printed Intelligence holds the promise of enhancing our daily lives, reducing environmental impact, and shaping a more intelligent future.

1. INTRODUCTION

Printed Intelligence (PI) represents a ground-breaking fusion of two seemingly distinct worlds: traditional printing technology and cutting-edge electronics. It is a multidisciplinary field that encompasses the development of functional electronic devices and components using printing techniques on various substrates, including paper, plastic, fabric, and even unconventional materials. This innovative approach has ushered in a new era of flexible, lightweight, and cost-effective electronics, revolutionizing industries ranging from consumer electronics to healthcare and beyond.

The essence of PI is briefly described while exploring its fundamental concepts, applications, and the transformative potential it holds.

PI relies on the integration of conductive, semiconductive, and dielectric inks into printed structures to create functional electronic devices. These inks contain materials like conductive nanoparticles, organic semiconductors, and dielectric compounds that can be precisely deposited onto substrates using various printing methods, such as inkjet, screen printing, and flexography.

The core components of PI include printed sensors, transistors, displays, and energy storage devices. These components are combined to create an array of innovative devices, such as flexible displays, wearable sensors, smart textiles, and even rollable solar panels. The flexibility and adaptability of these devices have opened new possibilities for design and functionality.

PI is finding applications in diverse sectors. For example, in consumer electronics, it has led to the development of curved, foldable, and rollable displays, making devices like smartphones and e-readers more versatile. In healthcare, printed sensors and diagnostic devices have enabled continuous monitoring of vital signs and rapid disease detection. Additionally, the technology has been instrumental in creating smart packaging, Internet of Things (IoT) devices, and environmentally friendly electronics.

One of the most significant advantages of PI is its potential for cost-effective mass production. Traditional silicon-based electronics often involve complex manufacturing processes and high material costs. In contrast, printed electronic devices can be produced efficiently, reducing manufacturing costs and enabling the creation of disposable or low-cost electronic products. Moreover, the flexibility and lightweight nature of these devices open possibilities for integration into various form factors and applications.

Despite its many advantages, PI faces challenges related to performance limitations, durability, and scalability. Researchers are continually working on improving the conductivity and reliability of printed materials, as well as developing sustainable and eco-friendly printing processes.

Looking ahead, PI is poised to play a pivotal role in the development of smart cities, wearable healthcare technologies, and environmentally sustainable electronics. The integration of artificial intelligence (AI) and machine learning (ML) with printed electronics is expected to enhance device intelligence and autonomy, opening exciting opportunities for innovation.

PI, thus, represents a convergence of print and electronics, offering a flexible and accessible path to the creation of innovative electronic devices and systems. As this field continues to evolve, it holds the promise of transforming how we interact with technology, making it more adaptable, ubiquitous, and environmentally responsible.

1. HISTORICAL PERSPECTIVES

A historical perspective on PI helps us understand how this field has evolved over time and how it has reached its current state of development as described below:

* *Early Development (1960s-1970s):*

The roots of PI can be traced back to the 1960s and 1970s when researchers began experimenting with printing conductive materials, such as conductive inks and polymers, onto various substrates. Early applications included printed antennas and simple electronic circuits.

* *Emergence of Organic Electronics (1980s-1990s):*

The field gained momentum in the 1980s and 1990s with the development of organic electronics. Organic semiconductors and conductive polymers became key materials for printed electronics. Organic Light Emitting Diodes (OLEDs) emerged as one of the most prominent applications, leading to the development of flexible displays.

* *Rise of Flexible Displays (2000s):*

The 2000s saw significant advancements in flexible displays, with companies like E Ink and Plastic Logic pioneering the development of e-paper displays and e-readers. These devices showcased the potential of PI for creating lightweight and flexible electronic devices.

* *Expansion into Wearables and IoT (2010s):*

PI found its way into the wearable technology and IoT sectors. Wearable fitness trackers, smart clothing, and IoT sensors integrated printed electronics leads to their flexibility and low cost.

* *Research into Organic Photovoltaics (2010s-Present):*

Research into printed organic photovoltaics (solar cells) gained momentum as a sustainable and cost-effective way to harness solar energy. This research continues to advance with the aim of making solar energy more accessible.

* *Smart Packaging and Sensors (2010s-Present):*

PI has been applied to smart packaging, enabling interactive and information-rich packaging for consumer goods. Additionally, printed sensors have been developed for applications in healthcare, environmental monitoring, and industrial automation.

* *Emerging Materials and Manufacturing Techniques (2010s-Present):*

Researchers have been exploring new materials and manufacturing methods to improve the performance, reliability, and scalability of printed electronics. Advances in materials science and nanotechnology have expanded the range of their possible applications.

* *Integration with AI and Machine Learning (2010s-Present):*

AI and ML have been integrated into PI for various purposes, including optimizing manufacturing processes, enhancing device performance, and processing data from sensors and IoT devices.

* *Standardization Efforts (2010s-Present):*

As the field matures, efforts have been made to establish industry standards and best practices for PI, which can aid in interoperability and regulatory compliances.

* *Prospects (Beyond 2020s):*

PI continues to evolve, with ongoing research aimed at addressing challenges and expanding the range of applications. As materials become more advanced, manufacturing processes more efficient, and integration with AI more seamless, the possibilities for PI are expected to grow.

PI has evolved from early experiments with printed conductive materials to a diverse and dynamic field with applications in displays, wearables, IoT, energy harvesting, and more. Its future holds great promise as researchers and industry professionals continue to push the boundaries of what can be achieved with printed electronics.

1. PRINTING TECHNOLOGIES, FUNCTIONAL INKS AND SUBSTRATES

Printed electronics (PE) is an area of technology that allows for the efficient and cost-effective manufacturing of electronic components and devices. PE leverages several well-known printing technologies, which are adapted for depositing electronic components onto substrates. These technologies include the following types:

* 1. Gravure Printing,
  2. Flexography,
  3. Offset Printing,
  4. Screen Printing, and
  5. Inkjet Printing

These printing processes can be categorized into contact printing and contactless printing i.e., non-impact printing processes that don't require a master. Some applications combine different printing and deposition techniques in hybrid printing processes to achieve specific results. The behaviour of the ink on the substrate is influenced by various factors, including viscosity, density, surface tension, solvent evaporation rate, solubility, and curing characteristics of the ink, as well as the wettability and permeability of the substrate.

A wide range of applications deploy PE including sensors, batteries, capacitors, transistors, solar cells, memories, electroluminescent structures, large screens, light panels, and RFID systems. For example, printing RFID antennas on flexible substrates is cost-effective and efficient. Different printing methods are suitable for various applications. Gravure printing, for instance, is good for high-resolution and high-quality structures, while offset and flexographic printing are primarily used for inorganic and organic conductors. Combining different printing and deposition techniques including gravure printing and electroless plating, can be used in hybrid printing processes.

New printing processes like the ‘form-fuse’ process and 4D printing techniques have been introduced. ‘Form-fuse’ involves printing silver nanoparticle patterns on thermoplastic films and then forming and sintering them to achieve desired shapes and reduce resistivity. 4D printing involves 3D extrusion and melt-electro writing for printing anisotropic structures used in biomedical applications. PE offers a versatile and cost-effective way to manufacture a wide range of electronic components and devices, opening new possibilities for various industries [Cerqueira, et al, **2018**; Kujala, et al, **2018**; Devaraj, and Malhotra, **2019**; Devaraj, et al, **2020**; Constante, et al, **2021;** Dimitriou, and Michailidis, **2021;** Wicklund, et al, **2021**]. Inkjet printing is often preferred for R&D or special applications in printed electronics. It may not be as suitable for mass production due to its lower throughput. However, it offers the advantage of fine feature sizes, with the ability to create layers as thin as 20µm.

Screen printing is excellent for stacking multiple thick prints. It can produce layers with a thickness of up to 100 µm. While it has a lower throughput compared to other methods, it is well-suited for specific applications where thicker layers are needed.

Flexographic printing is known for creating thin printed layers with a feature size of around 80 µm. It offers a higher throughput compared to inkjet printing and makes it suitable for certain mass production needs in PE.

Offset and gravure printing provide similar features to those of flexographic printing. Gravure printing is noted as the fastest printing technology in terms of print speed. These methods are also suitable for mass production of PE.

The throughput of these printing methods varies. For instance, flexographic printing offers a throughput ranging from 3 to 30 m2/s, making it a good choice for high-speed production. Screen printing has a throughput of 2–3 m2/s, while inkjet printing has a lower throughput of 0.01–0.5 m2/s. Gravure printing is also known for its high-speed capabilities.

The choice of printing technology in PE depends on specific application requirements. Each method has its strengths and limitations, and selecting the most suitable one involves considering factors like feature size, layer thickness, throughput, and the scale of production. Researchers and manufacturers choose the printing method that aligns best with their project goals [Cerqueira, et al, **2018;** Wicklund, et al, **2021**].

*3.1 Contact Printing Methods*

Contact printing, also known as roll-to-roll (R2R) printing, is a method where ink is directly transferred to the substrate through direct contact between the ink and the substrate.

Contact printing involves the direct transfer of ink onto a substrate, typically using a roll-to-roll process. This means that there is physical contact between the ink source and the substrate. Roll-to-Roll (R2R) printing is a specific type of contact printing where the substrate is typically a roll or continuous sheet, and the printing occurs in a continuous manner. This is advantageous for high-speed production.

Contact printing methods often have higher initial setup costs and may require longer preparation periods compared to some other printing methods. This can include the setup of rolls, inking systems, and other equipment. Despite the higher initial costs and preparation times, contact printing technologies are favoured for mass production because they offer lower production costs. Once the printing process is established, it can be highly efficient and cost-effective, especially when producing large quantities of printed electronic components.

Contact printing techniques are known for their high manufacturing speeds, making them suitable for mass production where rapid output is essential. Contact printing methods are known for their repeatability and consistency in producing printed components. This is crucial for ensuring the quality and reliability of electronic devices.

Contact printing techniques are well-suited for mass production in the field of PE due to their lower production costs, high manufacturing speeds, and the repeatability they offer. While they may require initial investments and longer setup times, these drawbacks are often outweighed by the benefits when producing electronic components in large quantities [Wicklund, et al, **2021**].

*3.2 Gravure Printing*

In gravure printing, the image elements are engraved or etched onto the surface of a printing cylinder. Non-image areas remain at the original level. The engraved printing cylinder rotates in an ink fountain, partially immersed in ink. The entire surface of the cylinder collects ink from the fountain. A doctor blade is used to remove excess ink from the non-image areas, leaving the ink only in the engraved cells containing the image.

The ink is transferred from the engraved cells directly to the substrate in a printing nip under pressure. An electrostatic assistance system is employed to create an electric field across the nip, aiding in lifting the ink from the cells onto the substrate. The ink layer is dried by evaporating the ink solvent using hot air. Gravure printing is known for its high print quality and speed. It offers resolutions ranging from 20 to 400 lines per centimetre and print speeds of 13 to 16 m/s.

Gravure printing offers several advantages, including a relatively simple printing process, accurate ink application, and flexibility in press design. It is often used in publication presses for fast printing of high-quality magazines, catalogues, and brochures. The introduction of laser engraving technology has further improved the print quality in gravure printing.

Despite its advantages, gravure printing faces challenges due to increased demand for short production runs and personalization. The production of a printing cylinder is time-consuming and expensive, making it less suitable for short-batch or personalized printing jobs.

Gravure printing is a high-quality and high-speed printing method commonly used in the production of magazines, catalogues, and other printed materials. While it offers excellent print quality and efficiency, it may face competition in markets where there is a need for shorter production runs and personalized printing due to the time and cost associated with cylinder preparation [Wicklund, et al, **2021**].

*3.3 Offset Printing*

This printing is an indirect one in which the ink is not applied directly to the substrate but is transferred through an intermediate surface. The process involves a printing plate and an intermediate blanket cylinder. The printing plate has hydrophilic (water-attracting) non-image areas and oleophilic (ink-attracting) image areas. Damping rollers apply a thin layer of moisturizing water to the hydrophilic non-image areas of the plate. This water helps to keep these areas ink-repellent. Ink rollers transfer a thin film of ink over the oleophilic image areas. Ink adheres to these areas due to their ink-attracting properties. The difference in surface energy and chemistry between the image and non-image areas is crucial. Image areas accept ink but repel water, while non-image areas accept water but repel ink. This prevents ink from spreading outside of the intended image areas. The inked image on the printing plate is then transferred to the blanket cylinder, which has a surface that is suitable for transferring ink to the final substrate. Offset printing is a wet-on-wet printing method in which the inks are applied sequentially without intermediate drying stages. Some ink may also be transferred to the blanket cylinder of the next print unit. After the final printing stage, the ink layer on the paper is dried. This drying can occur through various mechanisms, including absorption, polymerization, oxidation, or evaporation.

Offset printing is known for its high-quality output, making it suitable for a wide range of printed materials, including newspapers, magazines, brochures, and packaging. The use of an offset printing process with multiple units allows for the creation of full-colour images by applying different colours in sequence, creating a broad spectrum of hues and shades [Wicklund, et al, **2021**].

*3.4 Flexography*

Flexography uses soft and flexible printing plates in which the pixels are raised on the top surface of the plate. Printing ink is applied to the raised pixels through an anilox roll having small cells evenly engraved on its surface, which hold the ink. The ink is applied to the anilox roll's surface from an ink chamber, and excess ink is removed with a doctor blade. Consequently, ink is retained only in the cells of the anilox roll. The ink is transferred from the cells of the anilox roll to the raised pixels on the surface of the printing plate. This ink transfer occurs in a nip where pressure facilitates contact between the ink and the substrate. Some of the ink is transferred to the substrate at the nip outlet. The ink layer on the substrate is dried by blowing hot air onto its surface. This heat causes the ink solvent to evaporate, leaving the ink layer adhered to the substrate.

Flexography is used for various applications, including printing RFID antennas, batteries, organic electronic circuits (e.g., OLEDs), and solar cells. OLEDs are used in diode displays (e.g., TV and computer monitors) and lighting (diode lamps). Flexography is also used for producing smart labels and thin films on materials like polyester film, which can be used for monitoring temperature during drug transport. Flexography typically offers a resolution of about 60 lines/cm and a print speed ranging from 3 to 12 m/s. One of the challenges in flexography is maintaining colour saturation and density in fixed areas, which is important for achieving consistent and high-quality printing results.

Flexography is suitable for a wide range of printing media, including both non-porous and porous substrates, making it a versatile printing method. Flexography is used in various industries for applications that require the printing of electronic components and flexible substrates. It offers good resolution, flexibility in printing media, and is especially well-suited for applications where maintaining colour consistency is crucial [Wicklund, et al, **2021**].

*3.5 Screen Printing*

Screen printing involves pushing ink through a stencil-covered fine fabric screen onto a substrate. The stencil defines the printed image, and a squeegee is used to force ink through the open areas of the screen onto the substrate. Screen printing allows for a thicker ink layer compared to some other printing methods like offset printing or digital printing. This thickness can be advantageous for applications where durability or a tactile texture is desired. The drying of the ink layer can occur through various methods, including natural air drying over time, chemical reactions with the surrounding air to cure the ink and using UV light to quickly cure the ink. UV curing is particularly efficient for screen printing and is often used for fast production.

The choice of screen material, which can be made of plastic or metal fibres or wire, affects print quality. The fineness (measured in fibres per cm) and thickness of the screen mesh impact the level of detail and ink deposit. The distance between the top and bottom of the screen affects ink flow and print quality. The percentage of open area in the screen mesh influences ink transfer and the level of detail in the print. Screen printing is highly versatile and can be used to print on a wide range of substrates, including paper, fabric, ceramics, glass, plastic, and metal. It's also capable of printing on curved surfaces, making it suitable for various applications. Screen printing finds applications across diverse industries, from art and crafts to industrial manufacturing. It can be used for both small-scale and large-scale production. Some common applications include signage, textiles, posters, packaging, apparel, electronics, and more.

Screen printing is widely used in electronics manufacturing for printing components like electromagnetic enclosures, capacitors, membrane switches, and transistor electrodes. It's valued for its cost-effectiveness and flexibility. Screen printing has also been explored for printing advanced materials such as carbon nanotubes (CNTs) and graphene nanoparticles on flexible substrates. These applications show promise for flexible electronics and energy storage devices. Screen printing is a time-tested printing method that offers a unique combination of versatility, simplicity, and durability. While it may have some limitations in terms of print quality compared to certain digital technologies, its ability to handle various substrates and its cost-effectiveness make it a valuable choice for many applications.

*3.6 Pad Printing*

Pad printing is a unique process that allows for the transfer of a planar image onto three-dimensional objects. It is particularly useful for printing on irregularly shaped or contoured surfaces where other printing methods like screen printing may not be suitable. Pad printing is an indirect offset printing technique involving several key components. This is a metal or plastic plate that contains the image to be printed. The image is etched or engraved onto the cliché. A soft silicone pad is used as the transfer medium. It conforms to the shape of the object being printed and picks up the ink from the cliché. The substrate is the 3D object onto which the image is transferred.

The process starts with cliché inking with the desired colour or pigment. The silicone pad is pressed against the cliché, and the ink adheres to the pad's surface. The pad is then pressed onto the substrate, transferring the inked image onto the 3D object's surface. The pad's flexibility allows it to conform to the object's shape, ensuring accurate image transfer. Pad printing is one of the few printing methods that can effectively print on curved or irregularly shaped surfaces. This makes it suitable for a wide range of products with complex geometries. It offers high precision and fine detail, making it suitable for applications where image quality is crucial. Pad printing can be used on a variety of materials, including plastics, glass, metal, ceramics, and more. The ink used in pad printing is typically durable and can withstand environmental factors and wear and tear. Pad printing is commonly used in industries such as automotive, electronics, medical devices, promotional products, toys, and consumer electronics. It is particularly valuable for printing on items like buttons, switches, control panels, medical instruments, promotional items, and electronic components like transistor electrodes.

Pad printing is often considered an alternative to screen printing for certain applications. While screen printing is versatile and widely used, it may have limitations when it comes to printing on 3D objects with complex shapes. Pad printing excels in such scenarios by allowing precise and consistent image transfer on curved or irregular surfaces. Pad printing is specialized printing process well-suited for applications requiring the transfer of images onto three-dimensional objects. Its ability to work on complex shapes and deliver high-quality prints makes it a valuable choice in various industries, including electronics manufacturing for tasks like printing transistor electrodes and other components on irregularly shaped substrates [Kujala, et al, **2018**; Wicklund, et al, **2021**].

*3.8 Non-Contact Printing Methods*

In non-contact printing, nozzles or other mechanisms are used to deposit inks or materials onto substrates without direct physical contact. This helps in reducing nozzle contamination compared to contact printing, where the printing element comes into direct contact with the substrate. Non-contact printing methods are generally slower than R2R contact printing methods. This is because the nozzles or mechanisms in non-contact printing often need to move precisely to deposit ink, which can be a slower process compared to the continuous motion of R2R printing.

Non-contact printing methods are well-suited for digital printing, which allows for the printing of digital models and designs directly onto the substrate. This is advantageous in situations where you need to change patterns or designs frequently without significant setup changes. Contact printing methods, on the other hand, may require physical adjustments or changes to the printing unit to switch between different patterns. Non-contact printing is particularly efficient for prototyping and on-demand production. In these scenarios, one may only need to print a specific model or design once or in limited quantities. The flexibility of non-contact printing allows for quick and easy adjustments to the design without the need for major equipment changes.

The choice between non-contact and contact printing depends on the specific requirements of the printing application. Non-contact printing excels in situations where flexibility, customization, and precision are the key factors, such as in digital printing and prototyping. Contact printing methods, on the other hand, are often faster and can be more suitable for high-volume production where the same pattern or design is repeated over and over.

*3.8.1 Inkjet Printing*

Inkjet printing is a digital printing method that involves spraying liquid ink droplets onto a surface (usually paper) based on digital page information. It is known for its simplicity, compact structure, and the ability to print different pages without the need for printing plates. Inkjet printing offers high print quality with resolutions of up to 2880 dpi (dots per inch). However, it typically has a limited print speed, ranging from 2 to 5 meters per second (m/s). Inkjet printing is widely used in various applications, including commercial, graphic, and packaging printing. It is commonly used for direct mail, wide-format products, and publication printing. The use of UV inks in inkjet printing has grown due to their suitability for different substrates, lack of volatile organic compounds, and durability.

Inkjet technologies can be categorized into two main types: continuous-stream (CS) and drop-on-demand (DOD) inkjet. CS Inkjet is primarily used in high-speed, high-volume printing applications. It doesn't have strict speed limits, and print quality depends on various factors, including droplet size, nozzle diameter, and ink properties. CS inkjet printers generate a continuous stream of ink droplets, but only some are printed on the substrate based on digital information. Unprinted droplets are directed to the gutter and collected for recycling before printing. DOD inkjet is used for smaller-scale applications, including home and office printing, desktop publishing, and high-quality wide-format printing. While DOD inkjet offers slower print speeds, it provides very high resolutions (up to 2880 dpi) and smaller droplet sizes. In DOD inkjet, every ink droplet is deposited onto the paper without the need for charging, deflection, or recycling systems. The most common DOD inkjet technologies are thermal and piezoelectric inkjets.

The versatility of inkjet printing technology makes it suitable for a wide range of printing applications, and advancements in both CS and DOD inkjet technologies continue to improve print quality and speed, expanding its use in various industries [Wicklund, et al, **2021**].

*3.8.2 Aerosol Jet Printing*

Aerosol jet printing, also known as Maskless Mesoscale Materials Deposition (M3D), is a printing technology that utilizes the atomization of ink to produce very small droplets in the form of an aerosol. Aerosol jet printing relies on the atomization of ink, which breaks the ink into tiny droplets ranging in size from 1 to 5 µm in diameter. This atomization process can be achieved using either pneumatic or ultrasonic techniques. The atomized ink droplets are delivered to a ceramic nozzle attached to the print head. A vacuum, generated by a nitrogen sheath gas stream, helps in propelling the droplets as a high-velocity jet onto the surface of the substrate. This delivery mechanism allows for precise control over the deposition of ink. Aerosol jet printing is capable of printing on both flat and conformal surfaces, making it suitable for a wide range of applications, including 3D printing. To print complex and 3D patterns accurately, a shutter is used in front of the nozzle to selectively interrupt the ink jet. Maintaining a specific distance between the nozzle and the substrate (between 1 mm and 10 mm) is crucial to ensure printing accuracy. Deviating from these distances can result in overspray defects.

Aerosol jet printing similar to inkjet printing, allows for the printing of designs based on digital models. This flexibility makes it suitable for prototyping and on-demand production. Unlike some inkjet printers that can suffer from nozzle clogging, aerosol jet printing is free from this issue. This contributes to its reliability and consistent performance. Aerosol jet printing can achieve high-resolution printing, with feature sizes as small as 10 µm. One of the main drawbacks of aerosol jet printing is its relatively slow printing speed, with a maximum speed of up to 12 meters/min. This limitation makes it less suitable for mass manufacturing of printed electronics, where higher throughput is often required.

Aerosol jet printing is a precise and versatile printing technology that excels in producing high-resolution patterns on various surfaces, including complex and 3D shapes. However, its speed limitation may restrict its use in applications that require high-volume production at fast speeds, such as mass manufacturing of PE [Wilkinson, et al, **2019**; Chen, et al, **2020;** Dimitriou, and Michailidis, **2021;** Wicklund, et al, **2021**].

*3.9 Inks for Printed Electronics*

PE deploys different types of inks to create structures with specific electronic functions. These inks can include conducting inks, semiconducting inks, dielectric inks, and, in some cases, light-emitting or photovoltaic inks. Each type of ink serves a specific purpose in building electronic devices.

Functional inks must be capable of forming homogeneous layers to ensure the reliability and performance of electronic components. Achieving uniformity is crucial for consistent electrical properties. When printing complex electronic structures, multiple types of inks are often used simultaneously. Therefore, it is essential for these inks to be compatible with each other to avoid issues such as chemical reactions or adverse interactions.

Functional inks typically consist of several components, including solvents, resins, and/or polymers. These components play crucial roles in the ink formulation and printing process. Solvents are used to adjust the viscosity of the ink, optimize drying rates, and dissolve the polymer or resin. They also help maintain the integrity of the particles within the ink. The polymer or resin component of the ink serves as a carrier for metal particles, helping to adhere them to the substrate during the printing process. These materials provide structural support and stability to the printed layers.

The components within functional inks can be both organic and inorganic materials. In some cases, materials must be in micro- or nanoscale form to prevent printer clogging issues and to achieve the desired electrical properties. Metal particles are commonly used instead of pigments in conducting inks. Additives, such as dispersants, may be included in the ink formulation to modify its properties according to specific application needs. Dispersants help ensure that particles are evenly distributed within the ink, preventing clumping, and improving ink stability.

The functional inks are crucial for printed electronics, enabling the creation of complex electronic structures with different functions. These inks are formulated to provide specific electrical properties, adhere to substrates, and work seamlessly with other inks when needed. The careful selection and formulation of functional inks are essential for the successful fabrication of printed electronic devices.

*3.9.1 Conducting Materials*

The conducting inks are in printing of electronic circuits and devices cover different types of materials used in conducting inks, their properties, advantages, and challenges. Metals like silver, copper, gold, and aluminium are commonly used. Silver-based inks offer high conductivity and resistance to oxidation. Copper-based inks are slightly less conductive but may suffer from oxidation over time, which can be mitigated with antioxidants or protective layers. Gold-based inks are stable and require relatively low sintering temperatures, while aluminium inks are prone to oxidation.

Metallic single-walled CNTs (m-SWCNTs) offer stability, flexibility, and light transmittance. Graphene has high conductivity, light transmittance, mechanical strength, and elasticity but may lose some transparency with increased layer thickness.

Conductive polymers like PEDOT:PSS are gaining attention due to their cost-effectiveness, flexibility, light weight, and compatibility with solvents. However, they typically have lower electrical conductivity than metals and may present solubility, stability, and processability challenges. Doped conductive oxide ceramics, such as ITO (indium tin oxide), are used. ITO offers superior conductivity but is rare and expensive. It's available in two ink types: sol-gel ink (higher conductivity but requires high sintering temperatures) and nanoparticle ink (forms less dense oxide films with lower conductivity).

Metal nanoparticles are often used due to their small size, making them easy to disperse into inks for printing. However, their production can be labour and energy intensive. Stabilizers are needed to prevent agglomeration of NPs in inks. Silver NPs, when exposed to UV light in water, release toxic silver ions, limiting their applications. Metals like copper are susceptible to oxidation over time, affecting their long-term conductivity. Various methods, such as the use of antioxidants or protective layers, can be employed to mitigate this issue.

*3.9.2 Conductive Polymer Challenges*

Conductive polymers with lower electrical conductivity require low ink concentrations resulting in longer drying times. ITO inks come in two types: sol-gel and nanoparticle. Sol-gel inks offer better conductivity but require high sintering temperatures, while NP inks may not form dense oxide films with high conductivity. These conducting inks find applications in various fields, including printed electronics and flexible electronics, where they are used for printing circuits, sensors, and other electronic components. The choice of conducting ink material depends on the specific application's requirements, considering factors such as conductivity, stability, cost, and processing conditions. Researchers and engineers are continuing to work on improving the properties and applications of conducting inks in the field of PE.

The semiconducting layer in PE plays a crucial role as the active component where electronic activity occurs. Various materials have been explored for this purpose, each with its unique properties and advantages. Silicon and germanium have traditionally been the most common semiconductor materials due to their physical stability and excellent performance in electronic devices. Semiconducting Single-Walled Carbon Nanotubes (s-SWCNTs) are known for their high flexibility, light transmittance, and mobility. They are a promising candidate for advanced printed electronics. Graphene, especially in the form of nanosheets and nanoribbons, possesses unique semiconducting and mechanical characteristics. Even a single layer of graphene can be used as a semiconductor material in certain applications.

The oxides of metals including tin, zinc, indium, and gallium can serve as semiconductor materials. They are known for their non-toxic degradation properties. However, they often require high sintering temperatures and can be expensive due to their rarity. Recent studies have shown that transition metal dichalcogenides exhibit semiconducting properties. These materials are gaining attention for potential applications in printed electronics.

In PE, semiconducting inks are often formulated using polymer blends and appropriate solvents. These polymers can be used to create both p-type and n-type semiconductors. Polymers that primarily use holes as charge carriers fall into the p-type category. Prominent examples include polythiophenes (PT) and polyfluorenes (PF). Specific polymers within this category include poly(3-alkylthiophene) (P3AT), poly(3-hexylthiophene) (P3HT), and poly(3,30-dialkyltetrathiophene) (PQT). Polymers that use electrons as charge carriers fall into the n-type category. One example is poly(9,9-dioctylfluorene-co-bithiophene) (F8T2). The choice of semiconductor material depends on the specific requirements of the PE devices, including its intended function, performance, and cost considerations. Researchers continue to explore and develop new semiconductor materials and ink formulations to advance the field of printed electronics [Garlapati, et al, **2018**; Chaves, et al, **2020**].

*3.9.3 Dielectric Materials*

Dielectric inks play a critical role in printed electronics by serving as insulator and capacitor layers. These materials are essential for isolating conductive or semiconducting components and for storing electrical energy in capacitors.Dielectric layers need to be thick enough to prevent electric leakage, which can be challenging to achieve through printing processes. Natural materials like cellulose, gelatine, shellac, and silk can act as insulators and are suitable for use as dielectric materials in certain applications. Ceramic oxides can be used as dielectric materials, but they may tend to form pinholes and cracks, which can compromise their insulating properties.

*3.9.4 Polymeric Dielectric Materials*

PMMA is a widely used polymer dielectric material. It has low surface roughness, surface trap density, and sintering temperatures. It is also compatible with organic semiconductors. PI is known for its excellent thermal stability and electrical insulation properties, making it suitable for high-temperature applications in printed electronics. PVP is another polymer dielectric material with good insulating properties and compatibility with organic semiconductors. Polystyrene (PS) is known for its ease of processing and compatibility with various printing techniques. It can be used as a dielectric material in printed electronics. Polylactic Acid (PLA) is a biodegradable polymer that can serve as a dielectric material in environmentally friendly printed electronics applications. Polydimethylsiloxane (PDMS) is a flexible and transparent dielectric material used in flexible and stretchable electronics. Polyvinyl Alcohol (PVA) is known for its good dielectric properties, low cost, and compatibility with organic semiconductors. Benzocyclobutene (BCB) is a thermosetting polymer with excellent insulating properties. It is often used as a dielectric material in microelectromechanical systems (MEMS) and integrated circuits.

The choice of dielectric material depends on the specific requirements of the printed electronic device, including its intended function, performance, and environmental considerations. Dielectric inks are essential for creating reliable and efficient electronic components in printed electronics, such as capacitors and insulating layers. Researchers continue to explore new dielectric materials and ink formulations to improve the performance and versatility of printed electronics.

*3.10 Substrates for Printed Electronics*

The choice of substrate in PE is a critical decision that can significantly impact the performance, durability, and application of electronic devices. The substrate serves as a base for the electronic components and provides electrical insulation to separate them from each other and from the external environment. Traditional electronic substrates have been rigid and durable, but they are often brittle, making them unsuitable for applications that require flexibility, stretchability, or implantability. Flexible synthetic polymer substrates have enabled the development of lighter, flexible, and even recyclable or biodegradable electronic devices. These substrates are better suited for applications where flexibility, stretchability, or biocompatibility are required. Natural materials such as fibres, resins, and proteins have demonstrated insulating properties suitable for use as substrates in PE. They can be biodegradable and non-toxic, making them environmentally friendly options.

The choice of substrate material depends on the specific requirements of the printed electronic device. Considerations include flexibility, stiffness, high transparency, surface smoothness, low thermal expansion, heat resistance, cost, thinness, and weight. Different printing methods may have varying requirements for substrates. Some printers may require substrates with specific thicknesses, flexibility, or mechanical properties to ensure successful printing processes. PE inks often require post-printing treatments, such as curing at high temperatures, chemical processes, or exposure to UV radiation, to achieve the desired electrical and mechanical properties. It's important to choose a substrate that can withstand these treatments without damage.

The intended application of the printed electronic device is a key factor in substrate selection. For example, wearable electronics may benefit from flexible and lightweight substrates, while implantable medical devices may require biocompatible materials. Consider the environmental impact of the substrate material, especially in applications where sustainability and biodegradability are important. Cost is another critical factor in substrate selection, as some materials may be more cost-effective than others, depending on the application and production scale. Selection of substrate material in printed electronics is a complex decision that involves balancing various factors, including the device's intended use, performance requirements, printing method, post-printing treatments, and environmental considerations. Careful substrate selection is essential to ensure the success and longevity of printed electronic devices [Han, et al, **2019**; Wang1,2, et al, **2020**].

*3.10.1 Natural Polymeric Substrates*

The use of paper and other natural biodegradable materials as substrates in printed electronics offers several advantages and challenges highlighted below.

*Paper Substrate*

Paper substrate is a cost-effective substrate material, making it suitable for various applications, including disposable electronics. Paper is naturally flexible, allowing it to conform to different shapes and applications. Paper is biodegradable, making it an environmentally friendly choice for disposable or short-term electronic devices. The biodegradability of paper is an attractive feature, especially for applications where sustainability is a priority.

Despite the above-mentioned advantages paper exhibits several challenges. For example, paper typically has a high surface roughness, which can affect the resolution and quality of printed patterns. The porous nature of paper can lead to ink absorption and spreading, potentially reducing printing precision. Paper is permeable to water vapor, which can be a drawback in moisture-sensitive electronic applications. Paper has poor moisture resistance, making it susceptible to damage in humid environments.

Attempts have been made to improve the substrate performance of paper by introducing surface modifications by coating or laminating it with other materials to reduce roughness and porosity. Specialized coatings can be applied to enhance the moisture resistance of paper substrates for specific applications.

*3.10.2 Nanocellulose Substrate*

Nanocellulose offers several advantages including high optical transparency that makes it suitable for transparent electronic devices. It exhibits impressive mechanical strength despite its biodegradable nature. Nanocellulose has good heat resistance and low thermal expansion. It can provide a smooth surface for high-resolution printing.

3.10.3 Porous Substrates

The performance of inkjet-printed devices on porous substrates is influenced by multiple factors, including substrate porosity, surface chemistry, ink composition, solvent properties, and the printing, drying, and sintering processes. These factors collectively determine the electrical conductivity and mechanical stability of the printed devices.

Achieving successful functional printing on soft, porous substrates requires a careful and rational selection of materials and process parameters. Unlike graphical printing, which is more forgiving, functional printing requires precise material-substrate compatibility. Porous substrates play a crucial role in controlling the spreading and absorption of ink. They can also help mitigate issues like the ‘coffee ring effect’, which can lead to uneven ink distribution. However, the optimal pore size distribution and porosity for specific conductive inks are not yet well-defined. While some reports suggest that porous substrates can enhance the mechanical durability of inkjet-printed electrodes, comparative studies are limited. Understanding how porosity affects the mechanical properties of printed devices is important. Designing porous substrates for use in flexible electronics involves complex considerations, particularly for multi-component materials like paper. Achieving the right balance between porosity and mechanical strength is a challenge.

Future research should aim to develop measurable characteristics of substrates and inks that can predict printability and device performance. Developing mechanistic models to guide material selection and printing processes will be crucial. Sintering copper and other metals typically require additional steps and can be prone to oxidation and aging. Investigating whether porous substrates can protect these inks from degradation is an interesting avenue for research. The field of porous substrates-based flexible electronics holds significant potential for advancements in materials science and various engineering disciplines. This area is likely to offer numerous research opportunities in the coming years.

The inkjet printing of metal inks on porous substrates is a complex and promising area of research with numerous challenges and opportunities. Achieving reliable and reproducible results in this field requires a deep understanding of material-substrate interactions, improved predictive models, and innovative approaches to ink formulation and substrate design [Kang, et al, **2022**].

*3.10.3 Other Natural Biodegradable Materials*

Silk is a biodegradable and biocompatible natural protein fibre with excellent chemical stability, mechanical properties, and flexibility. It has shown promise as a substrate for various electronic applications. Shellac is a natural resin known for its biodegradability, high surface smoothness, and solubility in alcohol solvents. These properties make it suitable for forming substrate films in printed electronics. The choice of substrate in printed electronics depends on the specific requirements of the application. Paper and natural biodegradable materials offer eco-friendly and cost-effective alternatives but may require surface modifications or coatings to address their inherent limitations. Advances in material science and manufacturing techniques continue to expand the possibilities for using these materials in various electronic applications [Agate, et al, **2018**; Kim, **2020**].

*3.10.4 Synthetic Polymeric Substrates*

The choice of polymer substrates in printed electronics, including their properties and applications is very important as discussed below:

PET is a popular choice for printed electronic substrates. It offers high optical transparency, flexibility, solvent resistance, affordability, and dimensional stability at high temperatures. Polyethylene naphtholate (PEN) has good heat resistance, but lower transparency compared to PET. It is often used in applications requiring higher temperature stability.

Polyimide (PI) substrates provide excellent heat resistance. However, they have lower transparency and are relatively more expensive. Polycarbonate (PC) offers high stability, low weight, and good mechanical properties, including rigidity, impact resistance, and hardness. Various biodegradable polymers can also be used as substrate materials in printed electronics, including PLA, PDMS, PVA, PCL, PLGA, PU, PBS, and PEG. These materials are suitable for eco-friendly and biocompatible applications.

PLA (Polylactic Acid) is stiff and transparent but has limited heat resistance, which can be improved with modifications. PDMS (Polydimethylsiloxane) is highly elastic and biocompatible, making it suitable for stretchable electronics and biomedical applications.

As the demand for wearable electronics has increased, there is growing interest in directly printing electronic devices onto textiles, such as polyester fabrics. Traditional high-temperature sintering methods can damage fabric substrates. Low-temperature sintering techniques, like intense pulsed light sintering, have been developed to overcome this issue while enhancing the conductivity of printed patterns on fabrics.

The choice of substrate material in printed electronics depends on the specific application's requirements, such as optical transparency, heat resistance, flexibility, and cost-effectiveness. Researchers and engineers select substrates based on the desired properties for their electronic devices and the manufacturing conditions they need to meet.

[Hwang, et al, **2018**].

*3.11 Ink Characterisation*

The characteristics of ink, including viscosity, surface tension, particle size, and solid content, are critical factors that significantly impact the performance of printed electronics. Viscosity is a measure of a fluid's resistance to flow at a specific shear rate. Different printing processes require inks with specific viscosity levels. The viscosity of an ink is crucial because it affects how easily the ink can flow through the nozzles or printing equipment and how it spreads on the substrate. Various printing processes, such as flexography, gravure, and inkjet printing, require low-viscosity, liquid inks that can flow smoothly through fine nozzles or rollers. In contrast, processes like offset, screen, and pad printing use high-viscosity, paste-like inks that adhere well to the substrate. Modifying the viscosity of an ink can be challenging because it can alter the ink's electrical properties. For PE, maintaining consistent electrical performance is crucial. Changes in viscosity may affect the ink's ability to form uniform and conductive traces. Viscosity control can be achieved through various means, including adjusting the ink temperature. Increasing the temperature typically decreases ink viscosity, making it more suitable for certain printing methods. Conversely, solvent evaporation can increase the ink's viscosity over time.

The solvent present in the ink plays a significant role in tuning its viscosity. By altering the solvent composition, ink manufacturers can adjust the ink's flow properties. Solvents are essential for adjusting ink viscosity and can also influence drying rates and adhesion to the substrate. The size of particles in the ink, especially in conductive or semiconductive inks, affects the ink's ability to form precise, conductive traces. Smaller particle sizes are often desirable for achieving higher resolution and finer details in printed electronics. Solid content, also referred to as solid loading, indicates the percentage of solid particles (e.g., conductive materials) in the ink formulation. Higher solid content can contribute to better conductivity in printed electronic components. However, it can also impact the ink's viscosity and printing characteristics. Surface tension is another critical parameter that influences ink spreads and the substrate adherences. Proper surface tension control is essential for achieving sharp, well-defined patterns and ensuring good substrate adhesion.

Ink characteristics are carefully measured and optimized to meet the specific requirements of the printing process and the desired performance of PEs. Balancing these parameters is essential to achieve consistent and reliable results in the fabrication of electronic components and devices [Dimitriou, and Michailidis, **2021**].

4. APPLICATIONS OF PRINTED INTELLIGENCE

Printed intelligence is a cutting-edge technology that involves printing electronic components and circuits onto various substrates, such as paper, plastic, or fabric. This emerging field has a wide range of applications across various industries due to its potential for low-cost, flexible, and customizable electronics.

*4.1 Flexible Displays and Lighting*

Printed organic light-emitting diode (OLED) displays, and lighting panels represent a significant breakthrough in the field of flexible and curved electronics. How these printed OLEDs are incorporated into flexible and curved surfaces for their applications are summarized below.

OLEDs are a type of lighting technology that doesn't require a backlight, unlike traditional LCDs (Liquid Crystal Displays). Instead, each pixel in an OLED emits its own light when an electric current passes through organic materials. This property allows OLEDs to be much thinner, more energy-efficient, and capable of displaying true blacks and vibrant colours.

Printed OLEDs are fabricated using a printing process, typically using organic or polymer-based materials. The materials are deposited onto a flexible substrate, such as plastic or even paper, using techniques like inkjet printing, screen printing, or roll-to-roll printing. These processes are compatible with a wide range of substrates and can be adapted to various form factors.

One of the primary advantages of printed OLEDs is their flexibility. The organic materials used are inherently flexible, allowing the OLED panels to bend and conform to curved or irregular surfaces. This flexibility opens a world of possibilities for integrating OLEDs into unconventional shapes and designs. Printed OLEDs are well-suited for curved displays, such as those used in smartphones with curved edges or large curved TVs. The flexibility of OLED panels allows them to be manufactured to match the curvature of the device, providing an immersive viewing experience with minimal bezels.

Wearable devices, such as smartwatches and fitness trackers, benefit greatly from printed OLED technology. The flexible and lightweight nature of OLED panels ensures that they can be comfortably integrated into wearable designs. They can display notifications, health data, and other information, all while conforming to the contours of the wearer's body. Printed OLEDs are not limited to display applications. They are also used for innovative lighting solutions. OLED lighting panels are thin, lightweight, and emit a soft, diffused light that is easy on the eyes. This makes them suitable for various lighting applications, including architectural lighting, automotive lighting, and even art installations. Printed OLEDs offer a high degree of customization. Manufacturers can design OLED panels to fit specific shapes and sizes, making them ideal for creative lighting designs, architectural features, and customized displays.

OLEDs are energy-efficient because they only emit light where it's needed (each pixel emits its own light), and they don't require a power-hungry backlight. This energy efficiency is particularly important for battery-powered devices like wearables.

With the growing technology, printed OLEDs are expected to become even more versatile and cost-effective. Researchers are exploring ways to improve the longevity and efficiency of OLED materials, making them even more attractive for various applications.

Printed OLED displays and lighting panels have the unique ability to be flexible, lightweight, and customizable. This makes them suitable for a wide range of applications, including curved screens in consumer electronics, wearable devices, and innovative lighting solutions that can transform the way we interact with displays and light sources in our daily lives.

*4.2 Smart Packaging*

Printed sensors including radio-frequency Identification (RFID) tags, and near field communication (NFC) circuits play a pivotal role in the development of smart packaging solutions, which offer numerous benefits to both manufacturers and consumers.

Printed sensors are electronic devices that can be integrated into packaging materials or labels. These sensors can detect and measure various environmental parameters, such as temperature, humidity, gas levels, or even physical tampering. RFID tags consist of a microchip and an antenna, and they can store and transmit data wirelessly when exposed to radio frequency signals. RFID tags are commonly used in supply chain management and asset tracking. NFC is a short-range wireless communication technology that allows devices to communicate when placed in proximity (typically within a few centimetres). It's commonly used in smartphones and is well-suited for interactive applications. Printed sensors can be incorporated into food or pharmaceutical packaging to monitor the freshness and safety of the product. For instance, a printed sensor on a food package can continuously measure the temperature and humidity inside the package. If the conditions deviate from the optimal range, the sensor can detect it and trigger an alert. This information can also be made accessible to consumers via smartphone apps, allowing them to check the product's quality before purchase.

RFID tags are extensively used for inventory management. Manufacturers and retailers can attach RFID tags to their products or packaging. This enables them to track the movement of items throughout the supply chain with precision and efficiency. It helps reduce theft, minimize stockouts, and streamline the logistics process.

NFC technology in smart packaging allows consumers to interact with the product or packaging using their smartphones. By tapping their phones near the NFC-enabled packaging, consumers can access additional product information, such as ingredients, usage instructions, or promotional content. This interactive element enhances the consumer experience and can be a valuable marketing tool. RFID tags and NFC circuits can be used to combat counterfeiting. By verifying the authenticity of a product through RFID or NFC, consumers and supply chain stakeholders can ensure that they are dealing with genuine, authorized goods. This is particularly important for high-value or sensitive products like luxury goods or pharmaceuticals.

Smart packaging solutions that incorporate these technologies provide greater transparency in the supply chain. Manufacturers and consumers can trace the journey of a product from production to the store shelf. This transparency is especially valuable for products with complex supply chains or those that require strict quality control, such as organic foods or premium cosmetics. Smart packaging can also contribute to sustainability efforts. For example, printed sensors can monitor the condition of perishable goods in transit, reducing food waste. Additionally, RFID technology can aid in recycling by enabling automated sorting and tracking of recyclable materials.

The printed sensors, RFID tags, and NFC circuits are instrumental in the development of smart packaging solutions. These technologies empower manufacturers to enhance product safety, improve supply chain efficiency, engage with consumers, combat counterfeiting, and contribute to sustainability goals. Moreover, smart packaging solutions offer consumers valuable information and an interactive experience through their smartphones, creating a win-win scenario for both businesses and consumers.

*4.3 Healthcare Devices*

The integration of printed sensors and flexible circuits in wearable health monitoring devices represents a significant advancement in healthcare technology. These devices offer a non-invasive and comfortable way to monitor a person's health continuously, providing valuable data for both individuals and healthcare providers.

Printed sensors are lightweight, thin, and flexible electronic components that can be integrated into wearable devices. These sensors can detect various physiological parameters and environmental factors. Common types of printed sensors used in health monitoring devices. Temperature sensors can monitor body temperature, which is crucial for detecting fever or tracking temperature variations. Heart rate sensors use photoplethysmography (PPG) to measure heart rate by detecting blood flow changes through the skin. Electrocardiogram (ECG) sensors can record the heart's electrical activity, providing information about heart rhythm and abnormalities. Respiration sensors can monitor the rate and depth of breathing, which is important for assessing respiratory health. Printed sweat sensors can measure sweat composition and can be used for monitoring hydration and electrolyte balance. Some wearable devices incorporate printed glucose sensors for continuous glucose monitoring in individuals with diabetes.

Flexible circuits, also known as flex circuits or flexible printed circuits (FPCs), provide the electrical pathways and connections for the sensors and other components within the wearable device. These circuits are designed to be flexible and conform to the shape of the wearer's body, ensuring comfort and ease of use. Wearable health monitoring devices are designed to adhere comfortably to the wearer's skin, often using soft, skin-friendly materials like silicone or fabric. This ensures that the device stays securely in place without causing discomfort or irritation.

These devices continuously collect data from the integrated sensors in real-time, allowing for immediate monitoring of vital signs and health parameters. This real-time data can be crucial for early detection of health issues or emergencies.

Wearable health monitoring devices can track various vital signs, including heart rate, blood pressure, temperature, and oxygen saturation levels. This information can be valuable for individuals with chronic conditions, athletes, or anyone interested in tracking their health and fitness. Some wearable devices include features to remind users to take medication at scheduled times. These reminders can help individuals adhere to their prescribed medication regimens, which is especially important for managing chronic illnesses.

Data collected by the wearable device can be transmitted wirelessly to a companion smartphone app or a cloud-based platform. This data can be accessed by the wearer and, with their consent, shared with healthcare providers for remote monitoring and analysis. Wearable health monitoring devices can be programmed to send alerts or notifications when certain health parameters go outside predefined ranges. This feature is critical for individuals with specific medical conditions or for remote patient monitoring. Wearable health monitoring devices have a wide range of applications, including - monitoring patients with chronic diseases (e.g., diabetes, heart disease), supporting the elderly population in independent living, enhancing the fitness and performance tracking of athletes, tracking the health and well-being of individuals in real-world settings, and enabling telemedicine and remote patient monitoring.

Wearable health monitoring devices that incorporate printed sensors and flexible circuits offer a comfortable and non-invasive means of continuously tracking vital signs, medication adherence, and other health parameters. These devices provide valuable data for individuals and healthcare providers, contributing to improved healthcare outcomes and better management of chronic conditions.

*4.4 Wearable Technology*

PI plays a pivotal role in the development of wearable devices, including smartwatches, fitness trackers, and smart clothing. It provides the technological foundation that enables these devices to be comfortable, lightweight, and durable. How PI contributes to the success of wearable technology as described below. Wearable devices often need to monitor various physiological parameters, such as heart rate, body temperature, or motion. Printed sensors, which are thin and flexible, can be seamlessly integrated into the wearable's design. These sensors are comfortable to wear and can conform to the wearer's body, ensuring a non-intrusive experience. Printed circuits, specifically flexible printed circuits (FPCs), are used to interconnect various components within the wearable device. These circuits are lightweight, bendable, and durable, allowing them to withstand the stresses of daily use and movement. Printed intelligence enables the creation of wearable devices with ergonomic and comfortable form factors. Unlike rigid electronic components, flexible sensors and circuits can be integrated into soft and pliable materials, reducing the risk of discomfort, or chafing during extended wear.

Wearable devices with PI are lightweight due to the use of thin and flexible materials. This ensures that the device doesn't feel burdensome or cumbersome, making it suitable for everyday use and activities. Printed circuits are designed to be durable and resistant to wear and tear. This durability is particularly important for wearables that are exposed to various environmental conditions, such as moisture from sweat or rain.

4.4.1 Smartwatches

PI is instrumental in the development of smartwatches, allowing them to house sensors for tracking fitness metrics, heart rate, sleep patterns, and more. The flexible display technology used in some smartwatches also relies on printed OLEDs, enhancing display flexibility and durability.

4.4.2 Fitness Trackers

Fitness trackers use printed sensors to monitor physical activity, steps taken, calories burned, and sleep quality. These devices are often lightweight, slim, and comfortable to wear throughout the day.

4.4.3 Smart Clothing

Smart clothing integrates printed sensors and circuits directly into the fabric, enabling features like heart rate monitoring, motion tracking, and temperature regulation. Smart clothing is particularly advantageous for athletes and medical applications. Printed sensors in wearable devices continuously collect data, such as heart rate or step count, in real-time. This data can be displayed on the device's screen or transmitted to a companion smartphone app, allowing wearers to monitor their health and fitness levels. Wearables with printed intelligence often include wireless connectivity options like Bluetooth, enabling data synchronization with smartphones or other devices. This connectivity enhances the device's functionality and allows for data analysis and storage. The combination of comfort, lightweight design, durability, and real-time data monitoring contributes to a positive user experience with wearable devices. Users are more likely to adopt and use wearables regularly when they are comfortable and seamlessly integrate into their daily lives.

PI is, thus, a fundamental component of wearable technology, enabling the fabrication of devices that are not only technologically advanced but also comfortable, lightweight, and durable. As this technology continues to advance, it holds the potential to drive further innovation in wearables, expanding their capabilities and improving their integration into our everyday lives.

*4.5 Electronic Textiles (E-textiles)*

The integration of printed conductive inks into textiles has given rise to a fascinating field known as E-textiles or electronic textiles. E-textiles combine the traditional characteristics of textiles with electronic functionality, resulting in fabric-based materials capable of conducting electricity. This technology has numerous applications, including heated clothing, interactive fashion, and military gear with integrated electronics.

E-textiles are commonly used in heated clothing, providing warmth and comfort in cold environments. Conductive inks or threads are woven, printed, or embroidered into the fabric to create heating elements. These elements can be strategically placed in key areas, such as the torso, hands, or feet. A small, rechargeable battery or a power source is integrated into the clothing, often in a pocket or a concealed compartment. Users can typically adjust the temperature settings of the heated clothing using a control panel or a smartphone app. Modern E-textile heated clothing often includes safety features like automatic shutoff to prevent overheating. Heated clothing is particularly beneficial for outdoor activities, winter sports, and individuals who work in cold environments, providing a more convenient and efficient way to stay warm compared to traditional layers. E-textiles enable fashion designers to incorporate interactive elements into clothing and accessories, creating innovative and eye-catching designs. Conductive inks can be used to embed LEDs and other lighting components directly into the fabric. These LEDs can change colours, flash, or respond to environmental stimuli, adding a dynamic visual element to clothing. E-textiles can include conductive sensors that respond to touch, movement, or sound, triggering sound or music playback. This can result in clothing that "sings" or produces sound effects when touched or moved. E-textile sensors can detect gestures or body movements, allowing wearers to interact with their clothing. For example, a dress with embedded sensors could change its appearance or lighting patterns based on the wearer's movements. Interactive fashion blurs the line between clothing and art, providing opportunities for creative expression and self-expression.

E-textiles have gained attention in military applications due to their potential for creating high-tech, flexible, and lightweight gear. Conductive inks can be used to embed wiring and communication components within military uniforms and gear, reducing the need for bulky cables and connectors.

4.6 Health Monitoring

E-textiles can incorporate sensors that monitor a soldier's vital signs, such as heart rate, body temperature, and hydration levels, providing real-time data to enhance situational awareness. Some E-textiles explore the possibility of generating power from the motion of the wearer, potentially reducing the reliance on external power sources. E-textiles can enable seamless communication by integrating antennas and communication devices into clothing, improving the efficiency and security of military operations. The use of E-textiles in military gear aims to improve soldiers' comfort, safety, and performance while reducing the weight and complexity of their equipment.

The integration of printed conductive inks into textiles to create E-textiles opens a world of possibilities in various applications, including heated clothing for warmth, interactive fashion for creative expression, and military gear with integrated electronics to enhance the capabilities of soldiers. This technology continues to evolve and innovate, offering new opportunities for combining fashion and function in exciting and practical ways.

*4.7 Automotive Applications*

Printed electronics offer numerous advantages in the automotive industry, allowing for innovative solutions in various aspects of vehicle design and functionality. Some key applications of PE in the automotive sector are mentioned below.

Printed OLEDs and other printed lighting technologies are used to create unique and energy-efficient interior lighting solutions in automobiles. These flexible and thin lighting panels can be integrated into headliners, door panels, and centre consoles, providing customizable ambient lighting that enhances the vehicle's aesthetics and interior ambiance. Printed capacitive touch sensors can replace traditional physical buttons and switches in the car's interior. These sensors are integrated into surfaces such as the dashboard, steering wheel, or centre console, allowing for intuitive and responsive touch-sensitive controls for functions like climate control, infotainment, and lighting. PE enables the creation of flexible and curved display panels that can be seamlessly integrated into the vehicle's dashboard design. These displays can provide critical information to the driver, such as speed, navigation directions, and vehicle diagnostics. The flexibility of these displays allows for more versatile and aesthetically pleasing dashboard layouts.

Printed sensors, including pressure sensors and temperature sensors, can be embedded into car seats and interior panels.

* 1. Pressure sensors in seats can detect the presence and position of occupants, enabling the activation or deactivation of airbags and seatbelt reminders. Temperature sensors in seats and panels can provide feedback to the climate control system, allowing for personalized heating and cooling settings for passengers. Printed sensors can monitor seatbelt usage and detect driver fatigue, improving overall safety. Printed antennas are used in vehicles for various purposes, including keyless entry systems, remote start, and wireless communication. These flexible antennas can be discreetly integrated into the vehicle's design, ensuring efficient and reliable connectivity.

Printed electronics can be employed in heads-up display systems, which project important information onto the windshield, allowing the driver to access critical data like speed, navigation instructions, and safety alerts without taking their eyes off the road. Exterior lighting elements, such as turn signals and brake lights, can benefit from printed electronics. Printed LED arrays can be incorporated into the vehicle's exterior panels to create dynamic and attention-grabbing lighting effects. Printed electronics often have lower power consumption compared to traditional electronic components, contributing to energy efficiency in vehicles and potentially extending the life of the vehicle's battery or reducing fuel consumption in electric vehicles.

The use of printed electronics in the automotive industry is not only about enhancing aesthetics but also improving functionality, safety, and energy efficiency. As technology continues to advance in this field, it is expected to see more innovative and integrated solutions that transform the driving experience and contribute to the development of smarter and more connected vehicles.

*4.8 Consumer Electronics*

Printed electronics have the potential to significantly impact the manufacturing of traditional electronic devices, making them more cost-effective and accessible to consumers. Here's an elaboration on how printed electronics can reduce manufacturing costs and enhance affordability for devices like remote controls, game controllers, and home automation systems:

Printed electronics often utilize less expensive materials compared to traditional rigid circuit boards. This can include the use of conductive inks, flexible substrates, and organic or polymer-based components. Lower material costs directly contribute to reduced manufacturing expenses.

The manufacturing processes for printed electronics are generally simpler and more streamlined compared to traditional electronics assembly. Traditional electronics often involve complex and resource-intensive processes like surface-mount soldering, while printed electronics can be produced through printing techniques such as screen printing or inkjet printing. Fewer steps and less equipment are required, leading to cost savings.

Printed electronics generate less waste during manufacturing. Traditional electronics manufacturing generates waste from the etching and disposal of printed circuit boards and other materials. With printed electronics, manufacturers can minimize waste, contributing to cost savings and environmental sustainability. Printed electronics can be integrated into flexible and thin substrates, allowing for innovative and compact designs. This flexibility simplifies device assembly, reduces the need for bulky enclosures, and lowers shipping costs due to decreased weight and size. Printed electronics offer greater flexibility in customizing and prototyping electronic devices. Design changes can be implemented quickly and cost-effectively, making it easier for manufacturers to adapt to market demands and create tailored solutions for specific applications. Printed electronics can be easily scaled for mass production, thanks to the efficiency of printing processes. As production volumes increase, manufacturers can benefit from economies of scale, which further reduce per-unit production costs.

Reduced manufacturing costs translate into lower retail prices for electronic devices. As a result, consumers can access a wider range of affordable products, including remote controls, game controllers, home automation systems, and other consumer electronics. Printed electronics open the door to innovative and diverse form factors. Manufacturers can create slim and lightweight devices with unique designs that cater to consumer preferences and aesthetics, further enhancing the appeal of their products. Affordable electronic devices made possible by printed electronics can benefit emerging markets where cost-sensitive consumers may have limited access to technology. This accessibility can lead to increased adoption of electronic devices in regions with growing consumer demand.

The printed electronics offering cost-saving advantages in materials, manufacturing processes, waste reduction, and scalability would enable the manufacturers to produce traditional electronic devices more affordably, ultimately making these products more accessible and appealing to consumers. Additionally, printed electronics foster innovation in design and functionality, driving advancements in the consumer electronics market.

*4.9 Environmental Monitoring*

Printed sensors are versatile and cost-effective tools that can be deployed to monitor various environmental parameters in remote or rugged locations. Their flexibility, affordability, and adaptability make them valuable assets in environmental monitoring efforts. Here's how printed sensors are used to monitor air quality, water quality, and soil conditions in challenging environments:

Printed sensors can be designed to detect and quantify specific gases or pollutants in the atmosphere. These sensors are particularly useful for tracking air quality in areas prone to pollution, industrial emissions, or wildfires. Printed particulate matter (PM) sensors can also monitor particulate matter in the air, including fine dust and aerosols. They can help assess air pollution levels, especially in regions where respiratory health is a concern. Due to their cost-effectiveness, printed sensors can be deployed in large numbers across different locations, providing a more comprehensive view of air quality over a wide area. Many printed sensors can transmit data wirelessly to a central monitoring system, allowing real-time data collection and analysis. Printed sensors can be customized to measure parameters such as pH, conductivity, turbidity, dissolved oxygen, and specific ions (e.g., nitrates and phosphates) in water bodies.

Researchers and environmental agencies use printed sensors to assess the impact of human activities, such as agriculture, industry, and urban development, on local water quality. Printed sensors can be easily deployed in remote or hard-to-reach areas, including rivers, lakes, and coastal regions, where traditional monitoring equipment may be impractical or expensive to install. Printed sensors can measure soil moisture content, helping farmers and agricultural researchers optimize irrigation and reduce water usage. These sensors can determine soil pH levels and nutrient concentrations, providing insights into soil fertility and health. Printed sensors can be used in soil erosion monitoring and conservation efforts, helping prevent soil degradation in sensitive ecosystems. Printed sensors can endure extended periods of deployment in the ground, making them suitable for long-term soil monitoring projects.

Printed sensors can be fabricated on flexible substrates, making them adaptable to irregular or curved surfaces and environments with varying topography.

Printed sensors are often more cost-effective than traditional sensors, allowing for larger-scale deployments and reducing the financial barriers to environmental monitoring projects. Sensor design and sensitivity can be tailored to specific environmental parameters and monitoring objectives.

Many printed sensors are designed to operate with low power consumption, extending their battery life and reducing the need for frequent maintenance in remote areas. Printed sensors can be produced in high volumes, making them suitable for large-scale environmental monitoring networks. Printed sensors are valuable tools for monitoring environmental parameters like air quality, water quality, and soil conditions in challenging and remote locations. Their flexibility, low cost, and adaptability make them accessible for a wide range of environmental monitoring applications, contributing to our understanding of environmental changes and aiding in conservation efforts.

*4.10 Smart Labels and Tags*

Printed RFID (Radio-Frequency Identification) tags and labels offer versatile solutions with a wide range of applications in various industries, particularly in inventory management, supply chain tracking, anti-counterfeiting measures, and interactive advertising within the retail sector. An elaboration on how printed RFID tags and labels are used in these contexts is given below. Printed RFID tags are attached to products or assets, allowing for real-time tracking and tracing throughout the inventory management process. This simplifies inventory audits, reduces manual data entry errors, and enhances inventory accuracy. RFID-enabled inventory management systems can trigger automated reorders when stock levels reach predefined thresholds, ensuring that products are replenished in a timely manner. RFID technology provides visibility and transparency throughout the supply chain, from manufacturing and distribution to the end consumer. This helps optimize logistics, minimize delays, and reduce the risk of product loss or theft. RFID-enabled supply chain systems streamline the flow of goods, minimize handling, and reduce the time required for each stage of transportation and delivery. Printed RFID tags and labels can be used to verify the authenticity of products. Consumers, retailers, and manufacturers can scan the RFID tag to confirm that the product is genuine and has not been tampered with. By embedding unique identification information in RFID tags, it becomes difficult for counterfeiters to replicate products without detection. This helps in identifying and mitigating counterfeiting threats. Retailers can incorporate RFID tags into product displays and marketing materials to create interactive experiences for customers. When shoppers interact with RFID-tagged items or displays, they can access product information, videos, reviews, and promotions through smartphones or interactive screens. RFID data can be used to collect information about customer preferences and behaviours. Retailers can then personalize marketing efforts, recommending products and services based on individual interests and buying history. RFID tags can help retailers monitor product availability in real-time. When an item is removed from the shelf, the inventory system is immediately updated, reducing the risk of out-of-stock situations. RFID technology is used for access control systems in various settings, including buildings, events, and transportation. Printed RFID cards or badges provide secure access and can be easily issued and deactivated as needed.

Libraries and organizations use printed RFID tags in books, documents, and assets for efficient tracking, check-out, and return processes. RFID tags are used in healthcare for patient identification, tracking medical equipment, and monitoring medication administration. Printed RFID tags and labels offer versatile and efficient solutions for inventory management, supply chain tracking, anti-counterfeiting, and interactive advertising. They provide real-time data, enhance operational efficiency, improve customer engagement, and contribute to better decision-making across various industries. As technology advances, one can expect continued innovation in the use of printed RFID technology for a wide range of applications.

*4.11 Energy Harvesting*

Printed solar cells and energy storage devices represent an exciting innovation in the field of renewable energy and have found practical applications in the development of self-powered sensors and low-power Internet of Things (IoT) devices. Here's an elaboration on how this technology works and its applications:

Printed solar cells, also known as organic photovoltaics (OPVs) or printed photovoltaics, are thin, flexible, and lightweight solar panels that can be fabricated using printing techniques. They are typically made from organic or polymer-based materials. Printed solar cells are designed to capture energy from ambient light sources, including sunlight and indoor lighting. While they may not generate as much power as traditional silicon-based solar panels, they are highly efficient at converting available light into electricity, even in low-light conditions.

In conjunction with printed solar cells, energy storage devices, such as printed batteries or supercapacitors, are used to store the harvested energy. These devices are typically thin, lightweight, and flexible, making them suitable for integration with other printed components. Printed solar cells and energy storage devices are employed in the development of self-powered sensors for various applications. These sensors can operate autonomously without relying on external power sources. Some examples include:

Self-powered sensors can measure parameters like temperature, humidity, air quality, and pollution levels in remote or off-grid locations, transmitting data wirelessly to a central monitoring system. Sensors integrated into buildings, bridges, and infrastructure can monitor stress, strain, and vibrations, providing early warnings of potential structural issues. Self-powered sensors can be used in industrial settings to monitor equipment health, track inventory, and optimize manufacturing processes.

The Internet of Things (IoT) relies on sensors and devices that can operate on minimal power. Printed solar cells and energy storage devices enable the development of low-power IoT devices that can function without frequent battery replacement or external power sources. Examples include: IoT sensors can monitor soil moisture, temperature, and crop health in remote agricultural fields, transmitting data for precision farming. Low-power IoT devices can monitor traffic, air quality, waste management, and energy consumption in urban environments. Printed solar cells can be integrated into wearable devices like smartwatches or fitness trackers, extending battery life by harvesting energy from ambient light and motion. Printed solar cells and energy storage devices can be integrated into flexible substrates, making them adaptable to curved surfaces, textiles, and unconventional form factors. Organic materials used in printed solar cells align with sustainable practices, and the technology itself supports renewable energy generation. Printing techniques allow for cost-effective fabrication, making these devices affordable for various applications. Researchers continue to work on improving the efficiency and durability of printed solar cells and energy storage devices. As technology advances, these devices are expected to become even more efficient and practical for a wider range of applications.

Printed solar cells and energy storage devices have paved the way for self-powered sensors and low-power IoT devices, enabling energy harvesting from ambient light and motion. This technology is well-suited for applications that require long-term, autonomous operation in remote or off-grid environments, contributing to more sustainable and efficient monitoring and communication systems.

*4.12 Biomedical Applications*

Printed sensors and circuits have made significant contributions to the field of biomedical devices, particularly in diagnostics and monitoring. They offer a range of advantages, including flexibility, customization, and cost-effectiveness, making them well-suited for various applications in healthcare. Here's a preview on how printed sensors and circuits are employed in biomedical devices for diagnostics and monitoring:

Printed glucose sensors are widely used in CGM systems for individuals with diabetes. These sensors are typically integrated into wearable devices or implanted under the skin to measure glucose levels continuously throughout the day and night. The sensors provide real-time data on glucose levels, allowing individuals to make informed decisions about insulin dosages and dietary choices, ultimately improving diabetes management and minimizing the risk of hyperglycemia or hypoglycemia. Printed biosensors can be tailored to detect specific biomarkers associated with various medical conditions. These biomarkers may include proteins, enzymes, hormones, or DNA sequences. Printed biosensors find applications in diagnosing diseases and conditions such as cancer, infectious diseases, cardiac markers, and neurodegenerative disorders.

Miniaturized printed biosensors are often used for point-of-care testing, allowing for rapid and accurate diagnostic results at or near the patient's location. This enhances early diagnosis and treatment. PSs and circuits can be integrated into wearable devices to monitor vital signs such as heart rate, respiratory rate, body temperature, and blood pressure.

These wearables transmit data wirelessly to healthcare providers, enabling remote patient monitoring and timely intervention in case of abnormalities. Wearable devices equipped with printed sensors are valuable for managing chronic diseases such as hypertension and heart disease.

PSs can detect environmental factors such as air quality, humidity, and temperature, which can impact a patient's health. These sensors are used in healthcare settings and home environments to ensure optimal conditions for patient well-being. Sensors can also monitor other physiological parameters, including oxygen saturation (SpO2), electrocardiogram (ECG) signals, and brain activity (EEG), providing valuable data for healthcare professionals. Printing techniques allow for the cost-effective mass production of sensors and circuits, making healthcare devices more affordable and accessible. PSs are often thin and flexible, making them comfortable for patients to wear. This flexibility allows for conformable integration into various wearable and implantable devices. PSs can be customized to meet the specific requirements of different diagnostic and monitoring applications. Many PSs and circuits are designed to operate with low power consumption, extending battery life in wearable devices and reducing the need for frequent battery changes. PSs and circuits can be made on a small scale, facilitating the development of compact and unobtrusive medical devices.

Printed sensors and circuits are revolutionizing the field of biomedical devices, enabling the development of advanced diagnostic tools, continuous monitoring systems, and wearable health devices. Their versatility, cost-effectiveness, and adaptability make them essential components in the quest for more efficient and patient-centric healthcare solutions.

*4.13 Aerospace and Defence*

Printed electronics have found valuable applications in the aerospace and defence sectors, where lightweight and flexible components are essential for a wide range of applications. These technologies offer several advantages, including reduced weight, improved versatility, and cost-effectiveness. Here's a description of how printed electronics is used in these sectors:

Printed antennas are employed in satellite communication systems and onboard aircraft for sending and receiving signals. Their lightweight and conformable nature make them ideal for integration into the aircraft's structure without compromising aerodynamics. For stealth and LO aircraft, conformal printed antennas are designed to maintain the aircraft's radar cross-section (RCS) while enabling communication and radar functions. PSs can be embedded into aircraft structures to monitor structural health in real-time. These sensors detect stress, strain, temperature, and other parameters, allowing for the early detection of potential issues and enhancing maintenance efficiency. The data collected by printed sensors can be used for predictive maintenance, reducing downtime, and ensuring aircraft safety.

PEs enable the development of lightweight and flexible wearable devices for soldiers. These devices may include communication systems, health monitoring devices, and sensors for situational awareness. Soldiers can benefit from reduced equipment weight, increased mobility, and improved communication capabilities using printed electronic components. Aerospace and defence organizations use printed RFID tags for tracking and managing inventory, equipment, and assets efficiently. Printed RFID tags and labels are used to enhance supply chain security by tracking the movement of sensitive materials and equipment.

Printed environmental sensors, including gas sensors and imaging devices, can be integrated into UAVs for surveillance, data collection, and environmental monitoring in various terrains and conditions.

Printed sensors on weather balloons can capture data on atmospheric conditions, such as temperature, humidity, and pressure, for meteorological research and forecasting.

Printing techniques allow for the cost-effective production of electronic components and systems, which is particularly advantageous for the aerospace and defence sectors, where cost control is crucial. PEs can be customized to meet the specific requirements of aerospace and defence applications, providing tailored solutions for unique challenges.

The technology facilitates rapid prototyping, enabling the quick development and testing of new electronic components and systems. PEs can be seamlessly integrated into flexible materials and structures, allowing for conformal placement, and reducing the need for additional structural modifications. PEs play a vital role in the aerospace and defence sectors by providing lightweight, flexible, and cost-effective electronic components and systems. These technologies enable improved communication, surveillance, structural health monitoring, and operational efficiency in various applications, from aircraft to soldier systems and environmental monitoring. With the ongoing advancements in printed electronics, their importance in these sectors is likely to grow even further.

*4.14 Educational Tools*

PEs offer a unique and engaging way to teach electronics and circuitry concepts in education and training programs. They provide hands-on experiences and visual demonstrations that can enhance the learning process for the students of all ages. Here's how printed electronics can be used effectively in education:

PEs allow students to engage in practical, hands-on activities. They can assemble circuits, experiment with components, and see immediate results, promoting active learning and a deeper understanding of electronics principles. Printed circuits and electronic components are tangible and visual, making it easier for students to grasp abstract concepts. They can physically connect components, trace circuit paths, and observe the flow of electric currents, enhancing the subject comprehension. PEs are often cost-effective to produce, allowing educational institutions to create custom educational kits and prototypes without significant investments. This affordability enables schools to provide students with the necessary materials for experimentation. Educators can design and print their own educational materials, including circuit diagrams, instructional booklets, and worksheets. This customization allows teachers to tailor lessons to the specific needs and skill levels of their students.

PEs enable the creation of interactive educational projects. Students can design and build simple electronic devices like LED displays, touch-sensitive switches, or simple sensors, fostering creativity and problem-solving skills. Students can quickly prototype their electronic ideas using printed components. This facilitates the development of proof-of-concept projects, encouraging innovation and entrepreneurship among students. PEs can be incorporated into various subjects, including science, technology, engineering, art, and mathematics (STEAM). This interdisciplinary approach encourages well-rounded learning and connects electronics to real-world applications. PEs can be used in diverse educational settings, from primary schools to universities. They are accessible and adaptable for learners of all ages and backgrounds. Demonstrating practical applications of printed electronics, such as wearable technology, flexible displays, and sensors, can help students understand the real-world relevance of electronics concepts. Teaching with printed electronics prepares students for future careers in technology and engineering fields, where knowledge of flexible and printed electronics is increasingly valuable.

Educational kits and workshops featuring printed electronics can be organized to provide students with structured learning experiences, fostering teamwork and problem-solving skills. PEs offer a dynamic and engaging way to teach electronics and circuitry concepts in educational settings.

Combining hands-on learning with visual and tangible demonstrations, educators can enhance the learning experience, inspire creativity, and prepare students for future STEAM-related careers. PEs bring electronics education to life, making it more accessible and exciting for learners of all ages.

5. CHALLENGES AND LIMITATIONS

PI being a promising technology with numerous applications faces several challenges and limitations that need to be addressed for its widespread adoption and success. These challenges span various aspects, including performance, reliability, scalability, environmental concerns, and more.

PE components, such as transistors and sensors, generally exhibit lower performance metrics compared to their traditional silicon counterparts. This limitation can impact the speed, accuracy, and efficiency of devices incorporating printed intelligence. Organic and printed materials may degrade over time due to environmental factors like moisture, UV exposure, and temperature fluctuations. This can lead to a reduced lifespan and reliability of printed components. Printed circuits and components on flexible substrates can be vulnerable to mechanical wear and tear, potentially affecting their long-term functionality. Maintaining stable electrical properties over extended periods is a challenge for printed electronic materials, impacting the reliability of devices. Achieving consistent quality and performance in large-scale production of printed electronics can be challenging. Variations in materials and printing processes can lead to inconsistencies in device performance. Achieving high-resolution printing for intricate circuit designs can be difficult, limiting the complexity of devices that can be manufactured using printed intelligence. The materials used in printed electronics are often limited in terms of electrical conductivity, thermal stability, and mechanical properties. Expanding the available materials is crucial for broader applications. Printed electronic devices often contain complex multilayer structures with a mix of materials, making them challenging to recycle. Addressing end-of-life disposal and recycling issues is essential for sustainability. The production of printed electronic materials may involve the use of chemicals that have environmental and health implications, necessitating safer and more sustainable alternatives. Some printed electronic devices may have higher energy consumption due to lower efficiency compared to traditional electronics. Optimizing energy usage is critical, especially for battery-operated devices. Integrating printed components with traditional silicon-based electronics can be complex due to differences in manufacturing processes and electrical characteristics. The field of printed intelligence lacks standardized materials, manufacturing processes, and performance benchmarks, making it challenging for developers to ensure compatibility and quality control.

Raising awareness and educating potential users and industries about the capabilities and limitations of printed intelligence is essential to drive adoption. Achieving cost-effective production at scale is a significant challenge, particularly when competing with established, mass-produced traditional electronics. The field of printed intelligence is characterized by a complex intellectual property landscape, which can hinder innovation and collaboration.

Striking the right balance between device performance and environmental impact can be challenging. Improving performance often involves using materials and processes that may be less environmentally friendly.

While PI holds great promise, it faces several challenges and limitations related to performance, reliability, scalability, environmental concerns, and more. Addressing these issues will require ongoing research and development efforts, as well as collaboration between academia, industry, and regulatory bodies to ensure the technology's continued advancement and responsible adoption. Overcoming these challenges will be essential for the realization of the full potential of printed intelligence in various applications.

PI holds great promise, but like any emerging technology, it faces several challenges and limitations. Here, we identify and analyse some of the key issues associated with Printed Intelligence:

Printed electronics typically have slower speeds compared to traditional silicon-based electronics. This limits their use in applications that require high-speed data processing. Many printed devices, such as organic transistors, may not be as power-efficient as their silicon counterparts. This can limit their battery life and operational capabilities. Printed components can be sensitive to environmental conditions like moisture, temperature, and UV radiation, which can impact their long-term reliability. Flexible and wearable electronics are subject to physical stress, which can lead to wear and tear over time, affecting their performance and lifespan. Printed electronics are currently better suited for simpler components and devices. Complex integrated circuits and high-density components are challenging to produce with existing printing techniques. Achieving consistent quality and performance across large-scale production remains a challenge, which is essential for mass-market adoption.

The availability of suitable organic or printed materials can be limited, restricting the range of devices that can be created. Materials used in printed electronics must be carefully chosen to ensure compatibility with existing manufacturing processes and standards. Some materials used in printed electronics, such as certain conductive inks or semiconductors, may contain toxic substances, raising environmental and health concerns during manufacturing and disposal. Developing environmentally friendly and recyclable materials for printed electronics is an ongoing challenge. While printed electronics have the potential to be cost-effective for mass production, the initial setup costs for developing printing processes and materials can be high. Achieving economies of scale in the production of printed electronic components can be challenging, especially for niche or specialized applications. Integrating printed electronics with existing systems and technologies can be complex due to differences in form factors, power requirements, and communication protocols. The lack of industry-wide standards for printed electronics can hinder compatibility and hinder broader adoption. Printed IoT devices may be vulnerable to security breaches, raising concerns about data privacy and the potential for unauthorized access. As printed electronics become more prevalent, the risk of counterfeiting and tampering also increases, necessitating robust security measures.

While there are numerous potential applications for printed electronics, many are still in the experimental or developmental stage, limiting their practical use. Meeting regulatory standards for safety and performance can be challenging, particularly for medical or aerospace applications where strict guidelines must be adhered to. It's important to note that ongoing research and innovation in the field of Printed Intelligence are actively addressing many of these challenges. As materials, manufacturing processes, and design techniques improve, some of these limitations may be overcome. Additionally, the integration of AI and machine learning in optimizing printed electronics' performance and reliability can contribute to mitigating these challenges and expanding the field's possibilities.

6. CURRENT STATUS OF PROGRESS IN PRINTED INTELLIGENCE

Different components of printed intelligence as a system are examined in the followings to have a glimpse of the latest advances reported by several manufacturers [WP-01; 02; 03; 04]. A quick review of the R&D and manufacturing capabilities has been made including the salient features of the development in this area examined below. For more details, it will be better to consult very recently published reviews as well [Tan, et al, **2023**; Luo, et al, **2023**].

6.1 *Stretchable Electronics - Wearables*

Using ultra-stretchable liquid metals like Gallium-Indium-Tin (GaInSn) for stretchable electronics is indeed an intriguing development in the field of materials science and electronics. GaInSn can be moulded into a non-toxic, RoHS-compliant gel that is highly flexible and stretchable. This property makes it suitable for applications where traditional rigid electronics wouldn't work, such as wearable devices and soft robotics. GaInSn retains its conductive properties even when stretched, which is crucial for maintaining electrical connections in stretchable electronics. Liquid Wire Inc. has demonstrated impressive durability, with the material reportedly able to withstand around 1 million cycles of 100% stretch without any noticeable change in resistance. This durability is a significant advantage over many other stretchable inks and materials. Liquid Wire Inc. is working on a full platform that integrates GaInSn-based stretchable interconnects with other electronic components like microprocessors, strain gauge sensors, and rigid integrated circuits (ICs). This integration allows for the creation of fully functional, deformable sensor systems with embedded electronics.

The potential applications of this technology are extensive, ranging from wearable health monitoring devices to soft robotics and even electronic skin for prosthetic limbs.

It's important to note that while GaInSn is highly stretchable, it does have limits to its hysteresis. This means that it can follow the form of the substrate as it stretches, but care must be taken not to exceed these limits, as it may affect its performance.

The development of GaInSn-based stretchable electronics holds great promise for the future of electronic devices, enabling the creation of flexible, durable, and highly functional systems that can conform to the shape and movement of the human body or other deformable structures. This technology has the potential to revolutionize industries ranging from healthcare to consumer electronics and beyond [WP-01].

6.2 *High Temperature Inks*

Another development of Celanese Micromax™ Electronic Inks and Pastes, specifically the HT (High Temperature) ink series, addresses a critical need in the field of PE. These high-temperature inks with tunable electrical properties open possibilities and applications in this industry.

6.2.1 The ability to tune electrical properties such as conductivity, dielectric strength, and electrical resistance is crucial in printed electronics. These properties can be tailored to meet the specific requirements of different applications, which is a significant advantage.

6.2.2 The HT series inks stand out due to their ability to withstand high operating temperatures, up to 300°C, which is well beyond the typical limit of conventional Polymer Thick Film (PTF) inks (limited to around 200°C). This opens opportunities for applications that demand elevated temperatures, such as aerospace, automotive, and industrial environments.

6.2.3 The use of polyimide resin is a key innovation. Polyimide is a flexible thermoplastic material that provides more flexibility compared to rigid thermoset epoxy resins commonly used in high-temperature applications. This flexibility is advantageous in applications where conformability and flexibility are essential.

6.2.4 The chemical resistance of the polyimide resin is another valuable characteristic. It ensures that the inks can withstand exposure to various chemicals and environmental conditions, making them suitable for a broader range of applications.

6.2.5 Substrate Compatibility

The HT series inks can be printed additively on various flexible and rigid substrates, including Kapton® FPC, Kapton® RS, FR-4, aluminium, alumina, and glass. This versatility in substrate compatibility increases their potential for diverse applications.

6.2.6 These inks can be applied using additive printing methods such as screen printing or nozzle dispensing, which are common techniques in the printed electronics industry.

6.2.7 Potential Applications

The high-temperature resistance and flexibility of HT series inks make them well-suited for applications such as high-temperature sensors, flexible electronics in automotive engine compartments, aerospace components, and industrial equipment subjected to extreme conditions. The chemical resistance also makes them suitable for harsh environments.

6.2.8 Celanese Micromax™ Electronic Inks and Pastes' HT ink series represents a significant advancement in the field of printed electronics. These inks have potential to enable new applications that were previously unachievable with conventional PTF inks, particularly in high-temperature and high-power environments where both flexibility and robustness are required. Their versatility and tunable properties make them a valuable addition to the toolkit of materials available for printed electronics manufacturers [WP-02].

6.3 *SMART SKIN PATCHES*

The advancement of electronics miniaturization has indeed brought about significant developments in the field of medical technology, particularly in the design and functionality of adhesive skin patches. Here are some key points from your description:

Traditional skin patches contained single wired sensors, but modern smart skin patches now incorporate a wider range of functions. Hybrid printed electronics enable the integration of sensors, microcontrollers, wireless connectivity, and batteries into a thin and flexible substrate. This expanded functionality allows for comprehensive patient monitoring. Smart skin patches offer the potential for more comprehensive patient monitoring in clinical or home settings. Patients can wear these patches comfortably while healthcare providers or patients themselves monitor vital signs and activity noninvasively. This technology simplifies monitoring, making it more accessible and comfortable. The COVID-19 pandemic highlighted the need for remote patient monitoring in hospitals and clinics. Smart skin patches played a crucial role in allowing doctors to track patients' vital signs while maintaining social distancing. They also helped address hospital overcrowding and staffing issues. The market for home health monitoring is growing rapidly. Smart skin patches enable users to monitor various health parameters, including heart activity, temperature, muscle health, sleep, and brainwave activity. Their low profile and lightweight nature make them particularly suitable for these applications. Smart skin patches come in various design architectures tailored to specific applications. Some patches are disposable, with electronics directly affixed to a flexible substrate. Others are reusable, with electronics housed in a removable "puck" that connects to the substrate. Reusable patches reduce waste but may involve refurbishing challenges and costs. Designers of monitoring systems have flexibility in selecting features for smart skin patches. These patches can include various electronic devices, sensors (e.g., temperature, chemical, electrodes, optical), batteries, microcontrollers, and RF antennas for wireless connectivity.

Smart skin patches represent a significant advancement in healthcare technology, offering versatile and non-invasive solutions for patient monitoring. Their ability to provide real-time data in a comfortable and portable format has made them valuable tools in both clinical and home settings. Further innovations are expected in this field to improve patient care and healthcare efficiency [WP-03].

6.4 MASS PROUCTION OF WEARABLES

The description you've provided highlights the key processes and technologies involved in the cost-effective mass production of wearable biosensors.

Vertical integration is crucial for cost-effective mass production. This means having control over the entire manufacturing process, from the printing of conductive inks on flexible substrates to converting operations and final packaging. This approach allows for greater efficiency and quality control. The ability to print conductive inks on flexible substrates is essential for creating wearable biosensors. Conductive inks, such as silver, silver/silver-chloride, carbon, zinc, and gold, are used to create the necessary electrical connections for the sensors. Converting operations involve various processes to transform raw materials into the final wearable biosensors. These operations include lamination of medical-grade hydrocolloids, adhesives, non-woven materials, and foam layers. Hydrogel dispensing and placement are also part of these operations, ensuring patient comfort when wearing the biosensors. Surface-Mount Technology (SMT) is used when components are required in the biosensors. SMT allows for the placement of electronic components onto the flexible substrate, enabling additional functionality in the biosensor. The ability to print small via holes (.010" diameter) and fill them with conductive material is essential for establishing continuity between the skin contact area and any external communication devices. This ensures reliable data transmission and patient comfort. The biosensor manufacturing process involves various techniques, including screen printing, laser cutting, and die-cutting. Screen printing is used for applying conductive inks, while laser cutting is likely employed for precision cutting of materials. Die-cutting is used to shape components and layers as needed. Printing through-hole methods are used to create connections between the top and bottom printed circuits. This allows for the integration of multiple layers (up to 6 layers per side) within the biosensor, accommodating complex electronic designs and functionalities. The biosensors are finalized with appropriate packaging to protect them and ensure their usability. Proper packaging is crucial to maintain the integrity of the biosensors during storage and transportation.

The described manufacturing process for wearable biosensors is a highly integrated and technologically advanced approach. It combines various printing, cutting, lamination, and assembly techniques to create reliable and cost-effective biosensors capable of providing essential medical data while prioritizing patient comfort and usability. This approach aligns with the growing demand for wearable health monitoring solutions in the healthcare industry.

Printing can be done on sheets or using Roll-to-Roll (R2R) processes. Multiple print passes (typically 2 to 5) are often required to build up the necessary circuitry or electrodes. After each print pass, the ink is dried or cured using methods like oven drying or UV curing. Oven dwell times are usually short (≤10 minutes) at temperatures ≤140°C. To prevent ink rub-off, slip sheets or interleaf materials may be used, especially when using soft carbon inks. Routine in-process measurements are conducted to confirm dimensional accuracy, ink thickness, and electrical specifications.

Patterning of the spacer or adhesive layer can be achieved using various techniques like SRD (Spin Coating), Rotary methods, Match Metal, and/or Laser cutting. Similar techniques as for the spacer/adhesive layer are employed for patterning the lid or top layer. Dispensing and drying/conditioning of the functional material represent a critical stage in biosensor manufacturing, often involving specialized intellectual property (IP). OEMs traditionally perform this step, but more medical converters are adding dispensing capabilities to enhance their value. Laminating can be done using cold methods with pressure-sensitive adhesive (PSA) or heated (hot melt) processes. This step can be performed by the OEM or converter, depending on their capabilities. There's also the option of cartridge or cassette-type configurations, where lamination may be skipped, and individual sensor circuits are die-cut and installed into microfluidic cartridges or cassettes.

Large-format biosensor sheets or rolls are cut down to rectangular card formats. These cards are typically nested with sensors in rows, making them compatible with commercially available strip singulation equipment. Individual sensors are slit from the cards into separate test strips. This process allows for the creation of discrete sensor units. Singulated test strips are placed in plastic vials, often lined with desiccant to maintain environmental conditions. Caps (screw or snap) are installed, followed by the application of labels for identification and usage instructions.

The production of biosensors involves a series of specialized processes and technologies, each contributing to the creation of a functional and reliable medical device. Collaboration among companies with complementary capabilities is common in this field, as it allows for the efficient production of high-quality biosensors for various healthcare applications [WP-04].

6.5 FUTURE TREND

Printed Intelligence is an exciting and evolving field that combines traditional printing technologies with electronic materials to create flexible, lightweight, and cost-effective electronic devices. This field has numerous applications, ranging from flexible displays and sensors to smart packaging and wearable electronics. Here are some emerging trends, ongoing research, and potential future developments in Printed Intelligence, along with the implications of AI and machine learning:

Ongoing research focuses on developing flexible and stretchable electronic components, such as displays, sensors, and batteries, that can be integrated into clothing and accessories for health monitoring, fitness tracking, and augmented reality applications.

AI and machine learning play a critical role in optimizing the performance of these wearable devices, analysing data collected from sensors, and providing real-time insights for users. Printed Intelligence can enable cost-effective and lightweight IoT devices that can be easily integrated into various environments. For example, smart labels and tags could be used for inventory management, tracking assets, and monitoring environmental conditions. AI and machine learning algorithms help process the vast amount of data generated by IoT devices, enabling predictive maintenance, anomaly detection, and improved decision-making. Research is ongoing to develop printed energy harvesting technologies, such as printed solar cells and thermoelectric generators, which can power low-energy IoT devices. AI can optimize energy consumption and storage by predicting energy needs based on usage patterns and environmental conditions, extending the lifespan of these devices. Printed sensors and devices are being explored for healthcare applications, including continuous health monitoring, drug delivery systems, and disposable diagnostic tools. AI can aid in interpreting medical data from these devices, assisting healthcare professionals in making more accurate diagnoses and treatment decisions.

The development of eco-friendly materials and sustainable manufacturing processes is a key focus. Researchers are exploring bio-based and recyclable materials for printed electronics. AI can help optimize the production process by reducing material waste, energy consumption, and production costs. AI and machine learning algorithms can improve the efficiency of the manufacturing process by optimizing printer settings, quality control, and defect detection. This reduces production costs and ensures higher-quality printed electronics. AI can assist in designing and simulating new printed electronic components and systems, helping researchers identify optimal configurations and materials. This accelerates innovation and reduces trial-and-error in the development process. As printed intelligence becomes more prevalent, there will be increased concerns about the security and privacy of data transmitted and stored by these devices. AI-powered security systems will be crucial for detecting and mitigating potential threats.

Printed Intelligence devices will benefit from the rollout of 5G networks and edge computing capabilities, enabling faster data transmission and real-time processing. AI algorithms can leverage this infrastructure for more powerful and responsive applications.

Printed Intelligence is a rapidly evolving field with a wide range of applications, and AI and ML are integral to its growth and success. These technologies enhance the functionality, efficiency, and security of printed electronics while opening new possibilities for innovation. As research continues and more industries adopt printed intelligence, one can expect to see even more exciting developments and applications in the future. This is highlighted in the market projection of printed flexible electronics, excluding OLEDs, reaching US $12 billion by 2033 @ a CAGR of 10% [WP-05].

1. CONCLUSION

In conclusion, PI is a rapidly evolving field with significant potential to revolutionize the way we interact with and integrate electronic devices into our lives. It offers numerous advantages, including flexibility, lightweight design, cost-effectiveness, and the ability to create innovative and customized electronic solutions for various applications. However, as with any emerging technology, there are several challenges and limitations that must be addressed to fully realize its potential.

Printed electronics may have limitations in terms of speed, power efficiency, and long-term reliability, making them more suitable for specific applications that don't require high-performance computing. While suitable for simpler components and devices, scaling up to complex integrated circuits remains a challenge. Achieving consistent quality in large-scale production is also a hurdle. The availability of compatible materials and concerns about toxic substances and recyclability in the production process raise environmental and health considerations. Initial setup costs, as well as challenges in integrating printed electronics with existing systems, can hinder widespread adoption. The proliferation of printed IoT devices raises concerns about data security and the potential for counterfeiting and tampering. Meeting safety and performance standards, particularly in regulated industries like healthcare and aerospace, can be challenging.

Despite these challenges, ongoing research and innovation in Printed Intelligence holds promise for addressing these limitations. For example: Researchers are continually developing new materials that are more robust, environmentally friendly, and compatible with existing manufacturing processes. Advances in printing techniques and quality control methods are enhancing consistency and scalability. AI-driven design, simulation, and manufacturing processes can optimize performance, reliability, and security while reducing costs. Collaboration between materials science, electronics engineering, and other fields is fostering cross-disciplinary solutions to overcome challenges. The future developments are expected to offer a broader range of applications for Printed Intelligence, from flexible displays and wearable electronics to IoT devices and smart packaging. Additionally, as the technology matures and becomes more standardized, it may find its way into a wider array of industries and everyday products. Nevertheless, a careful consideration of the challenges and limitations remains crucial in steering the development of Printed Intelligence toward a more sustainable, efficient, and secure future.

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