OULUN AMMATTIKORKEAKOULU

Babakolade Adefolu Ojuri

Printed Electronics: Capabilities and Potentials for Intelligent Interactive Packaging.

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Babakolade Adefolu Ojuri
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ABSTRACT

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Author(s): Babakolade Adefolu Ojuri
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Printed Electronics as an emerging technology is a fast-evolving disruptive and enabling innovative technology that utilizes functional inks and conventional printing techniques for the mass production of flexible and low-cost devices. Printed Electronic (PE) is a rapidly evolving printing method in printing technology that enables the deposition of conductive inks easily at a low cost. Unlike the traditional microelectronics industry, this printing method is based on subtractive techniques.

Like any other emerging technologies, printed electronics have transitioned from the research stage to commercial production. The innovation advancement that enabled electronic printing on flexible unconventional substrates such as paper, thin films, plastics, and cardboards resulted in the production and introduction of a communication enhanced intelligent packaging into the market. The production of intelligent packaging was enabled by some of the properties of printed electronics: flexibility, lightweight, and low production cost. This resulted in printed electronics products such as printed displays, batteries, NFC tags, antennas, printed transistors, and resistors.

Printing electronics is an additive printing process capable of utilizing the same fictional materials as traditional manufacturing but is carefully deposited only in the needed areas on a chosen substrate through printing heads. Printed electronics depart from traditional electronics manufacturing (subtractive technique) that involves the deposit of functional layers through physical or chemical vapor. This is followed by multiple production steps involving using toxic chemicals to rid surplus metal layers. Printed electronics as a manufacturing process significantly eliminates the long traditional manufacturing steps, thereby reducing energy and waste generated.

In light of the above, this thesis, while be capitalizing on the properties of printed electronics at most, aims to explore the capabilities, characteristics, and potentials of printed electronics and its application for intelligent and interactive packaging, printing technology enablers such as the available printing methods, substrates, and functional materials. This research is based on an extensive literature review together with empirical observations. The findings of this thesis numerate the value chain and the manufacturing process of printed technologies in the context and application of intelligent and interactive packaging.

Keywords: functional inks, packaging, intelligent, printing, flexible, substrates

CONTENTS

Abbreviations and Acronyms

CNT	Carbon Nanotube
DSSC	Dye-Sensitive Solar Cells
IoT	Internet of Things
ITO	Indium Tin Oxide
LEC	Light Emission Electrochemical Cell
LED	Light Emitting Diode
MOD	Metal Organic Decomposition
NFC	Near Field Communication
OLED	Organic Light Emitting Diode
OSC	Organic and Plastic Solar Cells
PBS	Polybutylene Succinate
PC	Polycarbonate
PCL	Polycaprolactone
PE	Printed Electronics
PEG	Polyethylene Glycol
PEN	Polyethylene Naphtalate
PET	Polyethylene Terephthalate
PI	Polymer
PLA	Polylactic Acid
PLGA	Poly-milk-co-glycolic Acid
PU	Polyurethane
R&D	Research and Development
RFID	Radio Frequency Identification
RQ	Research Question
R2R	Roll-to-Roll
UPC	Universal Product Code
UV	Ultraviolet
WI-FI	Wireless Fidelity
WORM	Write-Once-Read-Man

1 INTRODUCTION

This chapter introduces and gives a synopsis of the research topic which includes study background, research aims and objective, methodology and data, research scope and thesis structure.

1.1 Study Background

In general, the packaging of goods has always served a primary function of holding goods or products, preserving and protecting the packaged products, and communicating through labels and sticking to instructions about the products (Underwood 2003). However, packaging as a means of containing packed goods has increased in importance due to increased functionality and other possibilities. Since it has evolved from its primary role, packaging has been actively used to communicate with its environment and visible brand merchandising (Mumani and Stone 2018). This development is only possible by the deployment of technologies to enhance communication in packaging.

Historically, printing in the packaging industry involves printing production methods such as screen printing, gravure, lithography, embossing, inkjet, transfer printing, offset, and stamping. All of these printing methods, each with its benefits and drawbacks, involve a common principle in the transfer of ink onto the desired pattern and substrate. The choice of printing method is usually determined by the material property of the substrate, the required resolution of the print, and the effectiveness of the printing method (Zheng, Tenhunen, and Zou 2016). The introduction of the Internet in the last two decades, followed by the Internet of things (IoT) (see Figure 1), has dramatically changed human lifestyle, and opened up more business opportunities in various industries. While logistics and healthcare industries benefited, both industries represent some of the industries where intelligent interactive systems are rapidly expanding (Arrese et al. 2017).

The novel advancements in technologies such as the Internet of things, printed electronics, electronic inks, and visual and augmented reality have primary communication functions related to intelligence packaging (Priyanka and Parag 2013). The advancement in these technologies has enabled the traditional packaging concept to communicate and create a path for interaction between the producers and consumers. This technology gives the IoT interactive capability (IoT). With the invention of technologies such as Radio Frequency and Identification (RFID tags), intelligent sensors, printed transistors, and capacitors, Near Field Communication (NFC), and other communication protocols, there is packaging design freedom and an increase in functionalities and applications (Lydekaityte and Tambo 2018).

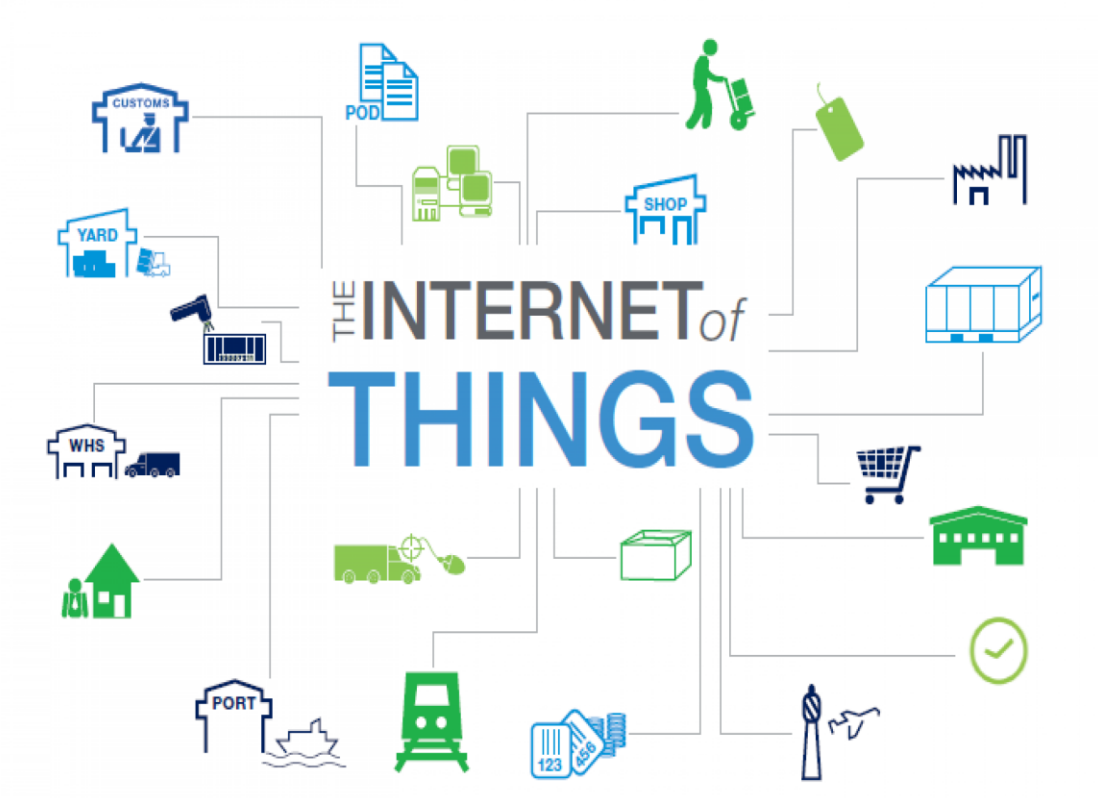

FIGURE 1: Diagram showing Internet of Things (IoT) (Weber 2016)

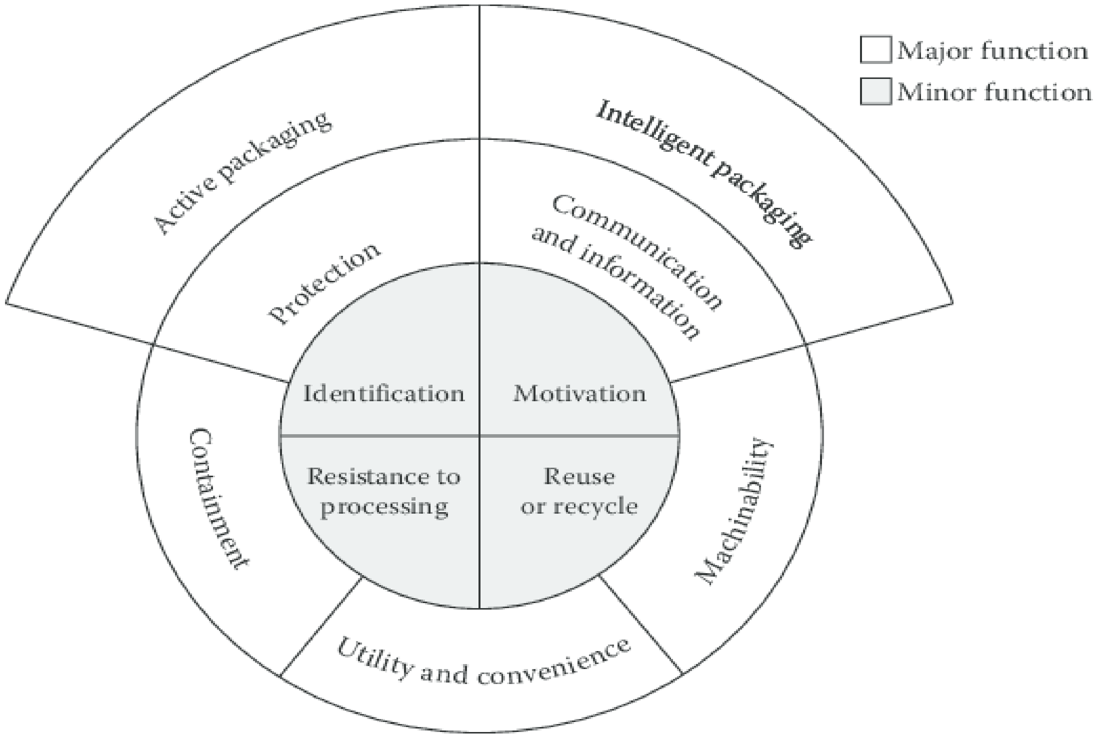

FIGURE 2: Diagram showing the functions of packaging (Aphisit et al. 2020)

The drive of package printing businesses to derive optimal profit margin through cost-effective and functional packaging brought about incorporating technologies into packaging. There was a need to Incorporate technologies and package design with the capability of low end manufactured at the highest volume available, hence the option of Printed Electronics (PE) as an intelligent interactive packaging technology (Jalkanen et al. 2015). Printed electronics as a technology refers to an alternative method used to produce or manufacture electronics with the possibility of printing in different kinds of substrate. Printed Electronics properties include low cost, stretchability, flexibility, quick and ease of production, easy integration be smart or digital, and the possibility of printing electronics in large-area makes PE the most suited enabler for intelligent interactive packaging (Arrese et al. 2017).

The application of PE extends to different industries. Its integration in technical packaging capabilities signifies a technological shift and creates a change with new functions and manufacturing measures (see Figure 2). Printed Electronic communication protocols have been recognized and proven to be one of the fundamentals of communication components for smart products (Arrese et al. 2017). Intelligent packaging allow product owners insight into customer buying preferences.

According to (Lisa 2018) the global market of intelligent packaging is expected to reach 48 billion dollars by 2024, allowing product manufacturers to connect and fulfill customer expectations directly.

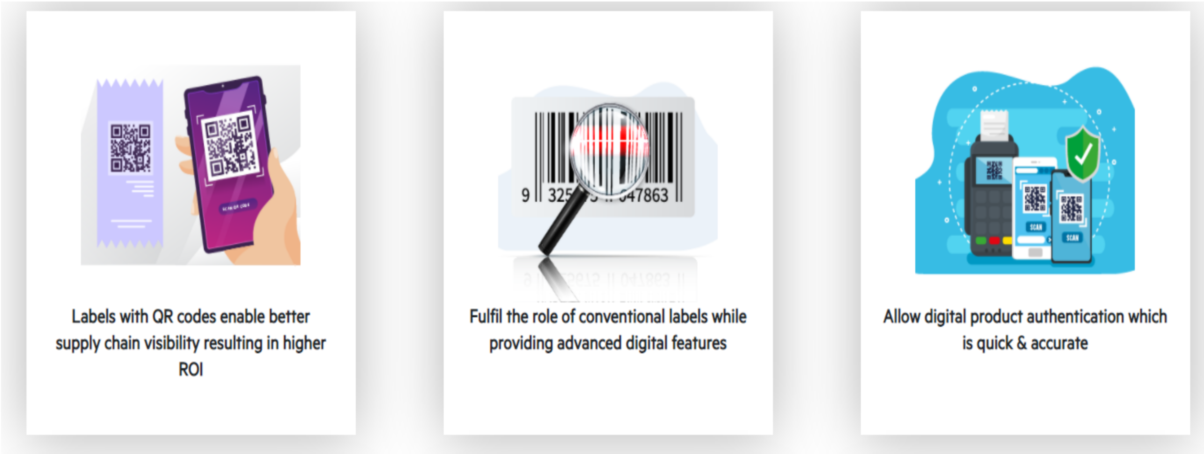

FIGURE 3: Intelligent labels for product authentication and logistics (Sepio Solutions 2021).

The logistics and distribution industry is one industry that benefited the most from the advanced development of printed Electronic Technology. The 20th century ushered a development in product packaging that brought about the application of antimicrobial indicators and oxygen scavengers for protection and prolonging product shelf life against environmental hazards (Mahalik 2009). Nevertheless, global trends, higher volume, and an interactive distribution chain brought the need to develop other packaging solutions that match the times and demand. The demand for cheaper, traceable, sustainable, functional, and interactive led to the emergence of Printed Electronics Technology. The adoption of PE in product packaging improved product safety, prolonged shelf life, and informed customers or distributors of needed information about the product (see Figure 3) (Kotler and Armstrong 2010)

This research paper aims to contribute to the existing knowledge of Printed Electronics Technology and explore its attributes and potential concerning logistics packaging intelligent systems. Attempts will be made to enumerate the available printing methods, conductive inks, substrates, recent innovations in communication protocols, and the potential of PE in intelligent packaging systems and innovations.

1.2 Research Aims and Questions

This thesis, at most, seeks to contribute to the available resource on the potentials, features, elements, and capabilities of Printed Electronics (PE) as technology in intelligent interactive packaging systems. This research explores the attributes of Printed Electronics as a technology in connection to the available printing methods, conductive inks, substrates, recent innovations in communication protocols, and the potential of PE in intelligent packaging and innovations. To actualize the above-stated aims of this thesis, three research questions were generated to address the research topic. The three research questions will be answered using an independent but extensively sourced literature review. The literature review as the primary methodology and data source will serve as the foundation and give clarity to the discussed topic.

Three research questions below were raised to actualize the above-stated aims of this thesis and gain more insights into Printed Electronics and their applications in achieving intelligent interactive packaging. These research questions are:

RQ1: What is the Term "Printed Electronics Technology" and its relation to Intelligent and interactive packaging in the manufacturing industry?
The answers to this research question, mainly sourced from literature reviews, can be found in the first chapter of this thesis. As a term in this research, Printed Electronics refers to an alternative method used in the production or manufacturing of electronics with the possibility of printing in different kinds of substrate. Due to the ability to print various substrates, flexibility, ease of production, and lightweight printed electronics are becoming adopted in the packaging industry. Printed Electronics Technology as terminology and its relation to Intelligent and interactive packaging in the manufacturing industry will be discussed in chapter 2.

RQ2: What are the major enablers of Printed Electronics (PE) Technology?
The second research question highlights the major Printed Electronic Technology enablers. These Printed Electronics (PE) Technology enablers will be extensively discussed in chapter 3. PE technology employs electrically functional inks on the desired substrate using traditional printing methods to fabricate electronics devices. Conductive inks, different from traditional printing inks, add intelligent interactive features to the packaging item.

RQ3: What are the PE manufacturing processes and potential applications in intelligent interactive packaging systems?
Printed Electronics as a manufacturing process utilizes nanotechnology on traditional printing techniques with improved nano-based conductive inks. PE technology utilizes low-temperature fabrication, which allows flexible substrates such as paper, plastics, and cardboards that are usually temperature-sensitive and low cost. While considering the manufacturing processes, the potential application of PE for intelligent interactive packaging fabrication depends solely on three primary enablers of PE, which are the printing substrate, printing method, and electrically conductive inks. PE manufacturing processes and potential application into intelligent interactive packaging systems will be discussed in chapter 3.

1.3 Methodology and Data

Secondary qualitative sources include literature reviews of related past journals and other scholarly articles and books. These sources will serve as the background as a significant data source for this research. Secondary data is used in the form of existing data collected through secondary research. Secondary research data is already available in primary and secondary sources because the information has already been gathered by individuals and institutions other than the researcher himself.

For this thesis research, the data sources will serve as the overview introducing Printed Electronics Technology, its characteristics, and its potential for intelligent interactive packaging industries. It will explain PE technology in simple terms and conclude by stating the possibilities of the technology in the logistics and packaging industry. The topics in the table of contents were carefully selected to fit the aim of this research and backdrop information for the thesis.

Part of the aim of this research to explore the characteristics, possibilities, and potentials of PE technology to be applied for intelligent interactive packaging systems will be viewed from a technology and business management perspective. Current situations, applications, and kinds of available devices will be enumerated in the 4th chapter.

1.4 Research Scope

Although an emerging technology and its adoption in industries such as logistics (passive physical packaging), Printed Electronics have created and added value to enterprises. Such additional value has made the packaging enterprises and the industry innovate manufacturing and fabrication with technological innovation. Since technology has been admitted to being key to economic growth and competitive advantage, the business owner, most especially in the logistics sector, has made bold technological decisions that would shape the sector's future in the long run. Such technological decisions will contribute to new processes, services, products, and deliverables. As a result, there must be consistent efforts in research and development (R&D) likewise engineering before there can be meaningful and tangible development.

This research will investigate the technological knowledge behind PE technology and present the base in which PE was turned into items and products regarding intelligent packaging. Printed technology, its capabilities, possibilities, and potentials, and regard to intelligent interactive packaging will be discussed in depth. At most, the outcome of this research will assist logistics, brand owners, printing, and packaging houses to identify where new technological capabilities are needed besides their core abilities to adopt printed electronics technology into their packaging products.

1.5 Thesis Structure

This research paper consists of five chapters and is divided into three sections. The first section introduces the research and provides a general overview of the research. The second section introduces the research topic and its possibilities for adoption in the logistics and packaging industry. The third section presents the research findings and conclusion. Each chapter will attempt to give answers to the research question and document Printed Electronics Technology and its application in the packaging industry.

The **First chapter** introduces the research's context, problems, aims, and objectives. This chapter will discuss the research methodology, data sources, and thesis structure further.

Chapter 2 details an in-depth general definition of the term "Printed Electronics Technology" through a literature review. This chapter gives the correlation between Printed Electronics Technology and intelligent packaging, thereby giving a more precise context and perspective to the research. This chapter answers research question one (RQ1).

Chapter 3 enumerates printing technology enablers that made the technology adaptable as a technology for an intelligent interactive system. This chapter goes further to present and review the enablers. This chapter answers research question two (RQ2).

Chapter 4 presents the technological potential of Printed Electronics Technology in intelligent packaging applications. Printed Electronics Technology has tremendously emerged over time, and logistics and packaging have been one of the primary beneficiaries of the innovations. This chapter documents the recent and advanced development in PE technology and its application in logistics and packaging. This chapter answers research question three (RQ3).

Chapter 5 presents the research findings, which hinge on the successful integration Printed Electronic Technologies into intelligent package manufacturing value chain. Technology integration is the end goal without which a package cannot be said to be intelligent. The five major aspects that are responsible for a functional PE technological integration, benefits, and challenges will be discussed in this chapter.

Chapter 6 presents the research conclusion, discusses the research limitations, and recommends how the research can be further developed.

2 LITERATURE REVIEW

This chapter gives a context to Printed Electronics as a term and its relation to the realization of intelligent interactive packaging in the logistics and packaging industry. The literature of related articles, books, reports, and journals is intended to justify the research topics and their aims. A literature review of prior works is essential for this research, especially for context and objective clarifications. The data obtained from the literature review are primarily used for addressing the research questions raised in this research.

2.1 Definition of Printed Electronics Technology

Printed Electronics Technology (PE) is an emerging technology that enables the use of conductive inks with traditional printing methods in the fabrication of electrical devices. Like any emerging technology, printed electronics has gained significant influence and shifted from the research phase to production (Daniel Savastano 2014). Technological advancement and the emergence of PE have demonstrated enormous potential for producing commercially viable and novel technologies. PE possesses conformable characteristics that make its outcome distinguished from other printing methods. Such characteristics include low-cost fabrication, large area printing, and a more comprehensive manufacturability range (Garlapati et al. 2018).

Printed Electronics Technology has proven to be a relevant featured technology in manufacturing environmentally sustainable light and thin weight devices. In the ever-emerging field of additive fabrication, PE has contributed immensely not only to low cost of production but also to a reduced material waste in production and various applications such as in energy storage, displays and intelligent packaging (Hyun et al. 2015). According to (Garlapati et al. 2018), PE as a technology has the inherent capacity to be equal with internet of things (IoT) when matured and would increase the smart performance in industries such as logistics and packaging.

In addition to the above-stated possibilities of PE, the technology ascribes nanotechnology to traditional printing methods by using conductive nano-based inks, which have been improved and developed since the emergence of the Printed Electronic applications. Furthermore, Printed Electronics as a printing technique is compatible with the already available traditional printing methods such as gravure, inkjet, screen printing, flexography, and other available traditional printing methods (Hyun et al. 2015). Generally, there are three major PE Technology enablers that have to be considered by PE manufacturers to achieve intelligent products. Such enablers are substrates, inks and the printing technique adopted (Lydekaityte and Tambo 2018).

2.2 Product Packaging

Product packaging is a way to guarantee safe delivery of the final consumer goods in good condition at the lowest price possible. This definition suggests that the functions that the package needs to perform are numerous. Some essential packaging functions are containment, protection, communication, information, utility, and convenience. However, the different functions that packaging performs depend on the type of packaging. Packaging can be classified as primary (consumer and retail packaging), secondary (multi-unit distribution and packaging), or tertiary (transport packaging). The primary package has direct contact with the product, while the secondary package consists of several primary packages. Tertiary packaging, such as pallets and containers, combines several primary or secondary packaging. This classification is usually considered when categorizing packaging as a system and describing the packaging hierarchy's components and levels (Hellstrom and Saghir 2007).

The performance of a packaging system is affected by the performance of each package level and the interactions between the package levels. Packaging as a system affects many areas related to business and management. In logistics and distribution, the packaging is recognized to have a significant impact on the cost and performance of the logistics system. Packaging affects the cost of any logistics activity. In addition, packaging affects the efficiency of many logistics activities, such as transportation and storage. In addition, packaging influences product development, design, and production (Ballou 2004).

2.2.1 Functions of Packaging

The primary function of packaging is to protect products or goods from external influences and damage, to contain the goods, and to intimate consumers with additional information. The function of packaging includes as shown in Figure 2 will be further explained below.

Containment

Containment is one of the most basic functions of packaging that can be easily ignored. However, a package serving as a container is vital in all other packaging features. All products must have been contained for shipment from the place of production to their final destination. Without packaging, it is widely believed that products are likely to be lost or contaminated. Early packaging used to contain grains or other liquids like animal hides, baskets, or tree leaves, etc. The packaging system protects or reduces the damages that goods suffer during storage and transport. Some of the damages might be physical damage due to shock, vibration, compressive forces, etc. The environment might cause other damage due to exposure to natural elements such as water or sunlight (Kuswandi et al. 2011).

Protection

Two types of damage occur to goods during storage and transportation. One of them is physical damage, and the other is environmental damage. A functional and practical packaging system should guide or reduce the impact of both damages stated above. For example, aroma and taste are essential for coffee or juice. Those can quickly evaporate or oxidize in an optimum barrier packaging if not contained. Canned food can retain its shelf life (especially against microorganisms) if the package contains the required protection (Venkatesh and Alsamuraaiy 2019).

Communication

The function of communication in packaging includes information given in the written text and elements of the packaging design, such as the shape of the packaging, colour, identifiable symbols, or marks. In addition to providing information, the communication feature is expected to lure consumers into purchasing the product. According to the packaging is considered a "Silent seller". In some industries, a package must be able to identify the product, the net content, the name, business address of the manufacturer, packager, or distributor, as well as other information (Venkatesh and Alsamuraaiy 2019)

Consumers easily identify products that can instantly see photographs or packaging, and simple packaging materials such as transparent packages allow the customer to see inside the product (Venkatesh and Alsamuraaiy 2019). Universal Product Code (UPC) is widely used to facilitate fast and accurate payment in retail stores. Most warehouses and distribution centres also monitor and manage their inventory through UPC. Today, manufacturers can use radio frequency identification (RFID) tags in secondary and tertiary packages to obtain better demand signals from customers and brands. RFID tags can collect item data automatically without human intervention or data entry. RFIDs Identifies, categorizes, and manages the flow of products and information at crucial control and decision points (Venkatesh and Alsamuraaiy 2019).

Convenience

End-users demand products that match their lifestyle, and the packaging industry must respond through packaging that guarantees such functions. Thus, convenience as a function, therefore, includes all the packaging features that provide added value and convenience to the end-users of a product (Kuswandi et al. 2011).

2.3 Intelligent Packaging in Logistics and Distribution Industry

The integration of sensors into packaging extended its definition not to be limited to storage, protection, and divulging of information about a particular product but to also be able to interact, sense, and inform. According to (Zheng, Tenhunen, and Zou 2016), the term “Intelligent” in technology is the process of integrating microprocessors in other to have a processing capability and ability to vary in actions according to situations or times. Smart packaging, or intelligent packaging as it is often called, can be referred to as a packaging system incorporated with indicators with the capability of performing intelligent operations to determine quality, preserve, guarantee safety, disseminate information, and notify of possible harm from the product (Yam, Takhistov, and Miltz 2005).

Packaging systems can be divided into primary packaging, secondary packaging, distribution as tertiary packaging, unit costs, and industrial and packaging for consumers. The first level of packaging that has direct contact with the product is called the "main packaging. Typical examples are the inner bag of a cereal box and the individual candy package in the bag. Their primary function is to contain and store the product. Primary packaging should be non-toxic and compatible and should not cause any changes in properties such as discoloration, adverse chemical reactions, taste, other environmental hazards. (Venkatesh and Alsamuraaiy 2019).

The secondary package protects primary packaging during transport and storage. This level of packaging prevents dirt and grime from contaminating the primary packaging; they combine groups into main packages. Shrink film, and plastic ring connector that connects two or more cans examples of secondary packages are for ease of administration (Venkatesh and Alsamuraaiy 2019).

A tertiary package is containerized shipping that usually contains multiple primary or secondary packages. It is also called the "distribution package”, in which cardboard boxes are the most common form of tertiary packaging. In general, the product's primary function is to protect distribution time and ensure efficient management. Also, the fourth type in a packaging system is called a unit load, which means a group of tertiary packages assembled into a single unit. The goal is to help with the automated management of multiple products. A forklift or similar device is used to transport the unit load (Venkatesh and Alsamuraaiy 2019).

Intelligent packaging as a logistics and supply chain technology's starting point is primarily surveillance. Onboarding PE technologies bring the functions or capability of sensing using (humidity, temperature, or gas sensors), security recordings using (sealing or instruction sensors), item tracing, and package identification through commination during transportation or warehousing (Ahvenainen and Hurme 1997). Intelligent packaging as an innovative packaging system has attracted enormous market interest due to its ability to sense changes and inform suppliers and customers of the status of a package or product (see Figure 4). As an essential component of IoT, intelligent packaging brought about a revolution in logistics and daily human life (Visiongain 2012).

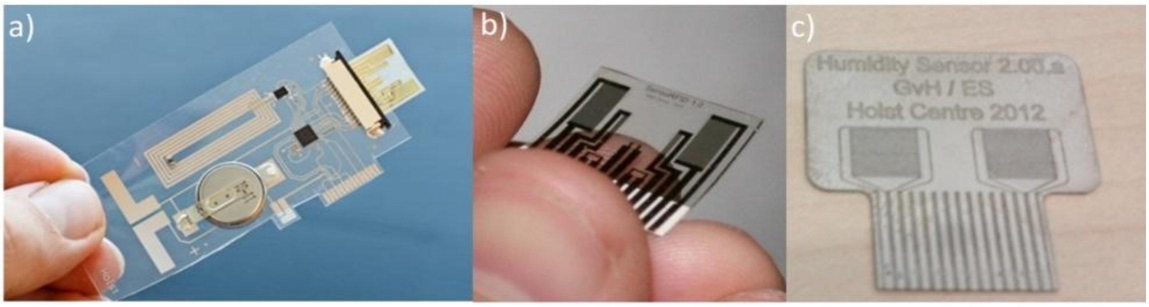

FIGURE 4: a) Photograph showing a smart label sensor. b) Sensor printed on PEN foil. c) Printed sensor on PET foil with interdigitated silver electrode ink (Smits et al. 2012).

FIGURE 5: An RFID sensor (Origin 2021).

Product packaging in logistics and distribution business is sensitive to price, hence the need to carefully choose the best manufacturing method and materials. The indispensable functionality of intelligent packaging which is to interact as well as inform customers and suppliers makes use of large area devices such as antenna, sensors, batteries and displays (Mantysalo, Xie, and Jonsson 2012). Therefore, a reliable integration system is required to achieve desired result. Each product package has distinct designs, therefore a package that is intelligent should be easily customisable and easy to manufacture. The above stated visions, need for low-cost manufacturability, sustainability, and ease of fabrication encouraged engineers and researchers to keep looking for new and better electronic manufacturing technique (H.-E. Nilsson, Andersson, and Manuilskiy 2011).

3 PRINTED ELECTRONICS TECHNOLOGY MATERIALS AND METHODS

This chapter will introduce Printing Electronics Technology materials and methods. The chapter will break down the Printing Electronics Technology enablers without which a device cannot be called intelligent. Conductive inks and substrates, two of the major material for PE, will be discussed in-depth in this chapter. Choosing the right printing method or technique is important to achieve the desired outcome in PE printing, either in the logistics packaging industry or any other industry desiring intelligence and interactive product. The four most common and widely used Printed Electronics printing methods will be enumerated in this chapter.

3.1 Conductive inks

Conductive inks are a major factor in the fabrication of PE devices and have therefore received increasing attention in recent times. As PE applications continue to emerge, conductive inks will continue to grow. Different materials, both organic (such as polymers) and inorganic, have been experimented with for use in PE. Organic inks are used as active layers for active devices such as Organic Light Emitting Diodes or for batteries, non-active components, and sensors. Inorganic inks contain metallic particles and are often used for the fabrication of sensors and other passive components (Nikolaos 2020).

Conductive inks for printed electronics should have properties or merits such as high conductivity, flexibility, low cost, and compatibility with multiple substrates. However, most conductive nanoparticle inks are expensive and have poor flexibility. Conductive ink is a Printed Technology enabler that has evolved over the years. Conductive ink's reach lies in its technological applications, such as for flexible and printable electronics, which make up most of the use of conductive inks. There is an enormous demand in today's market and fierce competition among technology giants in the production of such devices, which not only simplifies the lifestyle but also attracts a lot of attention. Thus, silver ink has become the choice amongst other inks such as copper, platinum, gold, tin, and iron in the industry, according to researchers (Karthik and Abhi 2015).

Conductive inks have three constituents such as a conductive pigment for conduction, a binder for adhesion, and a specific solvent as a carrier for delivering the composition. The conductive pigment often contains micro-particles (micro-inks) or nanoparticles (nano-inks). Micro inks tend to be more porous when placed on a substrate due to the larger particles that are present in them and are therefore less conductive than nano inks. The use of nano-inks saves a lot of material because the conductivity can be better; therefore, less material needs to be used to achieve the same target resistance. In addition, due to the large surface area of the conductive inks, nano inks have a lower sintering temperature compared to micro ink sets, which requires less energy in the subsequent processing (Karthik and Abhi 2015).

FIGURE 6: Printed Electronics using Nano silver conductive inks (Origin 2021).

Despite the benefits of nano inks, there are many problems with using nano inks. The production of nanoparticles is more expensive than microparticles from many metals. As a result, most commercial PE products today still use micro inks. Silver is the best known and most widely used material for metal particles (See Figure 6). The preferred use of silver is due to its very low volume resistance, and even silver oxides are more conductive. Alternative materials were explored, and one of the best materials was copper. This is because copper is cheaper and more valuable than silver, while its resistivity is not very different from silver. The big challenge is that copper oxides are not conductive, but copper ink is gradually becoming commercially available, and the future of PE is believed to be in copper (Nikolaos 2020).

Other conductive metals such as carbon allotropes, known for their unique properties, are also used as inks such as CNT and graphene. Graphene ink is a highly conductive, inexpensive, and super flexible ink based on graphene nanoplates. Graphene inks are used with screen-printing method on substrates such as plastics and paper. According to He et al., the combination of graphene ink with post-printing treatments, thermal annealing, and compression rolling, the printed graphene designs showed a high conductivity of 8.81 × 104 Sm - 1 and high flexibility with limited loss of conductivity after a 1000 s cycle of bending (He et al. 2019).

In addition to these polymers, hybrid inks have been successfully used for conductive inks. However, their use is limited compared to silver inks due to their applications which do not cover a wide area such as silver. Interestingly, not all conductive metal elements can be easily synthesized to form inks. The effects of ink formation are high and have a negative impact on ink properties, which in turn causes products to lag behind silver ink (Karthik and Abhi 2015)

3.2 Printing substrates

Substrates are the bases for electronics and act as electrical insulators to separate electrical devices from other components. Traditional electronic substrates are typically rigid and physically constant for indefinite time frames. Despite their high performance, they have fragile properties that make them difficult to use, for example, substrate's stretchability, cost, performance, etc. (see Table 1 and Table 2 for substrate properties and applicability). The development of lighter, flexible, and recyclable or biodegradable synthetic polymeric substrates has enabled the development of stretchable devices in short time frames (Hwang et al. 2012).

Printed electronics substrates can be made of synthetic or natural materials; however, different applications may favour flexibility, stiffness, high transparency, surface smoothness, low thermal expansion, heat resistance, low cost, thinness, and lightweight. In addition, different printers may have different requirements, such as certain thickness, flexibility, and mechanical properties. The ink used in electronic printing usually requires post-print treatment; this treatment may require high temperatures, chemicals, or UV radiation, damaging some substrates. This must be considered when selecting a substrate for printed electronic devices (Suganuma 2014).

There is a wide range of PE technology substrates suitable for packaging; these include polymers, plastics, and cellulose-based substrates. The properties of substrates are essential in manufacturing electronics (Jalkanen et al. 2015). Due to the impending transition from sheet-fed printing to R2R printing, a certain level of substrate flexibility is needed. The most commonly used substrates for printed Electronic fabrication (R2R) are thin glass, cellulose-based paper, polymer films, and metal foil (Hyun et al. 2015).

Each substrate material has its advantages and disadvantages (see Table 1); at the same time, each specific application requires a different type of substrate. Because glass and polymer films are transparent, they are used for optoelectronic applications, such as OLED or LED, allowing the construction of structures where light passes through the substrate. Thinner glass has favourable due to its bending properties than thicker glass; hence glass is more preferred for the production of R2R. Flexible plastic and paper substrates have become more common for consumer packaging applications with PE because they are already in use in the packaging industry (Abbel, Galagan, and Groen 2018) .

TABLE 1: Table showing the characteristics and benefits of commonly used PE substrates (Molex 2022).

Key:
Green = Better rating
Yellow = Middle rating
Red = Poor rating

	Traditional PCBs		Printed Electronic Substrates			
	Copper Flex PCB	Rigid PCB	PET (Polyester)	Polyimide	Fabrics & Paper	Stretchable Materials
Cost	Red	Yellow	Green	Yellow	Green	Yellow
Flexibility	Yellow	Red	Green	Green	Green	Green
Performance	Green	Green	Yellow	Green	Red	Yellow
Component Integration	Yellow	Green	Yellow	Yellow	Red	Red
Processing Characteristics	Green	Yellow	Yellow	Green	Yellow	Yellow

3.2.1 Natural polymeric substrates

Paper substrates are preferred and sustainable. Paper is flexible, environmentally friendly, and biodegradable, more resistant to thermal annealing or sintering used in R2R printing. However, conventional paper products have a porous surface, low high temperatures resistance, and complications from heat during flexible device production (Raheem 2013). As a result, it is constantly loaded with additives such as fillers and pigments in order to control and improve paper permeability, strength, smoothness, and optical properties. Another way to improve the surface properties is to cover the paper with plastic to reduce rough surface and porosity (Jalkanen et al. 2015).

Cellulose diacetate is another alternative and attractive material for PE because it is already commercially available, easily biodegradable in soil, and has high transparency and mechanical flexibility, making it attractive for sensing gases and OLED layers (Zimmermann et al. 2018). Cellulose foil has proven to be a good alternative to plastic substrates due to its dielectric properties, flexibility, and hardness (Samusjew et al. 2018).

Other naturally biodegradable materials that can be used as substrates are, for example, silk, shellac, gelatine, and starch. Silk is a biodegradable, biocompatible, and non-toxic natural protein fibrous material that has been shown to be a good candidate for use as a substrate. Silk is easy to process and has excellent chemical strength, mechanical properties, and flexibility. Shellac is a natural resin that has biodegradability, a high surface finish, and high solubility in alcoholic solvents, making it suitable for the formation of substrates (Välimäki et al. 2020).

3.2.2 Synthetic Polymeric Substrate

Polymers are hydrocarbons derived from basic hydrocarbons such as ethane and methane or derived from natural gas and oil (Asgari, Moradi, and Tajeddin 2014). Plastics can be cast into a wide range of useful products because they are fluid, malleable, heat sealable, easy to print, and for the most part, they can be easily integrated into existing production lines. Plastics possess satisfactory mechanical properties at low cost with high barrier properties, but recycling is a daily struggle for the industry. Polymer films are the most commonly used substrates for printed electronics, but the manufacturing and operating environments must be carefully designed and controlled to minimize surface defects and deformations. Polyethylene terephthalate (PET), polyethylene naphtholate (PEN), PI, and polycarbonate (PC) are the most commonly used polymeric substrate materials in printing electronics (Raheem 2013).

TABLE 2: Table showing glass transition temperature, maximum service temperature and general properties of substrate material (Wiklund et al. 2021).

Substrate Materials	Glass Transition Temperature (°C)	Maximum Service Temperature (°C)	Properties
PET	68 - 80	115 - 120	Water resistant, recyclable, low cost, available in assorted colors and finishes
PC	142 - 158	101 - 116	Water resistant, recyclable, transparent with wide range of thickness, texture and finishes, better abrasion resistance without hard coat
PEN	118 - 126	160 - 180	Water resistant, transparent, recyclable, UV durable
PI	240 - 260	221 - 241	Recyclable, expensive, high UV durability, high dielectric strength, tendency to absorb moisture, does not burn
PLA	52 -60	45 - 55	Transparent, recyclable, UV durable, biodegradable and renewable
Paper	47 - 67	77 - 130	Recyclable, biodegradable and renewable
Silk	77	77 - 87	Expensive, biodegradable and renewable

PET is the most popular polymeric substrate and has high optical transparency, flexibility, solvent resistance, low cost, and high-temperature dimensional strength. PEN and PI have better heat resistance but lower transparency and are expensive. PC has high strength, low weight, and good mechanical properties such as stiffness, impact resistance, and stiffness. Polycaprolactone (PCL), poly-milk-co-glycolic acid (PLGA), polyurethane (PU), polybutylene succinate (PBS), and polyethylene glycol (PEG) are some biodegradable polymers that can be used as substrates (Fischer et al. 2013).

3.3 Sintering

It is essential to use an appropriate form of post-print treatment to obtain the optimal property of the printing electronics, such as conductivity. Depending on the ink and substrate used in the printed electronic device, different post-print treatments can be used, such as photonic healing, annealing, thermal, microwave, plasma, or chemical sintering (see Table 3). These treatments may be based on physical or chemical reactions and aim to get rid of solvents and additives from the ink and improve the morphology and microstructure of the prints. Sintering processes are affected by particle size and shape, temperature, time, radiant energy level, and print pattern thickness. An increase in temperature and sintering time increases the level of sintering (Cui 2016).

Thermal sintering is usually performed in a furnace or hot plate at a specific temperature. It should also be noted that high temperatures can adversely affect the adhesion of the ink to the substrate and are not suitable for various substrates. Different inks possess different thermal strengths; while some inks can withstand very high temperatures without any change in conductivity, others may unexpectedly lose their conductivity at a specific temperature. Thermal sintering is an essential method after treating nanoparticle inks. This curing method is used for metal and oxide particles to prevent agglomeration; however, after printing, thermal sintering removes the stabilizers to form a continuous pattern (Popov 2004).

TABLE 3: Comparing some of the most common sintering methods on glass and PI substrates using nano silver ink (Wiklund et al. 2021)

Sintering Methods	Resistivity (μΩ·cm) Glass Substrate	Resistivity (μΩ·cm) PI Substrate
Thermal	4.00	3.60
Flash Lamp	5.59	3.30
IR Lamp	3.00	65.50
Laser	3.41	4.60
UV	48.00	6.50
Argo Plasma	8.73	15.00
Microwave	-	30.00
Electrical	2.47	17

In addition, electrical properties can be improved by the thermal sintering of particulate inks at temperatures below their melting point. The melting point and sintering temperature can be reduced by reducing the particle size used in ink by increasing the surface-to-volume ratio. Metal-organic decomposition (MOD) inks usually require very high sintering temperatures, limiting the possibilities for the substrates used and metal precipitation. The material properties can also be improved by relieving the internal stresses of the solution-treated semiconductors by annealing. Harvesting is usually done in an oven, hot air jet, or hotplate. The high temperature used in annealing limits its use (Wiklund et al. 2021).

Different temperatures required for thermal sintering of different nanoparticles in the glass substrates are compared in Table 4. The nanoparticle silver ink is transparent with the lowest resistance of the glass substrate at a relatively low sintering temperature; however, other factors affect the sintering temperature and the resulting resistance of the conductive structure, such as the size of the conductive particles. Photonic sintering transfers energy to the surface from a light source, such as a flashlight or laser. Fast, high temperature, and selective heating can be achieved by photonic sintering, which is practical when using substrates that cannot withstand high temperatures (Wiklund et al. 2021).

TABLE 4: Comparing different nanoparticle inks sintering temperatures on glass substrates (Wolf et al. 2013)

Nanoparticle ink	Sintering Temperature	Resistivity (μΩ·cm)
Silver	200	4
Copper	200	18
Gold	240	714
Aluminum	600 (starting from 25 increasing to 10 C/min	4.12
Nickel	230	460
ITO	400	100

Flashlights allow the print cartridge to sinter efficiently with a high intensity of millisecond light pulses, only increasing the ink temperature without damaging the substrate [200]. Powerful pulse lamps can be used to sinter large areas (58 cm2 or larger) in milliseconds with wavelengths (350-800 nm) [198,199,211]. Continuous and pulsed lasers can also sinter printed metal nanoparticle patterns. High-resolution patterns can be achieved using laser sintering, and the laser beam can be tuned depending on the pattern by adjusting the size and intensity (Kamyshny and Magdassi 2014). On the other hand, UV curing is often used for insulating and chemically stable materials such as dielectrics or insulators. UV curing ink can quickly solidify without heating with sharp edges and smooth morphology. However, because plastic absorbs in the range of wavelengths used in UV curing, it can cause damage to plastic substrates (Suganuma 2014).

Plasma sintering can be used on plastic substrates due to its ability to apply at low temperatures. However, the depth of plasma penetration limits the possible thickness of the printing pattern (Suganuma 2014).

Microwave sintering is a fast way of sintering metals. However, the penetration depth is minimal (approximately 1-2 m at 2.54 GHz), limiting the supported print cartridge thickness. Due to their thermal conductivity, metals with high thermal conductivity can use even thicker patterns and still form uniform patterns (Kamyshny and Magdassi 2014).

Electrical sintering heats the printed metal pattern with an electric current due to the application of pattern stress. This sintering method involves low temperature and fast. The printing pattern must be relatively conductive before electrical sintering (Kamyshny and Magdassi 2014).

Chemical sintering is performed with chemical agents to provoke the nanoparticles to bond at room temperature. Opposite charged polyelectrolytes are applied to metal nanoparticles to trigger a dynamic process in which the nanoparticles merge to form a conductive pattern. Polyelectrolyte can be added to the substrate (Wiklund et al. 2021).

3.4 Printing methods

Printing electronics are manufactured using inexpensive organic-based materials instead of traditional solid silicon-based materials, and electronic devices can be manufactured using printing technologies. It is widely used for various emerging applications in flexible electronics, wearable electronics, and biodegradable electronics, among other uses (Seekaew et al. 2014). The low-cost production of these electronics allows them to engage in the commercial application of intelligent packaging (Yousefi et al. 2019) The possibility of manufacturing biodegradable electronics from organic materials makes it ideal for producing perishable packaging products (Vanderroost et al. 2014).

Printing methods can be contact printing and contactless printing. In contact printing, the ink surface cartridge components are brought into physical contact with the substrate. In contactless printing, on the other hand, the inks are fed through holes or nozzles with pre-defined stage movements (substrate holders) that follow a pre-programmed pattern (S Khan, Lorenzelli, and Dahiya 2015). An excellent example of contact printing is gravure printing, and examples of contactless printing include screen printing and inkjet printing. In recent years, printing techniques have evolved because they are simple, inexpensive, fast, adaptable to manufacturing processes, reduce material waste, and enable high-resolution standards that can be easily controlled by adjusting specific process parameters (Moonen, Yakimets, and Huskens 2012).

TABLE 5: Comparing commonly used Printed Electronics printing methods (Paulo, António, and Cristina 2015).

	Gravure Printing	**Screen printing**	**Inkjet Printing**	**Flexography Printing**	**Offset Printing**
Printing Form	Engraved	Stencil	Digital	Relief	Flat
Image Transfer	Direct	Direct	Direct, Non-impact	Direct	Indirect,
Resolution (lines/cm)	100	50	60 to 250	60	100 to 200
Line Width	10 to 50	50 to 150	1 to 20	20 to 50	10 to 15
Ink Viscosity (Pa·s)	0.05 to 0.2	>1 to 50	0.001 to 0.03	0.05 to 0.5	40 to 100
Film Thickness (µm)	<0.1 to 5	Up to 12	0.5 to15	1 to 2.5	0.5 to 15
Printing Speed (m/mim)	100 to 1000	10 to 50	15 to 500	100 to 500	200 to 800

In addition, new and emerging polymer-based printing methods such as nano-printing, micro-contact printing, and transfer printing have also attracted great interest, especially in the production of flexible electronics such as inorganic mono-crystalline semiconductors (Sun and Rogers 2007). Below are the three major printed Electronics printing methods:

3.4.1 Gravure printing

Gravure printing is a contact printing method that involves the direct transfer of available colour by physical contact of the engraved structures with the substrate (Kuswandi et al. 2011) and provides a higher print resolution compared to contactless printing. This printing technique is used for the fabrication of prints with higher values of durability and capacity. As shown in Figure 6, the gravure printer consists of a rolling cylinder and a printing cylinder. Firstly, the cylinder is covered with copper, and a laser is then used as an electrochemical method to cut patterns on the cylinder. The rolling cylinder is then covered with a chrome layer to protect it from damage. Ink is introduced using an ink bath at the bottom of the cylinder or a nozzle at the top of the cylinder. A specialized blade is used to remove excess ink. Finally, the ink is transferred to a rolling substrate. See Figure 7 for the working principles of the gravure printing method (Yousefi et al. 2019).

Ammonia and humidity sensors are typical sensors printed using gravure. The sensors are produced by gravure printing on sensitive organic-based flexible PET film layers. In contrast, nitrogen dioxide (NO2) sensors are produced by gravure and screen printing on flexible poly substrates. This printing technique has successfully produced a wide range of flexible sensors. Therefore, Gravure printing is a practical and possible method for the large-scale and cost-effective manufacture of intelligent packaging (Lixing, Zhenning, and Changyong 2019).

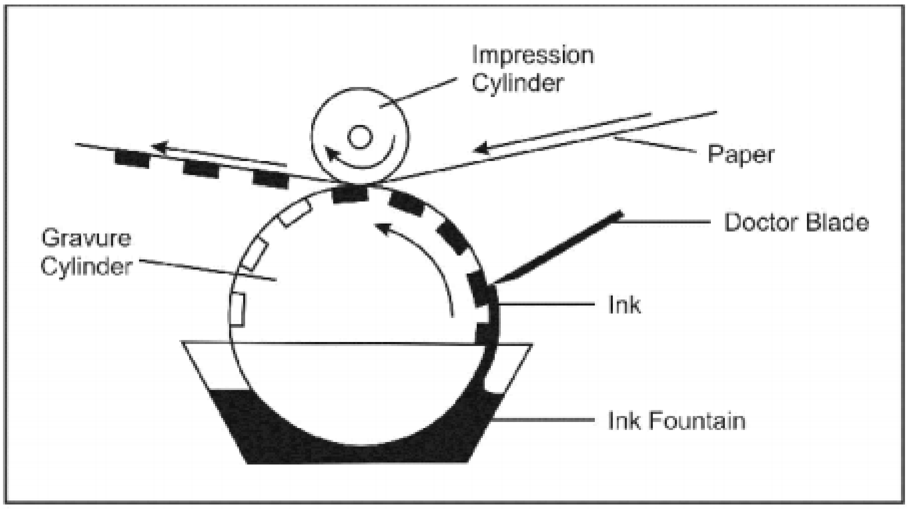

FIGURE 7: Functional principle of Gravure printing method (Press 2022).

Like all other printing methods, the main problem of gravure printing for printed electronics is production cost; hence, this technique is best suited for mass production. For this reason, the number of scientific reports on gravure uses for printed electronics is limited. However, the printing technology is commonly used for field-effect transistors, solar panels, and circuits (Jung, Kim, and Noh 2010).

3.4.2 Inkjet printing

The inkjet printing method is one of the most popular contactless printing for the production of flexible sensors. This technique uses a substance dissolved or dispersed in a solvent ink. The nozzle releases a certain amount of ink, and the ink dries after the solvent evaporates. Over the years, inkjet printing applications have grown and can be used to print on a wide variety of substrate materials such as conductive polymers, metal layers, and biomaterials (Yoshioka and Jabbour 2006) . Figure 8 shows one type of inkjet printing: the thermal and piezoelectric ink systems that apply a pulse capable of emitting tiny drops of ink. Inkjet printing can be used to produce fine-grained and thin films bearing polymers. Most of the available printed sensors are manufactured using inkjet printing due to its ease of use and digital design layout process (Lee et al. 2006).

Inkjet printer-printed flexible sensors are used in the intelligent packaging of perishable products. Using an inkjet printer for intelligent packaging, Wu et al, 2015 used an inkjet printer to fabricate a printed device called a "smart cap" that can monitor the quality of liquid foods such as milk or soups. All major electrical components such as resistors, capacitors, inductors, and circuits were inkjet printer printed. Feng et al fabricated a complete RFID humidity sensor tag using the inkjet printing technique printed on paper packaging for securing and monitoring humidity in packages. This test and fabrication showed that RFIDs as sensor labels could be printed directly on the package in a single application.

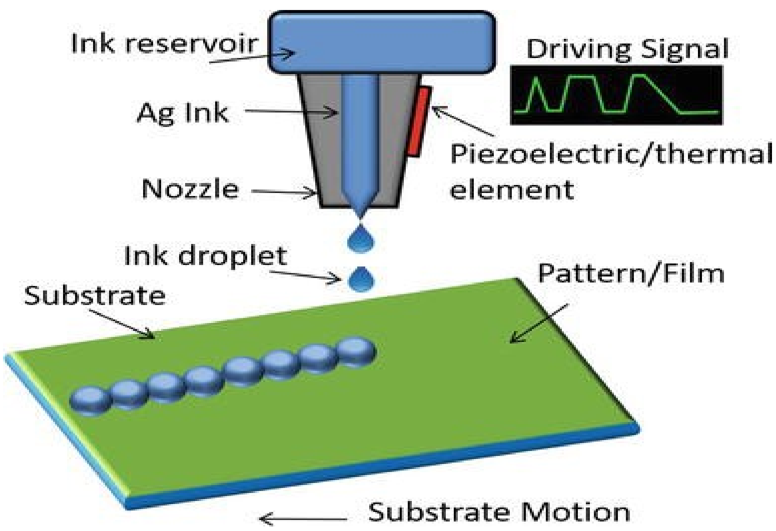

FIGURE 8: Working Principle of Inkjet printer (Saleem Khan, Ali, and Bermak 2019).

There are limitations to inkjet printing application as a printing technique. Printing of electronic components needs three-dimensional drop control for an even cross-section and smoothness of the layers, and to attain this, the nozzle jetting parameters are more complex than traditional graphics printing. These parameters are extensive on the properties of solvents and inks, such as boiling point, evaporation rate, surface energy, and viscosity. Properly setting all of these factors can lead to the desired result. Another well-known problem is the phenomenon - of the "coffee ring effect," a situation where ink materials collect along the edges. This is a significant concern to printing quality (Kanth, Wan, and Liljeberg 2011).

3.4.3 Screen printing

Screen printing is a non-contact printing method and the most popular printing technology introduced to printing. The essential components of a screen printer are the mesh and squeegee. The squeegee causes the ink to pass through the open mesh pattern on the substrate. See Figure 9 for the working principles of screen printing and Figure 10 showing EKRA E2 screen printer as seen in the Print lab (Development Laboratory for Printed Intelligence). Screen printing has been used to print metal circuit boards for many years in the electronics industry. It is more efficient and more versatile than other printing methods because it is easy to use, inexpensive, and the manufacturing process is adaptable (Chang et al. 2009).

Dubourg et al. 2017 manufactured a miniaturized resistance type humidity sensor by printing it on a flexible substrate on a large scale. The production process is comprised of two parts. One was the laser ablation in the design of the interconnected electrodes printed on a PET (polyethylene terephthalate) substrate. The second part was the deposition of sensitive materials using the screen-printing technique. This study presented a cheap and low-temperature printing process for the large-scale fabrication of humidity sensors on flexible PET substrates. The result shows that laser ablation is more suitable for the micro-scale interdigitated electrode pattern. Screen printing is more suitable for the industrial combination of sensitive metal oxide films on a flexible substrate.

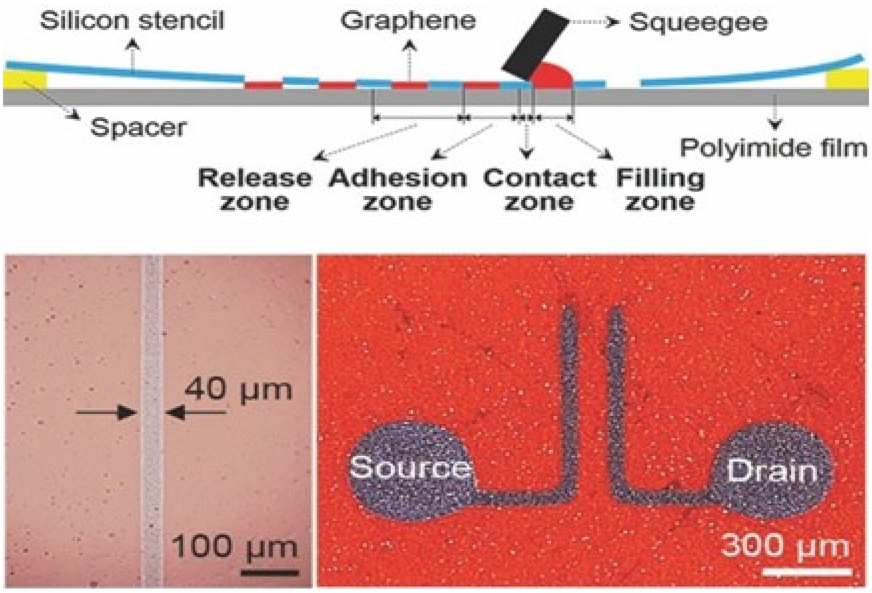

FIGURE 9: Working principle of Printed Electronics screen printing (Hyun et al. 2015).

FIGURE 10: Picture showing EKRA E2 screen printer as seen in Print lab Oulu.

In some cases, screen printing can be combined with inkjet printing in the electronics production process. Fernandez-Salmeron, J Rivadeneyra et al used screen printing to use a spiral inductor used as an RFID antenna and inkjet printing to use planar capacitive structures to create an LC resonator. Flexible polyimide was chosen as the substrate and sensitive material.

Some challenges exist in screen printing as a printing method for printed, electronic applications. The screen-printing method uses viscous inks to prevent ink movement during transfer. This sets the standard for functional electronic inks developed in research laboratories, often characterized by low viscosity. Large amounts of additives are available that can effectively increase the fluid's viscosity to meet rheological printing requirements. However, they reduce the electrical performance of the print design. Another disadvantage of this printing technique is low speed due to the operating principle (Zheng, Tenhunen, and Zou 2016).

3.4.4 Flexographic Printing

Unlike the gravure printing method, flexographic printing technology uses a flexible embossed plate. The desired design is embossed on the printing plate, usually made of rubber or a photopolymer. See Figure 11 for the working principles of flexographic printing. The roll-to-roll flexographic printing process is easy to use and faster for production. The inks are in a low viscosity range, suitable for water or solvent-based liquids. In addition, it uses flexible plates that are cheaper than screen printing and gravure printing plates allowing lower costs but high-performance printing (Zheng, Tenhunen, and Zou 2016).

This technique is relatively new for printed, electronic printing. Due to machine limitations, scientific reports on this printing method are rare. Nevertheless, it has started receiving attention and is used with other printing methods to manufacture electronic components, such as solar cells (Krebs, Fyenbo, and Jørgensen 2010).

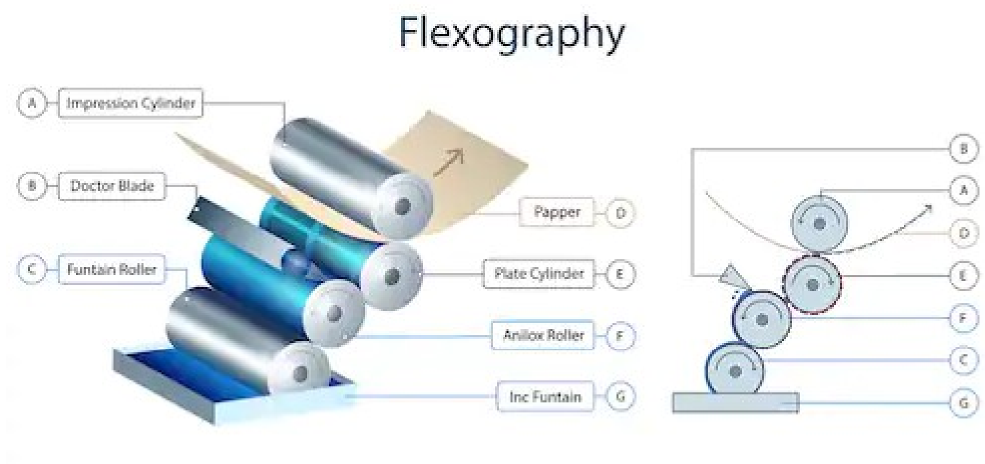

FIGURE 11: Schematics of Flexographic printing (Ordant 2019)

4 POTENTIALS OF PRINTED ELECTRONIC TECHNOLOGY IN PACKAGING SYSTEMS

The printed technology has gone further and enabled the printing on various substrates, such as flexible plastics, thin films, paper, and cardboard. As a result, traditional printed consumer packaging faces alternatives, and more advanced forms of packaging are being introduced to the market. Printed communication systems embedded in the package are usually low-cost, lightweight, and flexible electronics such as NFC tags, batteries, displays, antennas, etc. This chapter, therefore, aims to explore the features of Printed Electronics Technology applications and their potential for the innovation of intelligent interactive packaging.

4.1 Near Field Communication (NFC)

NFC is a low-range communication technology that allows interaction between compatible devices such as intelligent packaging or smartphones. The development of intelligent packaging driven by NFC is facilitated by IoT and integrated into everyday products. According to Pigini & Conti, NFC is a near-field wireless technology that provides reliable, secure, and efficient data exchange (see Figure 11). NFC tags are widely integrated into mobile devices compared to RFID tags; thus, no specific reading is required (Balliu et al. 2018). On the other hand, the NFC band only works at short ranges as opposed to RFID, which can transmit for several meters (see Figure 12). NFC tags are made up of initiators and targets consisting of antennas and memory chips. Energy is passively generated by the initiator (Pigini and Conti 2017)

FIGURE 12: Intelligent packaging for authentication and security (Packaging World Insights 2019)

NFC tags can be rewritten, data encrypted and stored, and password protected for WORM (write-once-read-many) memories. As a result, the concept of big data allows the market to be analysed in terms of consumer behaviour, ethics, and preferences, creating interactive links between businesses and consumers, and increasing product value. Thin Film provides more scalable and innovative printed electronic solutions by deploying NFC printing brands for various consumer and industrial applications (Zhu 2018).

4.2 Smart sensors

Fast Internet connections and IoT have made it easy to replace analog sensors with digital sensors. Recent advances in sensor technologies such as PE, IoT, Nanotechnologies, etc., resulted in a reduction in the cost and size of sensors and also in the expansion of the use of this intelligent technology in new market segments, such as logistics (see Figure 13 & 14) and distribution most especially consumer packaging industry (Nilsson, 2012). Low production costs and high efficiency allows low-power wireless sensors realization and growth within IoT. PE enabled the possibility of lightweight, rollable, flexible, and portable devices that can be applied directly to objects, regardless of shape or size. As a result, many logistics and distribution monitoring sensors have been developed (Biji et al. 2015).

FIGURE 13: Printed thin film sensor tag for product protection (Caliendo 2014)

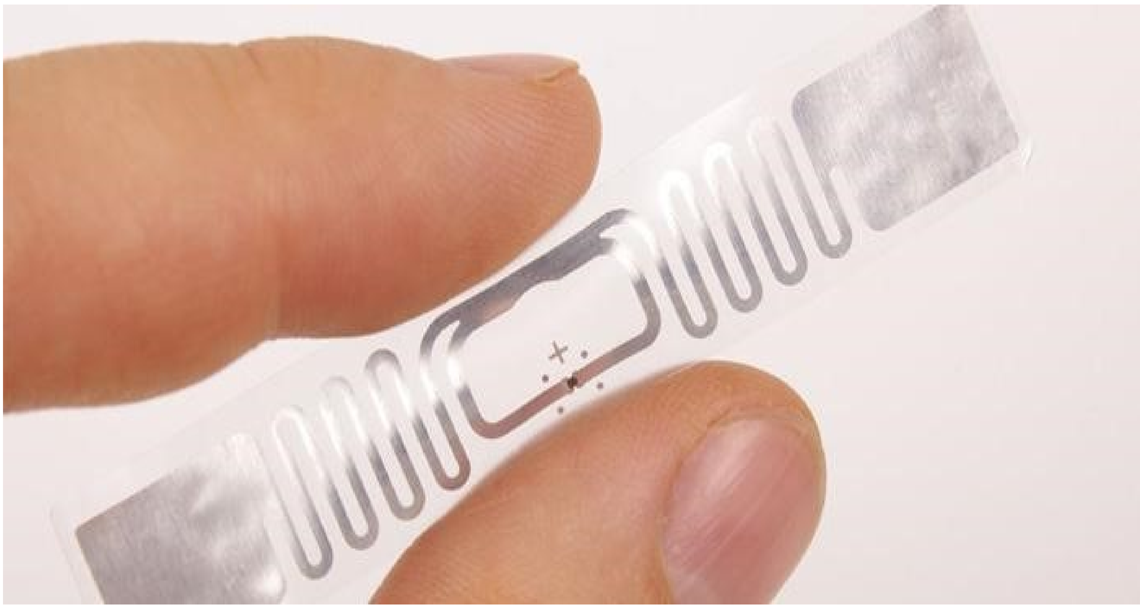

FIGURE 14: Printed smart sensor enabled for cold chain tracking in logistics (Essentra 2011).

Typically, the sensors can be integrated into the package by directly printed, printed on the label, or laminated to the package. The packaging industry uses several sensors with many functions, divided into two groups; some are aimed at monitoring, performing surveillance functions, and ensuring package protection (Nilsson, 2012). This group of sensors includes temperature sensors, humidity sensors, gas, moisture, oxygen, chemicals, and counterfeiting sensors. Interactive sensors enable objects to interact and connect to digital services over the Internet. Such sensors are IoT-based, especially in packages to improve communication, marketing, and branding opportunities (Mraović et al. 2014).

4.3 Radio Frequency and Identification (RFID)

RFID (Radio Frequency Identification) is an automated identification technology that uses wireless sensors to identify objects and collect data without human intervention. Most RFID tags (see Figures 15 & 16) can store some identification numbers, based on which the reader can obtain and trade information about the identification number of the database (Todorovic and Lazarevic 2014).

RFID tags fall into two categories: passive and active. Passive labels rely on the performance of the reader. When radio waves from the reader are detected on the passive RFID tag, the helical antenna inside the tag becomes a magnetic field. The tag draws energy from it and sends the encoded information to the tag's memory. Semi-passive RFID tags use a battery to store the tag's memory or power electronics, which allows the tag to modulate the electromagnetic waves emitted by the reader's antenna. Active RFID tags are powered by an internal battery used to perform microchip circuits and send a signal to the receiver (Vanderroost et al. 2014).

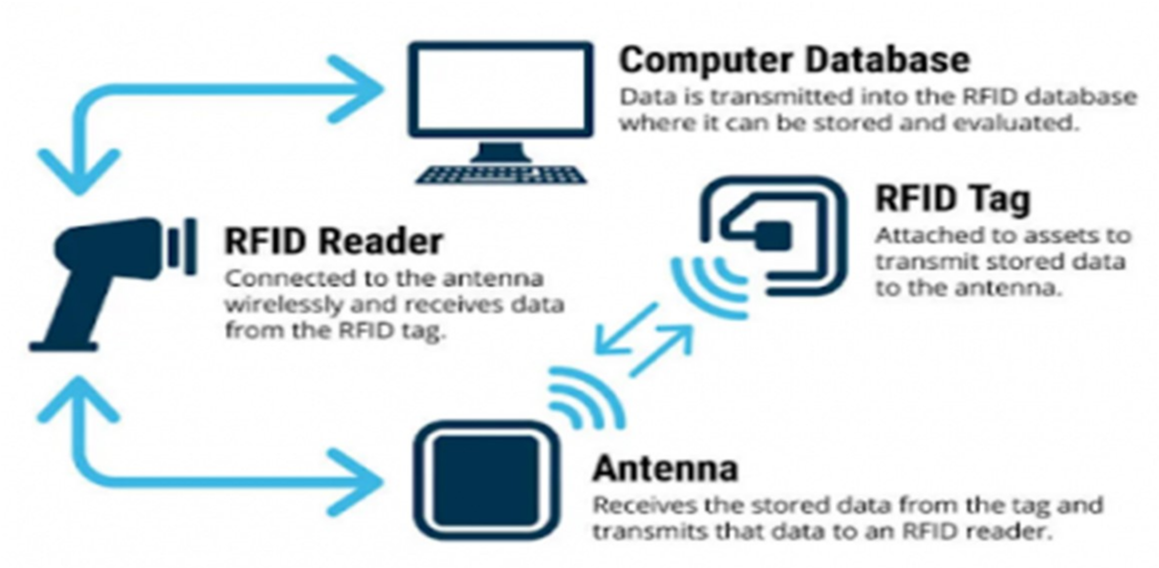

FIGURE 15: Intelligent packaging RFID processing schematics (Sepio Solutions 2021).

FIGURE 16: Printed RFID solution for labels for flexibility

RFID is successfully used to manage supply chain monitoring and management processes due to its ability to identify, categorize and control the flow of objects. Studies have shown that RFID is more advanced than zebra black and white paper, the barcode system for food traceability. RFID technology provides supply chain visibility, enables fast, automated supply chain visibility processes that enable fast and automated supply chain level processes, such as exception management and information sharing (Vanderroost et al. 2014).

Sensors such as mountable, non-integrated, and inflexible RFID tags based on sensors for controlling temperature, relative humidity, exposure to light, pressure, and pH products are available on the market. These labels have identified possible cooling chain disruptions that may affect quality and safety (Tajima 2007).

4.4 Light- Emitters

Conventional inorganic displays such as light-emitting diodes (LEDs) and liquids crystal displays (LCD) were the first displays to be commercially available. Those displays had high-performance visual displays but consumed a lot of energy and were made of conventional glass substrates. They were susceptible to the thickness of many layers of the various organic materials used. Furthermore, they used precious and rare metals to cover these layers, thus reducing the low-cost limits in printing techniques. As a result, a Transition to more sustainable materials and methods was eminent. Organic electroluminescent devices (see Figure 17) offer a better alternative because they are flexible, lightweight, biodegradable, low-power, and cost-effective roll-to-roll production process (Lydekaityte and Tambo 2018).

An alternative technology that is slowly emerging is light emission electrochemical cell technology (LEC). This is a very similar device to OLED technology but has the advantage that only one layer of light-emitting material is used between the two conductive electrodes and is relatively insensitive to the active layer thickness and electrode properties. In addition, LECs can be made entirely organically using organic conductive materials for electrodes. This simplifies their production, and end appliances can be recycled (Shen 2017).

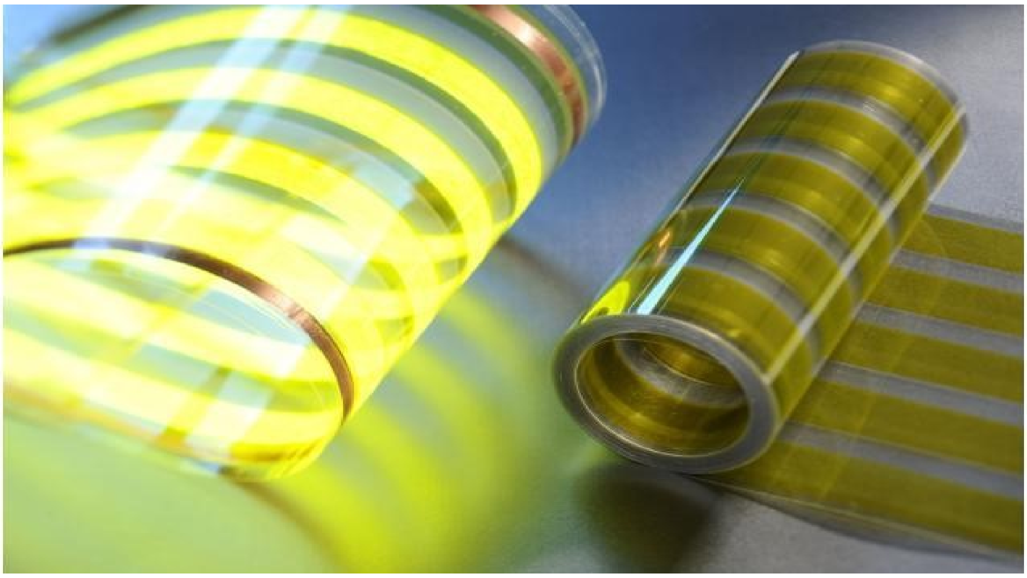

FIGURE 17: Organic OLED light emitting diodes for packaging (Lisa 2015).

Electrochromic displays are another emerging printed display gradually finding their way into the market. Electrochromic display materials are organic or inorganic that change colour upon electric charge. The changing colour continues, and energy is only needed to affect the colour change. This technology is widely used in applications such as dimming glass or intelligent glasses.
Electrochromic can be found in display rear-view mirrors in the automobiles, aerospace, and building industries for heat control use. Printed electrochromic displays are developed from flexible conductive polymers that can be integrated into any intelligent device as a visual interface. Such a display can be used in packaging or other similar devices that require thinner, more flexible, more durable, and the lowest power consumption display features (Nikolaos 2020)

Printed displays are often used in the consumer electronics market, such as wearable devices and mobile devices. The demand for ultra-thin and flexible displays for these applications has led to the development of print displays from leading manufacturers, primarily using organic light-emitting diodes (OLEDs). Today, PE manufacturers can produce many different flexible LED displays on paper, fabric, and plastic film, including transparent film with good circuit transparency (Zimmermann et al. 2018)

4.5 Batteries and storage devices

Storage devices are a fundamental building block of printed electronics and, in recent years, have shifted to new design and form factors such as printed storage devices, ultra-thin and flexible. These form factors can only be credited to the rise of the Internet of Things, sensors, and wearables. Printed storage devices can be identified in three subcategories: thin solar film cells, printed batteries, and supercapacitors. The present consumer electronic market needs functionality that traditional batteries cannot meet (Nikolaos 2020).

The consumer electronic market changes rapidly as new products and devices are constantly unveiled. Printed batteries are usually zinc-based and cannot be recharged (see Figure 18). Some printed batteries that are presently commercially available are as thin as paper and offer form factors capable of delivering more energy that lasts several peak currents. Those commercially available batteries are suitable for disposable devices that require flexible and thin features and can be customized as required (Blue Spark 2019).

FIGURE 18: Printed battery (David Savastano 2013).

Compared to traditional silicon-based devices, dye-sensitive solar cells (DSSC) and organic and plastic solar cells (OSC) are examples of flexible and inexpensive PE energy sources. These cells are lighter and more flexible, allowing the use of unique shapes and forms in photovoltaics. They also offer the potential to display and introduce new applications in intelligent devices. Printed supercapacitors are excellent alternatives for temporary energy storage in applications with low energy yields (Nikolaos 2020).

4.6 Printed logic and memory circuits

Memory and logic are the elements needed to create complex printing circuits and improve printed electronics' capability (Ng 2012). Memory arrays ensure that history information is maintained, while logic ensures reduced energy consumption and a stable circuit (see Figure 19). Printed memories used for intelligent packaging can store key codes to combat counterfeiting and safety management. For packaging applications, memory should be inexpensive, maintain stability after prolonged storage, and read multiple operations (Zhu 2018).

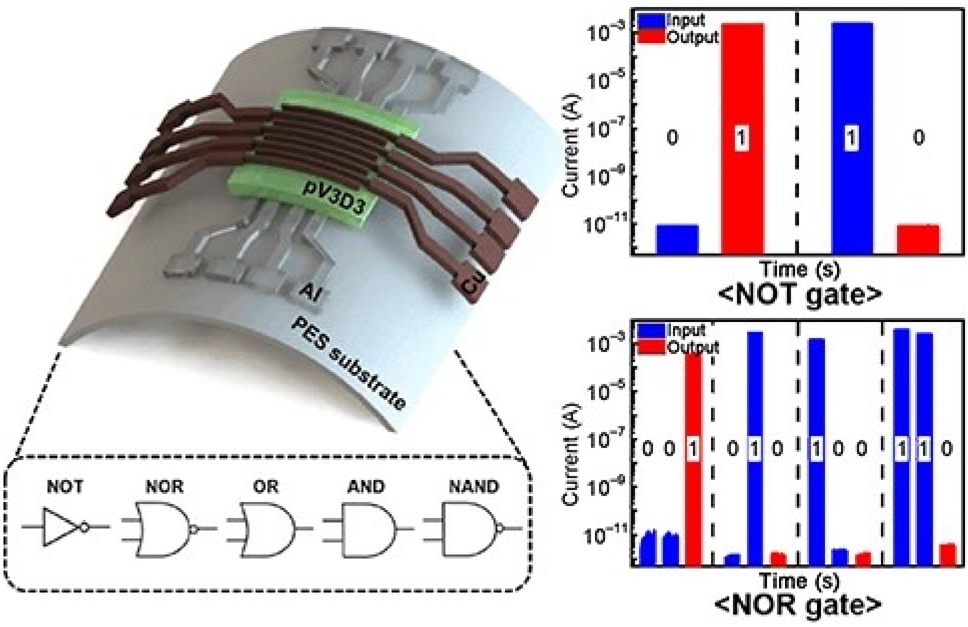

FIGURE 19: Diagram showing printed flexible printed logic and memory (Jang et al. 2017)

4.7 Touch sensors

A lot of touch screens are commercially available, such as capacitive touch screens, resistive touch screens, etc. Touch sensors are designed to value by package and environmental monitoring or ensuring pre- and post-interactive functions. Sensor technology is designed and developed to easily integrate high-quality prints focusing on applications such as logistics supervision as it concerns this research (Lydekaityte and Tambo 2018).

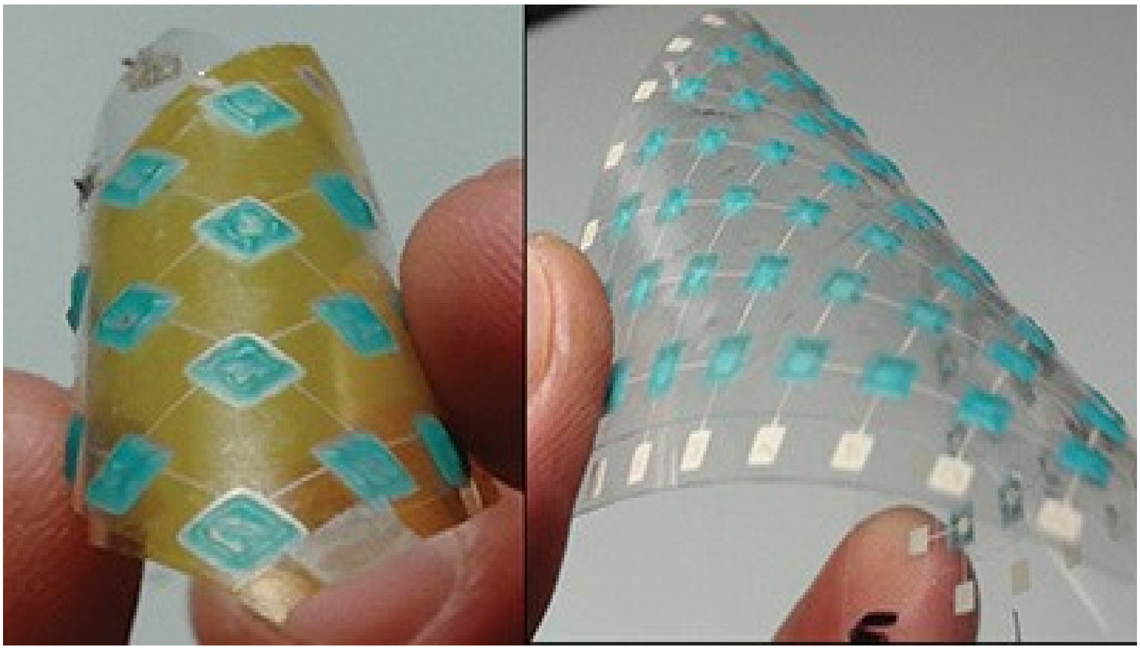

FIGURE 20: Diagram of screen printed touch cells (Dahiya et al. 2015).

Touch or manipulation changes any functional characteristics, either capacitance or resistance of any printed touch sensor (see Figure 20 Diagram of screen-printed touch cells). Such changes are then wirelessly communicated through a connection such as RFID, WI-FI, NFC tag, Bluetooth, or any connected analog wired interface. Finally, visual, and digital changes can be seen on the screen or passed on for further analysis. A typical example of a touch sensor is a capacitive touchpad that detects changes in capacitance through finger contact by applying the electrical impedance of the fingertip and the adequate capacity of the human body (Mazzeo 2012).

4.8 Advantages of Printed Electronics

PE is performed using standard printing technologies and requires only two processing steps. This process of self-creation results in many benefits. PE is very fast, and due to the complexity of the process, traditional silicon-based integrated circuits require months to produce, in contrast to PE, with a processing time that takes minutes. The cost of producing PE is much lower than that of conventional electronics, making the devices produced much cheaper. Production tools are cheaper because printing methods are simple and easy, and because these are just low temperatures, energy consumption is also kept to a minimum. The ability to use inexpensive substrates such as paper or plastic, as well as roll-to-roll, are factors that have contributed to overall low production costs (Nikolaos 2020).

4.9 Challenges of Printed Electronics

Despite the rapid growth in PE technology, The technology is not without challenges. The major disadvantage of PE devices is that they may not be as efficient as traditional silicon-based electronics. While it is clear that the application goals in traditional printing and Printed Electronics are different, PE as printing technology is making its way for new applications that do not require the high speeds of traditional electronic applications. Reliability is an issue in printed electronics. Although a print sensor is inexpensive to manufacture and probably easy to replace, it is less clear how long such a sensor will last or when and how it will fail. Therefore, hybrid systems are constantly being developed in such components that are most problematic in terms of long-term reliability, are manufactured as printed circuit boards, and have advantages over printed electronics over other components. Lastly, the size of components (how small objects can be) in PE devices is limited, while traditional semiconductor electronic components can be manufactured up to 3 orders of magnitude smaller. Printed technologies are more difficult to print in this respect than photolithography (Nikolaos 2020).

Table 6: Merits and challenges of Printed Electronics

Merit	Challenges
Fast and direct manufacturing process	Reliability
Low production cost	Performance
Less waste	Feature size (how small objects can be)
Possibility of mass production	
Unique form factors	
Lightweight	
More functionality	
Biodegradable possibility	
Transparency	
Flexibility	
Energy saving	

5 DISCUSSION AND FINDINGS

This literature review-based study shows a vast market potential for so-called "Intelligent" applications, but integration into the value chain might be an issue. Numerous industries and other commercial entities have found wide-ranging use for this technology. In particular, logistics and distribution packaging are some of the industries where PE intelligent and interactive applications have revolutionized. Intelligent package printing is in use only as it relates to the possibility of existing printing methods and processes to fabricate new substrates or integrate intelligent elements into the packaging.

The significant finding of this research is the adoption or integration of intelligent printing technology into the new requirements of the retail market and any industry that desires the technology. At present, PE as an electronic manufacturing technology is against traditional electronic manufacturing in order to establish itself on the market as the dominant application. Printed RFID seems to be at the forefront, but its application can now be found in secondary packaging, shipping, and identification of warehouses and pallets. RFID printings, usually in tags, are included as regular tags on packages.

This research study found out that most intelligent packaging elements (labels, antennas, printing polymers) are thin, flexible, and can be printed with all primary printing methods. However, an important question is whether intelligent packaging applications are based on the direct printing of these elements on a substrate or after various inlay processes such as lamination or embossing.

One of the significant findings of this research that will be further discussed are issues that pertain to Printed Electronic Technology integration into the value chain of production, in this case, packaging. As a result, this chapter will discuss Printed Electronics post-printing and fabrication stages that need to be considered in PE integration in intelligent packaging.

5.1 Integration of Printed Electronic Technologies into package manufacturing value chain

Based on research findings, most printed electronic components and devices involve the same manufacturing processes, which often involve functional inks; however, printing techniques and pre-and post-treatment processes may vary depending on the intended application. It is necessary to perfect the interplays that exist between the properties of the chosen conductive ink, such as viscosity and surface tension, properties of the printing substrate such as its roughness, surface porosity, and flexibility, lastly, the printing parameters such as the number of cells and grid for precise control.

5.1.1 Package design

Printed Electronics follows the same principles as traditional electronic fabrication, designed for specific measurements, layout, and publishing software. Schematic diagrams would have to be designed to illustrate the sequential arrangement of each element of the design, the technological design of each fabrication process, and, lastly, the graphic design layer by layer.

5.1.2 Ink preparation

Traditional printing inks are intended and customized to meet specific purposes; hence, conductive inks must be processed to fit requirements. Those ink preparation processes include filtering to remove larger nanoparticles, ethanol extraction through heating, degassing, and chemical crosslinking. Finally, the ink composition is stirred for a certain time to help the chemical composition's physical and performance qualities. For example, silver nanoparticle inks are usually coated with a polymer to prevent agglomerated dispersion that may adversely affect ink binding and backgrounding. However, post-processing is necessary to attain optimal electrical conductivity (Balliu et al. 2018).

5.1.3 Substrate preparation

In order to achieve optimal printability and performance, substrate surface usually should be pre-treated to improve roughness improve, smoothness, prevent excess ink penetration into substrates, and remove foreign particles. This treatment process is essential for paper substrates commonly used in the packaging industry. The substrate preparation process may include the deposition of layers and several coats of cleaning agents and drying afterward. Lack of inadequate or inappropriate pre-treatment can lead to a non-conductive and adhering printing result. It is essential to pre-heat paper and cardboard packaging applications to ensure an efficient printing process and smooth surface and facilitate continuity in creating passive and active layers (Samusjew et al. 2018).

5.1.4 Printing process

PE technology relies on printing and post-treatment of all layers in order. Therefore, a critical part of the printing process is ordering printed layers in succession, forming the electronic elements. Each layer has various electronic, mechanical, and physical functions, making it possible to be divided into dielectrics, conductors, semiconductor transistors, resistors, and capacitors. Antennas and printed circuits are simpler to manufacture. However, it is necessary to archive layer succession in the base layer to ensure the proper formation of the conductive ink layer on which it is printed. In addition, it reduces absorption on the substrate (Sowade 2016).

5.1.5 Post printing process

It is crucial to embark on post-print operations after each printed layer, and the whole elements are fabricated. This is done to ascertain the printing coat, control layer formation, conductivity, general print quality, and other electrical properties. Post-printing processes are usually temperature activities such as sintering, UV curing, UV ozone treatment, photonic annealing, and xenon lamps with heat-sensitive substrates. Therefore, post-print processes depend on the characteristics and sensitivity of the printing substrate (Grau et al. 2014).

6 CONCLUSION

All major printing processes are used for intelligent packaging applications and enable the implementation of printed electronics. However, Printed Electronic Technology is advancing, introducing new substrates, inks and coatings, and printing processes may need to be adopted into the new production environment. It is evident that PE technology has limitations in scalability, mass production, and longevity; they are not yet a complete replacement for conventional electronic technology. However, the technology allows for accessible design, rapid prototyping, and unlimited areas of application, mainly in low-temperature production. PE printing benefits from new printing techniques, solution-based materials, and combinations of other manufacturing processes.

Printed electronics are unlikely to be able to compete with conventional silicon-based electronics in terms of performance, reliability, and the ability to manage complex designs. However, printed electronics opens up new possibilities for applications that are not possible with silicon electronics due to the technology's unique properties. Some of the benefits of printing electronics found in this research are as follows:

- Inexpensive manufacturing compared to traditional silicon-based solutions.
- possibility to print electronics various substrates.
- Easily adapted to the specific needs of the application.
- Production time of printed electronics is much shorter compared with conventional electronics.
- Printed Electronic Technology is scalable with roll- to roll.
- Printed Electronic minimizes waste during production.

Printing Electronic Technology has proven to be a major disruptor with an enormous impact on the electronics industry. It emphasizes various printing technologies, processing requirements, operations, materials, and production constraints. Some of the novel impacts are the technology's flexibility and biocompatibility, which otherwise is impossible to achieve using conventional techniques and materials. , The ability to integrate printing technologies, enabling mass production of devices, circuits, and systems, is presented in the technology. In addition, it is believed that 3D printing plays a crucial role in packaging, but at the present stage, printed electronics suffer from limitations such as operating frequency, scalability, and durability. However, as research in this area continues and improvements are expected to address all these challenges in the near future.

Traditional packaging is primarily designed to contain, protect, store packaged items and communicate product information. Packages always perform the practical function of holding products and securing them within the logistics infrastructure until they reach the end-user. However, this research has been able to establish that logistic firms and package production companies are doing their best to obtain favorable margins derived from efficient packaging. Consequently, the incorporation of advanced technologies into the packaging design depends on the economical disposition of the production process. Printed Electronics, therefore, offer a practical opportunity to produce cheap products in large technology volumes.

PE is a growing technology capable of producing low-cost and large-area electronics through efficient and effective roll-to-roll (R2R) production. Therefore, PE is considered to have the potential to manufacture and participate in sophisticated but inexpensive, lightweight, and flexible electronic packaging design devices to improve the product's user experience. The integration of PE technology with the company's main capacity accelerates technological innovations and innovates or creates new activities in the production process.

Finally, as Printing Electronic Technology and its processes evolve to implement intelligent and interactive packaging applications, the primary challenge lies in the overall possibility of printing the entire system at the same time on the same production line. In the coming years, consumer manufacturers and the general electronics industry will increasingly demand the use of printed electronics technology. This can be attributed to the possibility of built-in printed electronics in any device, object, or shape at an extremely attractive cost. Research advancement in the field and the development of new nanomaterials, substrates, and other materials could be the answer to such ambitions. In addition, those challenges show that the technology is still emerging.

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