Sustainable Food Technology

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Sustainability Spotlight Statement

Considering the global economy, the production of plastics and paper has created a significant surge in the utilization of fossil fuels and forests respectively. The conventional methods of packaging are found to be single-use in nature, more susceptible to damage, and have adverse effect on environment. Thus, production of sustainable food packaging with inbuilt self-healing functionalities is a viable solution in minimizing the reliance on non-renewable resources. Embedding self-healing polymers with smart traceability technologies such as RFID, sensors or QR codes, it can provide real-time information of the food quality and food transparency to customers. Thus, this study completely aligns with UN Sustainable Development Goals (SDG) by reducing food and packaging waste (SDG 2, SDG 12, SDG 13), promotes safe food (SDG 3) and promotes innovative approach in industries (SDG 9).

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Comprehensive Review on Integration of Self-Healing Polymers with Smart Food Traceability: Scope, Application and Challenges

Name of Authors:

Krishna Gopalakrishnan [a], Arnav Bayan[a], **Poonam Mishra [a*]**

Affiliations:

[a] Department of Food Engineering and Technology, Tezpur University, Napaam, Tezpur, Assam, India

***Present address of corresponding Author:** Poonam Mishra is presently, Professor in Department of Food Engineering and Technology, Tezpur University, Napaam, Tezpur, Assam, 784028, India. Email: mpoonam1@rediffmail.com, poonam@tezu.ernet.in

Author Contributions

S.No	Author	Contributions
1	**Krishna Gopalakrishnan**	Conceptualization, Methodology and Writing- Original draft preparation
2	**Arnav Bayan**	Writing-Original draft preparation
3	**Prof. Poonam Mishra (Corresponding Author)**	Conceptualization, Validation, Supervision, Writing- Reviewing and Editing

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Abstract

Food traceability has been a key component in ensuring food safety, quality, and supply chain transparency. The growing global population and increased food demand highlight challenges in ensuring safe food. The invention of smart food traceabilty systems (such as RFID, barcode, blockchain) has been significant milestone in food industry. However, the development of an effective food traceability system is affected by various challenges such as the possibility of susceptible damage or scratches that may occur in food supply chain. The integration of self-healing technologies with smart food traceability systems represents a promising advancement in food technology. This comprehensive review explores various self-healing mechanisms (mostly covalent interactions such as, hydrogen bond, imine bond) utilized in food processing and even discusses developement of self-healing based biopolymers for food applications. It also focuses on the development of photo-cross-linkable polymeric film, self-healable based RFID tags, techniques on electronic tracking using data matrix codes and wireless based detection systems. But, limited studies have been conducted with the use of embedded symbology techniques for food traceability, thereby providing a good scope for future research in this field. This comprehensive review of current technologies offers valuable insights for researchers, manufacturers, marketers, and consumers to develop customized smart food traceability systems that incorporate self-healing functionalities for a wide range of applications.

Keywords: self-healing, biopolymer, food traceabilty, printing, symbology

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1. Introduction

The rapid growth of the global population poses a significant challenge to existing food production and distribution systems. Ensuring the safety, authenticity, and quality of food within increasingly complex supply networks has become a global priority. Recently in food industry, there has been growing emphasis on traceability due to increasing incidents of fraud scandals and food safety incidents. These type of scandals may cause threat to consumer's health, trust and even economic loses[1]. In recognition to these challenges, World Health Organization (WHO) has recently released the 'Global Strategy for Food Safety 2022–2030', outlines comprehensive approach on emerging technologies, new challenges, and innovative approaches to strengthen food safety systems and enhance laboratory facilities for foodborne disease surveillance.

Prominent regulatory authorities, including the United States Department of Agriculture (USDA) and the Food and Drug Administration (FDA), play a pivotal role in overseeing food safety[2]. These agencies are empowered to regulate food products and ingredients, including their labeling, which can help mitigate instances of food fraud. In India, while no mandatory traceability system exists, the government has collaborated with various state, central, and private organizations to develop traceability systems within the food supply chain. Key stakeholders include the Food Safety and Standards Authority of India (FSSAI), GS1 India, the Agricultural and Processed Food Products Export Development Authority (APEDA), Fruit Products Order (FPO), the National Bank for Agriculture and Rural Development (NABARD), Reliance Industries, and ITC's e-Choupal initiative [3]. To advance and transform its food industry and supply chain, India must strengthen its existing national food regulations and establish an efficient traceability framework. Despite the enactment of food safety laws, challenges related to food fraud and contamination persist, continuing to threaten the integrity of the food supply.

Conventionally, traceability data have been obtained through documented records or by measurements performed with various instruments, targeting the physical, chemical, biochemical, molecular, biological, and/or microbiological characteristics of foods[4]. Recently, advancements in digital tracebility technologies produced various smart systems such as Radio Frequency Identification (RFID), blockchain and Near Field Communication (NFC). The incorporation of blockchain technology into food logistics has revolutionized global food marketing and distribution. Blockchain offers a decentralized yet cohesive framework for tracking goods

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throughout the supply chain, addressing critical issues like food recalls and safety [5]. These systems have reduced food losses, increased efficiency and quality, and improved sustainable development. However, current food traceability systems face several challenges, including managing products with multiple ingredients sourced from diverse suppliers, regions, or countries; the inherent complexity and variability of supply chains; and the high costs and technical sophistication of devices required to collect, analyze, and manage traceability data [6,7]. Even due to physical tag fragility, it may lead to damage or loss of traceability data during logistics and handling. Therefore, existing traceability systems still exhibit gaps in linking food chain records, as well as issues with inaccuracies, record errors, and delays in obtaining critical data, which are vital in addressing foodborne outbreaks [8].

An ideal smart food traceability system should address these challenges by enabling an efficient, reusable and cost-effective system which can trace food products (location, ingredients, and packaging) throughout the supply chain from production to consumption [9]. Therefore, developing materials with inherent self-healing capabilities could substantially enhance the reusability and efficiency of physical identifiers. It has the inbuilt ability to restore their structural and functional integrity after sustaining damage. Incorporating self-healing ability into barcodes and RFID enhances reusability, durability, and sustainability within food traceability systems[10]. These materials could significantly reduce costs, resource consumption, and waste in the supply chain. Thus, self-healing technologies is a novel research which complements digital traceability advances and addresses a fundamental technical challenge currently hindering the food industry.

The adoption of a robust traceability systems aligns with several United Nations Sustainable Development Goals (SDGs) by ensuring safer and more reliable food supplies (SDG 2 : Zero Hunger), reducing foodborne illnesses (SDG 3 : Good Health and Well-being), food waste reduction enabled by precise recalls and quality control (SDG 12 : Responsible Consumption and Production) and by fostering technological innovation in supply chains (SDG 9 : Industry, Innovation, and Infrastructure). Additionally, the sustainability dimension of self-healing materials addresses by promoting resource-efficient and reusable packaging solutions (SDG 13 : Climate Action). Thus, these digital traceability systems with the incorporation of self-healing ability represent a significant leap in the direction of attaining the sustainable development goals.

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Despite growing research on blockchain and other digital traceability tools, research based on self-healing materials tailored for food traceability is limited [11]. This work consolidates existing knowledge on advanced traceability technologies (RFID, barcode, wireless technologies) and discusses its challenges. It has discussed the various mechanisms of self-healing and its commonly found applications. Further, it provides critical perspective on the potential application of self-healing technologies within food traceability systems. This review identifies key challenges, and outlines potential avenues for future research in the emerging domain of self-healing and traceability. This review paper will help the future researchers to pave the way for a paradigm shift in traceability systems to move towards a sustainable future.

2. Food Traceability : Significance of it in global economy

Traceability is the ability to access any or all information regarding an item throughout its entire life cycle via recorded identifications [12]. Traceability systems enables food manufacturers to provide a detailed information about their foods (such as the species, geographical origin, and conditions of transport and storage), transparency, and regulatory mandates based on consumers' demand. The food supply chain is critical in ensuring the safety of food products, encompassing stages from farm production to processing, distribution, and retail, ultimately reaching consumers or food service establishments. As complex processing and supply chains are involved in food industry, it breeds many risk points to be controlled.

Foodborne diseases annually impact around 7.7% of the global population (out of 7.8 billion people) and are responsible for 7.5% of worldwide deaths (from a total of 56 million)[13]. It has been reported that 3 out of 10 children under the age of 5 die from foodborne illness. However, due to widespread underreporting to health authorities, the actual burden of foodborne illness remains significantly underestimated. Contamination events occur at various stages of the food supply chain, including processing, distribution, retail, and catering (Food Standards Agency, 2019). Such contamination can lead to outbreaks of foodborne illnesses, posing significant public health threats. Notable incidents, such as the deliberate adulteration of infant formula with melamine in China [14] and outbreaks of *Escherichia coli* contamination linked to Chipotle Mexican Grill restaurants in the United States [15,16], have garnered attention from industry leaders and researchers, prompting detailed investigative studies. These studies reveal the limitations of conventional

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traceability systems, thus an effective food safety management systems is critical to map potential hazards, including physical, biological, and chemical threats. The growing integration of advanced technologies in conjunction with cutting-edge computational and simulation models [17,18,5], offers significant potential to enhance hazard identification throughout the supply chain (Figure 1).

Food fraud is defined as *"a collective term encompassing the deliberate and intentional substitution, addition, tampering, or misrepresentation of food, food ingredients, or food packaging, including false or misleading claims about a product, for economic gain"*[18]. The Food and Agriculture Organization (FAO) identifies three essential elements inherent in all cases of food fraud: intentionality, deception, and the pursuit of undue advantage (FAO, 2021). Buyuktepe et al. (2023) applied explainable AI (XAI) techniques to predict fraud risks using data from the Rapid Alert System for Food and Feed (RASSF) and economically motivated adulteration (EMA) databases[19]. Results showed that data quality strongly affects predictive accuracy, but discrepancies and incomplete reporting remain critical challenges, reinforcing the need for harmonized regulations and interoperable global data platforms.

Food Traceability Systems (FTS) are critical for integrating traceability activities with food logistics and improving communication among supply chain partners. However, the ease of use remains a significant concern. Developing an effective traceability system requires increased engagement from stakeholders, including industry participants, government agencies, and researchers. There is an urgent need to create a smart food traceability system that is user-friendly and capable of enhancing food safety, reducing foodborne illnesses, and ensuring food security. Research efforts should focus on designing and developing specialized smart traceability systems tailored for different food supply chains, utilizing Internet of Things (IoT) technologies, cloud computing, and sensing technologies. The extensive data gathered from critical control points across the food supply chain can be transmitted via the internet to cloud servers for real-time analysis. These technologies can optimize the recall process, reduce associated costs, increase transparency, and enhance the overall quality of food supply chain management by mitigating information asymmetries and strengthening coordination among network partners [20].

Thus rising prevalence of foodborne illnesses and food insecurity highlights the urgent need for the development of advanced food traceability systems that are rapid, accurate, reliable, cost-

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effective, and capable of performing multifaceted analytical functions [21]. Thus an effective food traceability system plays a crucial role in ensuring food authenticity, safety, and quality throughout the supply chain, minimizing risk of food borne illness, fraud and contamination[8,22].

3. Recent Advancements in Food Traceability

The rising incidence of fraud and counterfeiting in the food sector, particularly in high-value products such as ham, wine, cheese, and extra virgin olive oil, has led to significant economic losses, unfair competition, and detrimental impacts on brand reputation [23]. By integrating advanced technologies, tracking, tracing, and identification of products across the supply chain can effectively detect and prevent counterfeiting and fraud. Techniques like barcoding, blockchain technology, RFID, NFC (Near Field Communication), and printed graphic identifiers represent promising and potentially reliable methods for detecting and identifying instances of food fraud. This section provides an in-depth discussion of recent technological advancements that have contributed to improve food traceability.

3.1 Radio Frequency Identification (RFID):

Recent advancements in Radio Frequency Identification (RFID) technology, including the integration of data loggers and sensors, have significantly expanded its application in food traceability systems. RFID tags, particularly those equipped with temperature loggers, enable real-time monitoring and recording of the transportation and distribution conditions of perishable goods. Such insights are crucial for optimizing supply chain logistics, supporting intelligent inventory management practices like the first-expired-first-out (FEFO) approach [2425].

3.1.1 Key Components and Functionality

An RFID system typically comprises three primary components: a reader, a transponder (RFID tag), and an antenna, supported by application software. The RFID tag contains a coupling element and a chip for unique identification, with the antenna facilitating the transmission of radio frequency signals between the tag and the reader [26]. RFID tags are categorized based on their communication mechanism and power source into active and passive tags. Active RFID tags are powered by an internal energy source, such as a battery, which limits their operational lifespan to the battery's capacity. In contrast, passive RFID tags lack an internal power source and instead

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derive their energy from the electromagnetic field generated by the RFID reader. When activated, RFID tags facilitate data exchange by transmitting stored information to the reader, which then processes and transfers the data to a connected computer system for further applications.

3.1.2 Applications in Food Industry

RFID tags are extensively employed in food industry for enhancing product identification and traceability throughout the supply chain for faster recall of unsafe or expired foods [27], monitoring 30 cold chain logistics by recording and transmitting temperature data to safeguard quality of perishable goods [9], and improves automation and efficiency in enterprise management. Tags designed for cold chain logistics often feature enhanced protection against condensation, freezing, or heat, ensuring reliable data transmission and durability in harsh conditions.

A traceability system integrating RFID and IoT sensors was propsed by Alfian et al., 2020, to monitor environmental parameters of perishable foods during transportation and storage[29]. RFID technology was employed to track and identify the distribution of low-quality products along the supply chain, while IoT sensors measured critical environmental parameters. Additionally, the study incorporated a machine learning algorithm based on XGBoost which is used in tandem with RFID gates to distinguish whether goods are shipped or received, optimizing the tracking process. The XGBoost system was used to classify product movement direction and filter out false positive tag reads. Based on previously reported studies, temperature and humidity was found to be important parameters for monitoring agriculture food system[29]. Electronic Product Codes (EPCs) associated with each RFID-tagged item are transmitted through an EPC Information Service (EPCIS) to a host computer, thereby ensuring accurate, secure, and real-time traceability, as shown in trials involving the kimchi supply chain in Figure 2(a).

Similarly another tracebility system i.e., RFID-based Cattle/Beef Traceability System (RCBTS) was developed using a Personal Digital Assistant (PDA) to facilitate real-time traceability management throughout the cattle/beef production process[30]. The system integrates RFID technology, a PDA, and a barcode printer to collect, process, and transmit traceability data across the cattle/beef supply chain. RCBTS provides a comprehensive framework for cattle and beef identification and traceability, covering the entire production flow from cattle breeding to the final product, as illustrated in Figure 2(b). System trials demonstrated that the RFID-based traceability

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system significantly enhanced the automation, efficiency, and convenience in cattle/beef enterprise management.

3.1.3 Challenges in RFID

Eventhough several research studies have been conducted on RFID sensor technology, but still it faces key challenges which include, usage of food safe material, restricted energy harvesting and limited reading range, multi-tag collision, security and privacy risks, recycling issues and high cost[31]. As polymer based sensors were focused on developing sensors with smart functionalities, it lacks food safety credentials. Thus, future research must direct the usage of organic oils and biocompatible conductive inks and dyes as temperature-sensing materials as they do not compromise food safety. Another challenge was found in passive RFID tags as they are limited by their short read ranges and even create signal propagation issues. Functioning of RFID is also compromised by multi-tag collision that can reduce system efficiency, often requiring advanced algorithms such as binary tree or hybrid protocols for reliable identification. RFID also raises risks related to, unauthorized data access, privacy leaks about supply chain information, and tampering of traceability records. Moreover, RFID tags generate waste such as adhesives, chips, pieces of metal and conductive inks which can impact the recycling process of other food packaging[32]. High cost is another concern in RFID technology as the unit price of RFID tags varies from 0.11$ to 0.20$ (USD per unit). Therefore unit price can be lowered by 17-33% [33], improving fabrication techniques and materials such as affordable substrates, metals, and conductive inks are essential to lower tag prices. Further, the current economy emphasizes on sustainable technology, thus recyclable/reusable RFID tags will be beneficial for green economy.

3.2 Blockchain in traceability systems

The implementation of blockchain in food chain applications is still in early stages, but research interest in blockchain technology (BCT) dramatically increased in late 2020s[34]. A blockchain is a distributed database which comprises of orderly blocks that are chained together. Each block works like a ledger to store data. Decentralization is a defining characteristic in blockchain, which enables it to be applied in supply chain management including food supply chain. A study was reported in 2016, where RFID was integrated with BCT in tracking the agri-food supply chain[35]. The model integrates a centralized database for supply chain stages with blockchain for

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environmental data, enhancing transparency in the agri-food sector. This approach ensures food safety, sustainability, and quality while promoting low environmental and social impacts. By integrating food traceability technologies (barcodes, QR codes, RFID, IoT etc.) with blockchain, their effectiveness can be improved and costs reduced[36].

To demonstrate the practical benefits of blockchain-based food traceability systems within actual food supply chains, several companies have developed and implemented in pilot programs. Walmart and Kroger pioneered the adoption of blockchain technology in their supply chain operations, initially focusing on applications for Chinese pork products and Mexican mangoes [37]. The blockchain technology reduced the time required to trace mango sources and transport pathways from farm to retail store in few seconds. However, since each company uses its own system, it becomes challenging to implement a unified traceability system for all stakeholders across the supply chain.

BCT is in its initial stage of developing, therefore it requires great deal of financial assistance in implementing it in supply chain. Moreover as the blockchain network becomes more complex, computational power increases, and a lot of energy is required[36]. Further, BCT is considered to be an immature technology as it is unable to store large amount of data and even found to have negative effect on protecting privacy as all the information about supply chain will be available on distributed ledger [36]. By resolving these issues, it will help BCT to be implemented in real-time scenarios of food supply chain.

3.3 Printed Graphic Identifiers:

Printed Graphic Identifiers (PGIs) are visual barcodes or symbols printed on products, packaging, or documents that enable data storage and automatic retrieval through optical scanning technology. According to the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO), a barcode (1D, 2D, or 3D) is a machine-readable format used for encoding information. It is represented by patterns or regions of varying reflectance on an object's surface, which are interpreted as binary digits ('1's and '0's) by an optical scanner. The scanner transmits the encoded information to a system for storage and processing [38].

Printed Graphic Identifiers (PGIs) provide several advantages, including cost-effectiveness, rapid and accurate machine readability, and support for various symbologies (numeric, alphanumeric,

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and binary), which offer differing levels of error detection and correction. Additionally, PGIs can be produced on durable materials, such as printed media or metals, and are compatible with a wide range of optical scanning equipment [38]. This section examines the different types of PGIs employed in traceability systems.

3.3.1 Linear barcode symbology:

Linear barcodes are among the most widely utilized forms of Printed Graphic Identifiers (PGIs), encoding information in a single dimension through varying widths of parallel light and dark patterns (bars and spaces) [39].These barcodes typically include guard bar patterns at both ends, which assist scanners in detecting the start and end of the code, enabling bi-directional scanning[38]. The operational mechanism of barcodes is analogous to a laser beam scanning a horizontal cross-section of the vertical bars. As the beam moves across the symbol, it measures the relative durations spent on dark bars and light spaces, which are then decoded into individual characters using a lookup table [40]. To prevent data loss from damaged barcodes, 1D barcodes are often paired with corresponding alphanumeric characters for manual readability. Common 1D barcode symbologies include UPC, EAN, Code 39, Code 93, Code 128, ITF-14, Codabar, GS1-DataBar, and MSI Plessey [41], with examples illustrated in Figure 3. The primary advantages of linear barcodes are their simplicity and cost-effectiveness of reader technology. However, their major limitation is low data storage capacity, restricting their role to serving as indices that link to external databases and poor printing quality, such as excessively small sizes or low resolution, can adversely affect readability[42].

3.3.2 Two dimensional (2D) symbology:

Two-dimensional (2D) barcodes, with their higher data storage capacity, can encode significantly more information than their one-dimensional (1D) counterparts by utilizing matrices of geometric patterns such as rectangles, dots, or hexagons [384341]. These barcodes are categorized into two primary symbology types: stacked and matrix. Stacked symbols, such as Code 49 and PDF417, are arranged as rectangular blocks comprising multiple rows, each resembling a linear barcode. In contrast, matrix symbols, including DataMatrix, Maxicode, QR codes, and Aztec codes, consist of arrays of binary (black or white) cells organized in a grid [38]. The 2D barcodes enable high-density information storage within a compact footprint. Notably, Quick Response (QR) codes can store

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even larger volumes of data using four encoding modes: numeric, alphanumeric, byte/binary, and kanji. The decoding process for 2D symbologies requires scanning devices capable of reading data in both vertical and horizontal dimensions simultaneously [44].

3.3.3 Data Matrix (DM) Code:

Data Matrix (DM) codes are commonly used for labeling small items, goods, and documents. These codes can store up to 3,116 numeric characters, 2,335 alphanumeric characters, or 1,555 bytes of binary data [38 45]. The U.S. Electronic Industries Alliance (EIA) specifically recommends DM codes for labeling small electronic components. Similar to QR codes, DM codes exhibit high fault tolerance and rapid readability due to their encoding in a true digital format, which enhances error resistance, even under low-contrast printing conditions. Utilizing the Reed-Solomon error correction algorithm, DM barcodes of the 10 × 10 GS1 size (nominal dot size – 40 µm) can still be recognized despite up to 20% physical damage, a capability absent in traditional barcodes [45].

3.3.4 Application of PGIs in Food Research

The multi-technology integration approach by combining PGIs, RFID, and block chain technologies represent a promising approach in resolvling food traceability issues. A study was proposed by Wahab et al. integrating QR codes and blockchain technology for halal meat traceability [46]. The QR code data consists of origin, breed, rearing and slaughtering conditions. These datas are securely transmitted to the blockchain network at each stage, it maintains a continuous, tamper-proof record of product's journey. The researchers found this dual approach shows positive potential for enhancing transparency, restoring consumer trust, and improving compliance rates. However, limitations were found to be high implementation costs, standardization requirements, and infrastructure needs.

Another study was reported to develop traceability system for fresh tuna loin quality based on various handling temperatures using quick response (QR) codes [47]. Sampling involved selection of 19 respondents and detailed procedures for temperature-monitored collection, processing, and statistical analysis using One-Way ANOVA, supplemented by the design and expert validation of a QR Code traceability system. The research validated QR code effectiveness for accessing real-time quality information, with laboratory testing confirming compliance with Indonesian national standards for histamine content, Total Plate Count, and Salmonella detection.

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3.3.5 Limitations of PGIs

Despite their advantages, Printed Graphic Identifiers (PGIs) have notable limitations. Linear barcodes offer low storage capacity, typically below 100 characters, while even Data Matrix codes are capped at 2335 alphanumeric characters. Additional drawbacks include dependence on specific symbologies and the requirement for line-of-sight readability. Barcodes must be scanned individually and often rely on manual tracking, making them prone to human error. Moreover, their machine readability is significantly compromised if symbols are damaged by adverse environmental factors such as moisture or mechanical abrasion.

4. Different approaches to self-healing and its integration into food traceability

The accidental damage in the material is self-healed with different approaches, including physical, chemical, or physicochemical processes. This section discusses the classifications of self-healing mechanisms and details the different processes involved in self-healing mechanisms. Further discusses, the self-healing mechanism in printing technology for food traceability using printed graphic identifiers.

4.1 Mechanism of self-healing

Self-healing mechanisms can be generally classified into: extrinsic and intrinsic, wherein extrinsic mechanism requires the presence of healing agent which is incorporated into the matrix to heal the damage and intrinsic mechanism mainly takes place with the help of external stimuli (UV, heat, or relative humidity). These intrinsic mechanisms are crucial for modern food packaging, enabling materials to repair themselves and maintain barrier integrity, mechanical properties, and ultimately food quality and safety.

In food packaging, self-healing materials are developed using dynamic covalent and dynamic non-covalent interactions. Dynamic non-covalent bonds have a lower mechanical strength, but can heal a material with little to no energy consumption at ambient temperature [48], whereas covalent bonds exhibit higher stability and bonding usually occurs in the presence of external stimuli (force, light, and heat) (Liu et al., 2020). Some typical dynamic covalent and non-covalent bonds used in self-healing has been discussed and depicted in Figure 4(a).

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4.1.1 Dynamic non-covalent interactions

Dynamic non-covalent interactions consist of hydrogen bonding, dipole-dipole interaction, electrostatic interaction, hydrophobic interactions, van der Waals interactions, and ionic interactions, these interactions can be incorporated into diverse biochemical and chemical processes (Table 1). These interactions provide a great deal of flexibility and reversibility which is affected by pH value, molecular density, light irradiation, and temperature(Song et al., 2021).

4.1.1.1 Hydrogen bond

Hydrogen bonding is the strongest non-covalent interaction, occurring mainly between hydrogen and highly electronegative atoms such as fluorine, nitrogen, and oxygen. It plays a vital role in protein-ligand interactions, protein stability, and self-healing polymers based on chitosan, carrageenan, proteins, and starch. In polymer matrices, hydrogen bonds influence self-healing efficiency, with bond energies ranging from 5-30 kJ mol^{-1}, much weaker than covalent bonds (~345 kJ mol^{-1}) [51], but quickly restores once broken.

The cellulose structure has abundant hydroxyl groups exposed, which has an innate ability to facilitate hydrogen bonds. PVA (Polyvinyl alcohol) is a suitable candidate for binding with cellulose using hydrogen bonds as it has abundant hydroxyl moieties which contribute to better self-healing ability [52]. Numerous research demonstrating the self-healing properties of PVA and cellulose-based hydrogel have been published. According to a study by Liu et al., the mechanical properties of nanocomposite hydrogels were improved by the electrostatic interaction of cellulose nanocrystals (CNC), quaternary ammonium xylan (QAX), and an adequate amount of PVA (20 wt%). With the aid of hydrogen bonds and the entanglement of lengthy polymer chains, a cellulose-based optimized weight ratio of PVA and CNC to 60:1 produced a self-healing efficiency of 37.03% at room temperature without the need for any external stimulation (Li et al., 2021). However, hydrogen bonds are found to have weaker strength, and the self-healing materials made from hydrogen bonds exhibit weaker mechanical properties. Therefore, cross-linking agents can be used to improve mechanical strength. For example, the fabrication of a hydrogel with non-cytotoxic and antibacterial qualities using aluminum (III) ions (Al^{3+}) and carboxymethyl chitosan nanoparticles (CMCS NPs) to crosslink with polyacrylic acid (PAA) chains through triple dynamic non-covalent interactions (hydrogen, coordination, and electrostatic interactions) was used to study the synergistic effect of multiple non-covalent mechanisms. This mechanism of strong

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bonding achieved desirable mechanical property (fracture elongation of 1930%, fracture strength of 190.9 kPa) and self-healing ability (98.8% of strain, healing efficiency 92.9% of stress, 25 °C, 24 h of healing), which is not visibly affected by surface erosion or aging (e.g. alkali, salt solutions, and acid) [54].

4.1.1.2 Ionic interactions

Carboxypyridyl zwitterion, thiobetaine, or imidazolium ions are common structures found in self-repairing materials that rely on ionic interactions (Li et al., 2021). The ionic interactions in amphiphilic ions occurs due to unique water sensitivity, which dissociates negative and positive ions under humid conditions. The associations between positive and negative ions are reformed with the application of heat and drying treatment for the processing of self-healing material. In the case of thermal transition like glass transition or melting transition, the amphiphilic ions will reform from water-sensitive weak dynamic non-covalent bond to permanent network. Recently, reversible ionic interaction and H-bonding have also been used to produce the self-healing capabilities of zwitterionic polymers. A study was reported on novel zwitterionic multi-shape-memory polyurethanes (ZSMPUs) from thiobetine which is based on *N*-methyldiethanolamine (MDEA), hexamethylene diisocyanate (HDI) and 1,3-propanesultone (PS) (Chen et al., 2015). The thiobetaine forms an ionic bond with permanent dot of polyurethane, and the glass transition temperature of the polymer act as molecular switch to exhibit shape-memory properties. Additionally, because amphoteric ions are sensitive to water, PU films that were split into two sections successfully rebonded into a single piece at 30°C and 80% RH, though a visible healing interface remained. However, after drying at 50 °C for 2 hours, the interface disappeared entirely, and the tensile strength and fracture strain of the repaired PU film were comparable to those of the original. Similar study related to polyurethane elastomers (PU-n) was reported, where tertiary amine groups and carboxyl groups were introduced to PU-n and it formed H-bonds and intermolecular ionic interactions. This contributed to the formation of microphase separation structures which resulted in a maximum tensile strength of 20.61 MPa and toughness of 59.02 MJ/m^3 [56]. The self-healing ability of PU-n occurs at room temperature and is significantly accelerated by water, as the dissociation of hard phases enhances molecular mobility as depicted in Figure 4(b). Following self-healing with water, increased molecular movement and further ionization of ionic groups strengthen hydrogen bonds and ionic interactions, leading to more

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pronounced microphase separation. Consequently, mechanical strength improves, and the self-healing efficiency reaches 104.72%. In ternary polymeric complexes of branched poly(ethylenimine) (bPEI)/poly(acrylic acid) (PAA)/poly(ethylene oxide) (PEO), the combined effect of hydrogen bonds and ionic interactions has been found to produce exceptionally high tensile strength (27.4 MPa) and self-healing efficiency (96%) at ~90% relative humid conditions at room temperature [57] as depicted in Figure 4(c).

4.1.1.3 Host-guest interaction

According to Huang and Wang, the physical insertion and combination of the guest and host moieties results in host–guest interaction [58]. It results from hydrophobic interactions as well as the complimentary size and shape characteristics of the host and guest molecules. Crown ethers, cyclo-dextrin (CD), cucurbiturils, cuproaromatics, and so on are examples of common host molecules (Li et al., 2021). CD is used extensively because it is non-toxic, simple to produce, and contains a hydrophobic cavity to bind hydrophobic guests. Self-healing characteristics are demonstrated by the dynamic interactions between the host and guest molecules. Because it is easy to synthesize, cyclodextrin is frequently utilized as a host molecule and structurally resembles cyclic oligosaccharide with a cavity (Li et al., 2021). Adamantine, ferrocene, and 1-menthol are examples of guest molecules that can interact with cyclodextrins in a host-guest manner. It was discovered that the damaged coated region expanded under the external action of water, which self-healed within 20 minutes after β-CD grafted chitosan (CD-g-CS) was immobilized with 1-menthol through host-guest interactions [59]. The self-healing effectiveness of l-menthol-containing coatings was found to be 59.49%, roughly 13.18% greater than that of the control coatings.

4.1.1.4 Electrostatic Interactions

Another effective non-covalent interaction is reversible electrostatic interactions to form self-healing films, aerogels, and hydrogels. It is initiated between charged ions and polymers, polyampholytes, zwitterionic fusions, and, polyelectrolytes. Layer-by-layer (LBL) assembly of polydopamine (PDA) and sodium alginate (SA) results in polyelectrolyte multilayer (PEM) films with the self-healing ability [60]. In this study, (PDA/Alg)m PEM multilayer films were supplemented with nanocapsules made from chitosan and capsaicin (CAP). After mechanical scratching, the ions penetrate and free chains transfer in artificial seawater solutions, demonstrating self-healing characteristics in the electrostatic interaction between Alg and PDA [60].

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Itaconic acid (IA), which is negatively charged, and positively charged chitosan (CS) were assembled to generate self-healing biomass aerogels [61]. The aerogel showed excellent mechanical strength and a very quick rate of self-healing properties because of its very high electrostatic interaction. Upon disintegration, the aerogel restored its mechanical functionality and structural integrity in 30 seconds at room temperature by wetting the disintegrated surface.

4.1.1.5 Metal Coordination Bond

Metal coordination bonds have a substantially higher binding energy than other non-covalent bonds. One benefit of metal coordination bonds is that they are easily bindable, adaptable, and dynamically reversible. In order to produce a reversible supramolecular structure and accomplish a self-healing function, this process introduces a metal ion into a polymer matrix through coordination between metal ions and organic ligands[62]. Hussain et al. (2018) reported a study where Fe^{3+} can be loaded onto a network of polyacrylic acid (PAA) and hydroxyethyl cellulose (HEC) to fabricate self-healing hydrogel[63]. Due to hydrogen bonding, the polyacrylic acid and ethers possess abundant carboxyl groups, and the hydroxyl groups on the hydroxyethyl cellulose offer a significant amount of mechanical strength. The synergistic action of ion-dissipative coordination bonds between Fe^{3+} and the carboxylic group of acrylic acid, in addition to hydrogen bonds, helps to increase the mechanical strength of hydrogel materials. If hydrogel breaks, the free Fe^{3+} ions diffuse to the vicinal interface, where they interact with the oxygen in the HEC backbone and the carboxyl groups of the PAA network. High tensile strength (1.35 MPa), widespread fracture strain (1660%), high toughness (8.8 MJ m^{-3}), and exceptional self-healing efficiency (87%) were demonstrated by the HEC/PAA-Fe^{3+} hydrogel without the need for external intervention [63]. According to another study, a high-performance elastomer has been developed by stronger Zn–triazole coordination into an unvulcanized cis-1,4-polyisoprene (IR) matrix and employing several weaker hydrogen bonds, as illustrated in Figure 4(d). The elastomer achieves good healing efficiency of 72% at 80 °C and good mechanical characteristics of 21 MPa (Liu et al., 2017).

4.1.2 Dynamic Covalent Interactions

Dynamic Covalent polymer network provides the self-healing mechanism by providing sufficient energy in the form of irradiation or heat or by an increase in the change of reactants, e.g. the

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condensation reactions [65]. This bond provides excellent solvent stability and thermal stability. Summary of dynamic covalent interactions is enlisted in Table 2.

4.1.2.1 Imine bond

Imine bonds, which are reversible covalent bonds, are formed through the facile condensation of aldehydes or ketones with primary amines. The variation in aldehyde and amine groups within the material influences the strength of covalent interactions and the self-healing properties of the resulting hydrogels. Liu et al., (2020) synthesized a chitosan hydrogel crosslinked with dialdehyde debranched starch (DADBS) via dynamic Schiff-base linkages between aldehyde groups in DADBS and amino groups in chitosan[66]. This hydrogel demonstrated rapid gelation within 30 seconds and exhibited excellent self-healing capabilities. The mechanical properties of such hydrogels can be controlled by adjusting the reaction temperature and the molar ratio of aldehyde to amino groups. Similarly, Xu et al. fabricated self-healing hydrogels using chitosan and natural vanillin as cross-linking agent. Chitosan was dissolved in aqueous acetic acid (5% w/v), is mixed with different concentrations of vanillin dissolved in anhydrous alcohol. It was found in the study that 0.3g of vanillin gelated with 5% chitosan solution in 6 minutes and demonstrate optimal self-healing of around 5h without tackiness or overly rigid structure. In this system, the self-healing ability was primarily attributed to the reversible formation of Schiff-base bonds, while hydrogen bonds provided stability at room temperature. An optimal aldehyde-to-amino group ratio of 7:1 was found to balance self-healing efficiency and mechanical performance[67]. Another study was reported in which hydrogels were synthesized from gelatin and green tea. It exhibited self-healing properties due to the synergistic effects of covalent (Schiff-base and imine bonds) and non-covalent (hydrogen bonding) interactions[68]. The study involves development of self-healing hydrogel by oxidizing green tea polyphenols with sodium periodate and crosslinking them with gelatin in aqueous solution under alkaline conditions and these interactions contributed to a self-healing efficiency of 53.4%, which could heal in 2h. These studies underscore the critical role of dynamic covalent bonds and non-covalent interactions in designing hydrogels with tunable mechanical properties and self-healing capabilities.

4.1.2.2 Acylhydrazone bond

Acylhydrazone bonds are formed through the reaction between aldehyde and hydrazine functional groups under mildly acidic conditions (pH 4-7) or via catalytic environments at elevated

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temperatures. These bonds exhibit greater stability than imine bonds [58]. Chen et al. reported the synthesis of a degradable hydrogel in a mild $NaHCO_3$ solution by cross-linking poly(N, N-dimethylacrylamide-stat-4-formylphenyl acrylate) [P(DMA-stat-FPA)] with pectin acylhydrazide (pectin-AH) (Chen et al., 2021). This hydrogel demonstrated self-healing properties attributed to dynamic phenolic and acylhydrazone bonds and featured a microporous structure conducive to controlled drug release. Qiao et al. designed a self-healing hydrogel using dialdehyde-terminated polyethylene glycol (PEG–CHO) and adipic dihydrazide-modified alginate (ALG-ADH), which provided aldehyde and hydrazide functional groups, respectively, to facilitate dynamic acylhydrazone bond formation [70]. This hydrogel achieved a self-healing efficiency of 84.4% within 6 h under ambient conditions, driven by the reversibility of acylhydrazone bonds and multiple hydrogen bonding interactions.

4.1.2.3 Diels-Alder (DA) reaction

The Diels-Alder (DA) reaction, a click electrocyclic process between conjugated diene and dienophile pairs, is characterized by its excellent selectivity, high yield, and minimal side reactions. Despite its advantages, self-healing mechanisms based on the DA reaction often require prolonged durations and elevated temperatures to be effective. For instance, bio-derived block copolymers (BCPs), such as poly(lactic acid)-block-poly(2,5-furandimethylene succinate) (PLA-b-PFS), utilize furan groups in the PFS block for crosslinking with bis(maleimide) triethylene glycol, as demonstrated[71] by Cai et al., 2019. These materials achieved over 50% self-healing efficiency at room temperature within five days at lower crosslinking densities, while optimized crosslinking enabled 96.3% efficiency in just 5 min at 30°C. Moreover, integrating the DA reaction with other reversible interactions has been shown to improve self-healing properties. For example, Li et al., (2021) reported the development of hydrogel composed of furan-modified pectin and maleimide-modified chitosan exhibited a two-step self-healing mechanism: initial electrostatic interactions followed by DA-based network formation[73]. In the study, pectin was chemically modified with furfural to introduce conjugated diene groups, and chitosan was modified with 6-maleimidocaproic acid to provide dienophile sites. The hydrogel produced displayed outstanding self-healing properties in mild conditions and was able to support a load of 500 g without sustaining any damage. The healing analysis was conducted for 5 h at 37ºC, within that time the two pieces joined seamlessly.

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4.2 Self-healing based biopolymers in food packaging application

Food packaging materials are susceptible to damage during logistics and transportation, potentially compromising food quality[62]. Incorporating self-healing properties into these materials enables the restoration of functionality after damage, thereby reducing maintenance costs and enhancing the reliability, safety, and service life of polymeric materials[72].

4.2.1 LbL based self-healing films

The layer-by-layer (LbL) fabrication of polyelectrolyte multilayer films (PEMs) is a proven strategy to impart self-healing ability using various interactions, including π-π interactions, hydrogen bonding, host-guest interactions, and covalent bonding [74]. For instance, an edible PEM coating fabricated from chitosan (CS) and carboxymethyl cellulose sodium (CMC) via electrostatic deposition exhibited self-healing functionality driven by ionic bonds (COO^- and NH_3^+) and hydrogen bonding (Liu et al., 2017). This coating achieved an 87.4% self-healing efficiency and demonstrated effectiveness in preserving fresh-cut apples, highlighting its potential in fresh-keeping applications.

Similarly, coatings developed using host-guest interactions through LbL assembly involved alternating layers of carbon nitride (C_3N_4), poly(ethylenimine)-β-cyclodextrin (PEI-β-CD), and poly(acrylic acid)-adamantanamine (PAA-AD) [76]. Ultrasonication facilitated a homogeneous suspension of PEI-β-CD-C_3N_4 and prevented C_3N_4 agglomeration. These coatings, applied to bananas, effectively inhibited ethylene production or degradation, supporting their use in fresh-keeping packaging. Additionally, a study demonstrated the application of LbL assembly to create an edible coating using chitosan (CS) and sodium alginate (SA). The coating self-healed within 5 minutes upon water stimulation and exhibited recovery rates of tensile strength (19.89 MPa), oxygen permeability (95%; 4.78 ± 0.82 cm³/m²·day·atm), and water vapor permeability (63%; 40.56 ± 7.60 g/m²·day) (Du et al., 2021). Furthermore, this $(SA/CS)_3$ coating effectively delayed strawberry deterioration, emphasizing its potential in food preservation.

4.2.2 Structural modification based self-healing films

The enhancement of self-healing and functional properties of polymers and films through the incorporation of specific additives and structural modifications, has been reported in numerous

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studies. Recently a study was conducted to fabricate films from banana peel by incorporating emulsified beeswax. The emulsified beeswax was mechanically agitated with an iced alkaline urea solution of LiOH/urea (7 and 12 %, respectively). The results showed that aminolysis treated films enhanced the self-healing efficiency (~77 %) of the films[78]. The aminolysis treatment was provided by introducing NH_2 groups using 1,6 hexane diamine on cellulose-based matrix of banana peel based film. Even the results showed that aminolysis had betters printabilty property as it enhanced surface morphology with a better water contact angle for better ink absorption and higher surface energy.

For instance, a self-healing, mechanically robust polymer, poly(ether-thioureas) (PETU), was blended with small amounts of commercial cationic antibacterial agents such as poly(ethylene imine) (PEI) or cetyltrimethylammonium bromide (CTAB). These additives improved both the self-healing efficiency and mechanical robustness of PETU while effectively eliminating *E. coli* (Gram-negative) and *S. aureus* (Gram-positive) on its surface [79]. Another innovation involved multilayer films created via alternate deposition of polyacrylic acid (PAA) and PEI polyelectrolytes by robotic dipping system at ambient conditions. These films exhibited high glass transition temperatures, superior elastic modulus, and exceptional oxygen barrier properties. An eight-bilayer PEI/PAA film demonstrated a complete restoration of its oxygen transmission rate (OTR < 0.005 $cm^3\ m^{-2}\ d^{-1}\ atm^{-1}$) after ten stretching-healing cycles, achieving self-healing in high-humidity environments (>97% RH) within 10 minutes[80].

A study was conducted to develop cellulose-based films by dispersing natural wax emulsions into an iced alkali-urea aqueous solution containing dissolved cotton linter pulp to create a uniform cellulose-wax suspension. The self-healing was analyzed through annealing at 150°C as it allowed wax to migrate over the film surface and thereby enhancing self-healing without compromising mechanical strength (122 MPa) for about 10 scratching/annealing cycle[81]. These films exhibited increased water resistance (contact angle of 120°) and flexibility (11%). Similfor about 10 scratching/annealing cyclesarly, soy protein isolate (SPI)-based films combined with PEI (polyethyleneimine) and metal ions (Cu^{2+} or Zn^{2+}) demonstrated superior self-healing and antibacterial properties. In the study, SPI/PEI solution was uniformly dispersed and $CuSO_4$ or $ZnCl_2$ solutions were added dropwise under stirring for 8h. PEI's highly branched structure and abundant amine groups enhanced mechanical strength by disrupting SPI's ordered structure and forming extensive hydrogen bonds. The addition of Cu^{2+} further improved coordination bonds and

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antimicrobial activity, yielding tensile strain and stress of 81.78% and 10.09 MPa, respectively, which were recovered to 90.17% and 105.57% after self-healing at 25°C for 10 h [82] (Figure 5(a)). Low-temperature self-healing has been achieved using cellulose nanocrystals (CNC), hexamethylene diisocyanate, and dibutyltin dilaurate. Dynamic hydrogen bonding and metal-ligand covalent coordination conferred a rapid self-healing rate (99% within 1 h at 5°C) along with excellent mechanical properties, including high elongation (230%), toughness (2538 MJ/m³), tensile strength (25.49 ± 0.02 MPa), and thermomechanical stability [83] (Figure 5(b)). The self-healing mechanism of cephalopods has been emulated using ion doping and nanoclay complexation to create a coating capable of rapidly repairing surface scratches in water. By incorporating $CaCl_2$-derived counterions and montmorillonite nanobricks into polyelectrolyte multilayers through layer-by-layer self-assembly, the non-covalent polymer network was enhanced[84]. The strong electrostatic interactions between ions and nanoclay improved polymer chain mobility, enabling complete surface repair of scratches within 10 seconds.

4.2.3 Challenges in Large-Scale Implementation

Analysing the research conducted on bio-based self-healing films, it highlights the challenges in implementing on a commercial scale. Chitosan/CMC based polyelectrolyte multilayer coatings faces hurdles related to cost and scalability. The precursor such as PEI and 1,6 hexane diamine are beneficial in enhancing self-healing efficiency but not a sustainable solution, as they are not suitable to be in food contact. Moreover, as the films are developed from synthetic or non-biodegradable material, it raises environmental concern. Similarly, host-guest interaction-based LbL coatings, although effective in extending fruit shelf life, it also confronts biocompatibility and regulatory hurdles concerns.

Across these different systems, a recurring challenge is balancing functional enhancement, environmental sustainability, consistent performance under real-world logistics, and consumer acceptance. Especially, as biopolymers rely on additives such as wax or surface modification (aminolysis). Therefore, these studies emphasize that achieving robust self-healing films in food packaging not only requires innovation in material design but also have to focus on resolving interconnected issues of cost, regulatory compliance, processing, and consumer safety. These factors must be resolved for the transition from laboratory innovation to reliable, cost-effective commercial technologies in the food industry.

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4.3 Self-healing based inks utilized in 3-D Printing for food traceability application

The 3D printing technique, formally known as additive manufacturing (AM), is a fabrication method that builds objects layer by layer from raw material, contrasting with subtractive manufacturing processes, such as machining, which remove material to create objects (ASTM, 2012). This method minimizes waste by utilizing only the exact amount of material required for production, thereby reducing costs and conserving resources [86].

Additive manufacturing of smart materials facilitates the production of highly customizable printed components, with applications spanning soft robotics, shape-memory actuators [87], advanced soft machines [88], tissue engineering, and biomedical devices (Gao et al., 2016). Commonly employed 3D printing techniques include Vat Photopolymerization, Material Extrusion, and Powder Bed Fusion [90]. A study was reported to develop photoreactive resins with varying amounts of thermally reversible Diels–Alder cross-linkers for high-resolution stereolithography 3D printing [91]. By optimizing the dynamic cross-link content, specifically polyacrylate network of 1.8 mol %, achieved an excellent balance of 99% self-healing efficiency and strong shape stability after thermal repair, enabling durable, reprocessable printed materials suitable for sustainable manufacturing applications.

In additive manufacturing, incorporating Covalent Adaptable Networks (CANs) has established a novel paradigm for creating smart materials with self-healing and shape-memory capabilities.. Printed objects with dynamic covalent adaptable networks can self-repair under specific stimuli such as light, temperature, or pH changes, while remaining stable under ambient conditions [92]. These networks exhibit either associative or dissociative behavior. Recently, a research was reported on the development of polyhydroxyurethane (PHU) based luminogens which exhibited shape memory, fluorescence and rapid self-healing properties [93]. The PHU based paper composites samples were synthesized using catalyst-free reaction between bis(6-membered) cyclic carbonates and amines at room temperature, followed by thermal curing at elevated temperatures (90–105°C). Further fluorescent patterns were encoded using light-mediated ink-free screen printing. Due to the presence of polyfunctional cyclic carbonate and amines, it exhibits programmable fluorescence, shape memory, and rapid self-healing (over 95% healed in 30s at 160°C) due to thermally triggered transcarbamoylation reactions. These embedded patterns are erasable and

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temperature-sensitive fluorescent patterns suitable as anticounterfeiting labels in food traceability applications.

4.4 Self-healing integrated food traceability technologies

4.4.1 Embedded Symbology Technique to Enhance Food Traceability

Food traceability has been made simpler for primary agro-food with the usage of identification labels such as serial numbers or bar codes which are attached either to the packaging or product. TRU (Traceable Resource Unit) is an important component for implementing a traceability system [94]. It contains unique and precise data that accompanies TRU throughout the supply chain [12]. Various identification technologies are used to identify different TRUs which include RFID and barcodes [44]. Embedded symbology technology helps to imprint QR codes/bar codes onto food products, thereby acts as a carrier of the product information and helps in sustainable traceability. Even though this technology is an environmental friendly process, it is sensitive to harsh environments and thereby susceptible to scratches and cuts. Thus, developing a self-healing property-induced embedded symbology technology can be considered as a solution to this limitation.

Limited studies have explored the use of embedded symbology techniques for food traceability. Barry et al. (2010) investigated the potential application of electronic tracking in poultry by inkjet printing Data Matrix (DM) barcodes directly onto the beaks of broiler chickens in a live commercial environment [45]. The study aimed to identify a commercial ink capable of producing a durable barcode resistant to physical abrasion, as part of an integrated individual animal traceability system in a commercial setting. In the initial attempts barcodes printed very well with 100% readability within a period of 10s. However, after two days, it was found in visual inspection that the complete structure of the barcode eroded as shown in Figure 6(a). It appears that the hard keratinous surface of the beak did not support the retention of any commercially available ink types, even under the gentlest abrasive conditions such as preening. Thus, the abrasion on the barcode may make it unreadable, therefore this study proposes future scope in developing an ink that may adhere to the beak and self-healable inks can be a solution.

Recently a method was developed that utilizes 3D printing to embed information inside the food, and a decoding system has to be used to decode the information inside 3D printed food using backlight illumination and a simple image processing technique[95]. A cookie dough was used as

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target food to be embedded with a edible tag using black colour food grade material. This study determines a way to embed edible tags, whether with air space inside the food or with secondary materials, and to generate a specifc pattern inside the food without changing the food geometry or by adding any artificial materials to food. While the proposed study represents a novel approach to address durability limitations in embedded symbology systems, but there is a constraint in the application to meat due to shrinkage in post processing. This compromises the readability and scanning accuracy of embedded identification tags in meat based products.

Another study explored the feasibility of printing on starch-based films for potential applications. Corn and potato starch films were developed using 50% glycerol, and Quick Response (QR) codes, text, and pictograms were overprinted using inkjet printing [96]. Results demonstrated that both types of films exhibited good print quality, with the overprinted QR codes being readable on smartphones. However, while potato starch films displayed higher optical density, the quality of lettering and sharpness was observed to degrade compared to corn starch films. Print quality was evaluated using image analysis, colorimetric parameters, and optical density measurements. The optical densities of potato starch films (1.61 ± 0.06) and corn starch films (1.46 ± 0.06) were significantly higher than those of conventional paper. These findings highlight the potential of starch-based films as modern, environmentally friendly packaging materials, capable of achieving high-quality printing. Further investigations could explore their applications in the food industry.

The application of barcoding technology can also serve to mitigate counterfeiting, which incurs significant financial losses for governments and private industries annually. As a potential solution, a study explored the use of lanthanide-doped β-$NaYF_4$ nanoparticles for security printing applications [97]. The ink formulation incorporated β-$NaYF_4$ nanoparticles doped with Yb^{3+}/Er^{3+} and Yb^{3+}/Tm^{3+}, with oleic acid serving as a capping agent, dispersed in toluene and methyl benzoate, and stabilized using poly(methyl methacrylate) (PMMA) as a binding agent. This ink was utilized to print Quick Response (QR) codes via Optomec's direct-write aerosol jetting technique. Enhanced security was achieved by combining green and blue upconverting inks, derived from Er^{3+}/Yb^{3+} and Tm^{3+}/Yb^{3+} pairs, respectively, within a single QR code, as shown in Figure 6(b). The printed codes were invisible under ambient lighting conditions but could be activated using a near-infrared (IR) laser and scanned with a smartphone. This research highlights

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the development of security inks for QR code printing, offering potential applications in secure information sharing and anti-counterfeiting measures.

A self-healing, photo-cross-linkable polymeric film was developed using poly(ethyleneimine) (PEI) and photoreactive poly(acrylic acid) (PAA) assembled through a layer-by-layer (LbL) interaction, forming $(PEI/PAA\text{-}N_3)_{10}$ structures [98]. This material exhibits dynamic surface which allows smart labeling pattern of 2D barcodes with distinct color contrast, which can be reliably scanned CortexScan barcode reading application on a smartphone. The films remain stable for at least one year under standard temperature and humidity conditions. When subjected to abrasion with sandpaper, the barcode patterns became fuzzy and unreadable as shown in Figure 6(c). However, in a 100% relative humidity (RH) environment, the film's macroscopic appearance and machine readability were effectively restored. This recovery was attributed to the stable covalent network developed within the cross-linked regions, which restricted the mobility of most polymer chains. These embedded symbology technique show promising potential for use in food traceability systems, the summary of self-healing based embedded symbology has been enlisted in Table 3.

The integration of self-healing embedded symbology into food traceability systems offers substantial sustainability benefits across economic, environmental, and social dimensions. As reported in the research, self-healing systems frequently employ highly corrosive reagents (such as PEI, acrylamide derivatives), harsh organic solvents, and photoreactive initiators that exhibit significant ecotoxicological risks. Therefore future research must be focused on development of biodegradable material with intrinsic self-healing polymeric coatings. This lowers the overall ecological footprint of supply chains. Self-healing mechanisms extends the functional lifespan of identification tags, decreasing the frequency of reprinting and material consumption, which in turn reduces energy use and carbon emissions associated with label production and replacement. Collectively, self-healing technology aligns with global sustainability goals by employing biopolymers in agro-food systems.

4.4.2 Wireless-based detection technologies

Wireless-based food safety detection systems utilize devices that collect data on food properties and wirelessly transmit this information for further analysis. This technology eliminates the need for additional circuits, enabling the wireless transfer of data in both active and passive modes [99].

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Wireless Sensor Networks (WSNs) possess key features such as self-configuring, self-organizing, self-diagnosing, and self-healing capabilities [100], making them advantageous for mobile and user-friendly food safety detection.

Wireless Sensor Networks are interconnected through gateways and coordinating devices, which monitor the physical and environmental conditions of the system. Each node in the network contains one or more passive or active sensors that communicate with each other to transmit data to a server computer that manages the entire network [101]. Common technologies and communication protocols employed in WSNs include Bluetooth and Wi-Fi for physical and Media Access Control (MAC) layers, and ZigBee and 6LoWPan for network, security, and application layers [101]. A study involving a farm-to-fork project combined RFID technology with WSNs for wine traceability, tracking the product from vineyard to consumer glass [102]. In the pilot study, ZigBee protocol was deployed in vineyard to monitor environmental parameters. The datas were collected in databases and consumers will be able to retrieve information using RFID/NFC/QR code. By integrating RFID and sensor network technologies, this system enables the precise recording of a food product's history, allowing Small and Medium-sized Enterprises (SMEs) to optimize business processes and maximize returns. Additionally, it enhances consumer confidence and producer margins by demonstrating the quality and freshness of the product.

Self-healing technology has the potential to revolutionize the electronics and wireless based sensors by developing a system with soft, elastic and ultra-comfortable structures [103]. Recently, the development of flexible and self-healing electrodes has enabled wireless-based detection to monitor food safety [6]. Pournoori et al., (2024) reported to design a multiphase-heterogenous blend for UHF RFID tag which has the ability to autonoumsly repair any micro-scale damage [103]. It consist of conductive network (PEDOT (Poly(3,4-ethylenedioxythiophene)-rich nanaofibrils) which is a multiphase, self-healing elastomer matrix, achieving conductivity of approximately 150 S/m. Thus, PEDOT polymer can reorganize itself to restore both conductivity and mechanical integrity, if any damage has occurred. This work aims to fabricate the proposed self-healing RFID antenna, which has a huge potential in the industry.

5. Future Scope and Challenges

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The conventional techniques in food traceability have become outdated in this current digital era and further advancements require the usage of blockchain, AI, IoT and big data. These advanced technologies can enable digital, intelligent, and real-time food traceability systems to improve food authenticity, quality, and safety, and prevent food fraudance and reduce food waste. For instance, numerous studies have highlighted the advantages of combining IoT and blockchain to improve traceability [104]. The research was mainly conducted in aquatic animals in cold chain logistics. The results ensured integrity and accuracy of data, tamper-proof and improved customer's trust. Therefore, IoT can be combined with other smart traceability tools like RFID,WSN, barcode to improve efficiency of traceability system. Blockchain has also received research attention as a promising technique to ensure safety and prevent fraud. However, consumption of large amounts of energy, high implementation costs, latency, and scalability compromise the functioning of blockchain[4]. AI has a potential to enhance digitalization and automation, detect adulteration and food fraud, while big data helps to enhance food quality and safety and improve decision-making. Thus, integration of AI based technologies has a greater potential to enhance food traceability real-world scenerios.

Integrating self-healing capabilities into digitized food traceability systems promises to reduce maintenance costs, extend operational lifespans, and bolster reliability across diverse supply-chain applications. As regulatory frameworks increasingly emphasize transparency and sustainability, self-healing materials are capable of autonomously repairing sensors, labels, and packaging films which has the ability to enhance the resilience of next-generation traceability platforms. Nevertheless, widespread adoption of fully digitized traceability faces persistent barriers: high implementation costs, poor compatibility with legacy industrial processes, and a shortage of technical expertise to manage advanced digital tools [4]. Overcoming these challenges will require sustained technical innovation, cross-sector collaboration among industry, regulators, and academia, and targeted training programs to build the skills needed for deploying AI-driven traceability and self-healing technologies at large scale.

6. Conclusion

Food traceability systems are inherently data-intensive, as they involve the collection of large volumes of data from various critical control points throughout the food supply chain, including harvesting, transportation, storage, processing, and distribution. There is a pressing need to

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develop advanced smart food traceability systems to enhance food safety, mitigate foodborne outbreaks, and ensure food security. Recent studies have focused on the development of self-healing materials through dynamic non-covalent and covalent interactions, or their synergistic effects. This review highlights recent advancements that have the potential to incorporate self-healing capabilities into food traceability systems.

Although literature on integrating self-healing with technologies such as RFID, WSN, and barcodes into food traceability systems is limited, substantial progress has been made in applying self-healing materials to food packaging, where films and coatings restore mechanical and barrier functions to enhance product protection. Efforts have explored self-healable UHF RFID tags and barcode-encoded photo-crosslinkable films; however, industrial adoption remains hindered by high implementation costs and the need for reliable long-term stability. This review highlights innovative perspectives for developing industry-oriented, self-healable, digitized food traceability tools, aiming to inspire future advancements in this interdisciplinary field.

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Non-covalent interaction	External stimulation for healing	Strength	Sustainability	Application	Reference
Hydrogen bond	Room temp	Moderate	High	Cellulose/PVA hydrogels, starch, protein films	[105,106]
Ionic interaction	Room temp/RH	Moderate	High	Zwitterionic polyurethanes, polyelectrolytes, PEI/PAA	[73,107,108]
Host-guest	Room temp/water	Moderate	High	Cyclodextrin-adamantane coatings/1-menthol	[109]
Electrostatic	Room temp	Moderate	High	Layer-by-layer PEM films	[110]
Metal coordination	80°C	High	Moderate	PAA/HEC hydrogels, Zn-triazole elastomers	[111,112]

Table 1: Summary of dynamic non-covalent interactions and its application in self-healing

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Covalent Interaction	External stimulation for healing	Strength	Sustainability	Applications	Reference
Imine/Schiff	Heat, pH	High	Moderate	Chitosan starch hydrogels, gelatin/green tea based hydrogel	[66,113]
Acylhydrazone	pH, temp	High	Moderate	Phenolic pectin hydrogels, PU elastomers	[114,115]
Diels-Alder	30°C	Very high	Low	Bio-derived BCPs, furan-modified pectin/maleimide-modified chitosan	[71,116]

Table 2: Summary of dynamic covalent interactions and its application in self-healing

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Table 3: A summary of self-healing based polymers and its interaction in food related studies

Technology	Bio-polymer	Interaction	SHE	Purpose	Reference
	Chitosan (CS) and Carboxymethyl cellulose (CMC)	Ionic bonds (COO^- and NH_3^+) and hydrogen bonding	87.4%	Preserving fresh-cut apples	117
Fabrication of polyelectrolyte multilayer films (PEMs) with self-healing properties	Carbon nitride (C_3N_4), poly(ethylenimine)-β-cyclodextrin (PEI-β-CD), and poly(acrylic acid)-adamantanamine (PAA-AD)	Host-guest interactions through LbL assembly		Fresh-keeping packaging film in banana	76
	LbL assembly of chitosan (CS) and sodium alginate (SA)	Hydrogen bond and ionic bonds	97%	Fresh-keeping packaging film for strawberries	77
	Polymeric blend of poly(ethylene imine) (PEI) and	SHE was enhanced using poly(ethylene		High bactericidal rate	79

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Enhancement of self-healing efficiency	cetyltrimethylammonium bromide (CTAB), into poly(ether-thioureas) (PETU)	imine) (PEI) and cetyltrimethylammonium bromide (CTAB),		(>99.9%) against E. coli. and S. aureus and has potential application in food industry	
	Soy protein isolate (SPI)-based films combined with PEI and metal ions (Cu^{2+} or Zn^{2+})	Amine groups in poly(ethylene imine) (PEI) enhanced the mechanical strength and formed extensive hydrogen bonds with SPI	SHE was recovered to 90.17%	Superior self-healing and antibacterial properties	82
	Corn and starch films were developed with 50% glycerol	Self-healing mechanism were not reported. Quick Response (QR) codes, text, and pictograms were overprinted		Potato starch films showed superior printing properties	96

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		using inkjet printing			
Embedded Symbology techniques and the assessment of self-healing and printing properties	Photo-cross-linkable polymeric film was developed using (PEI/PAA-N3)$_{10}$ assembled through a layer-by-layer (LbL) interaction.	Stable covalent network developed within the cross-linked regions, which attributed to recovery		Label material	118
	Biodegradable film fabricated from banana peel and by incorporating beeswax	Aminolysis treatment was provided by introducing NH_2 groups using 1,6 hexanediamine	SHE was enhanced to 77%	Better printability properties and has potential application in food traceability	78

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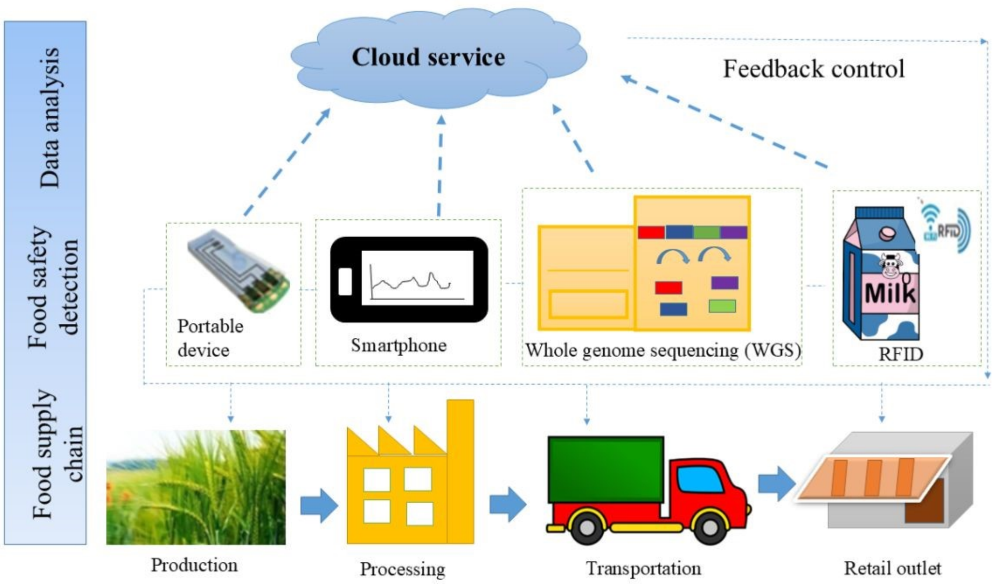

(a)

Figure 1. (a) A schematic overview of a smart food traceability system. Adapted and modified from [30] Copyright © 2020 Taylor & Francis

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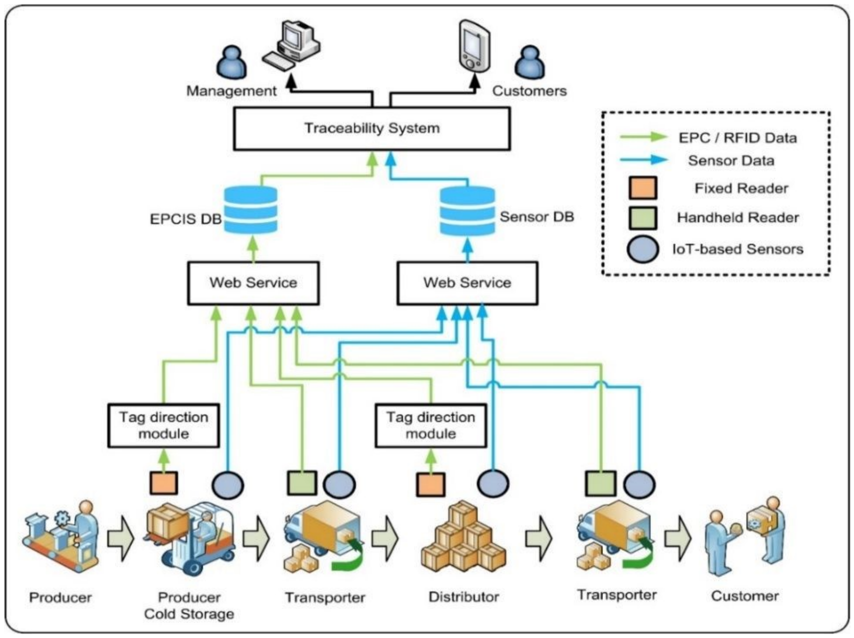
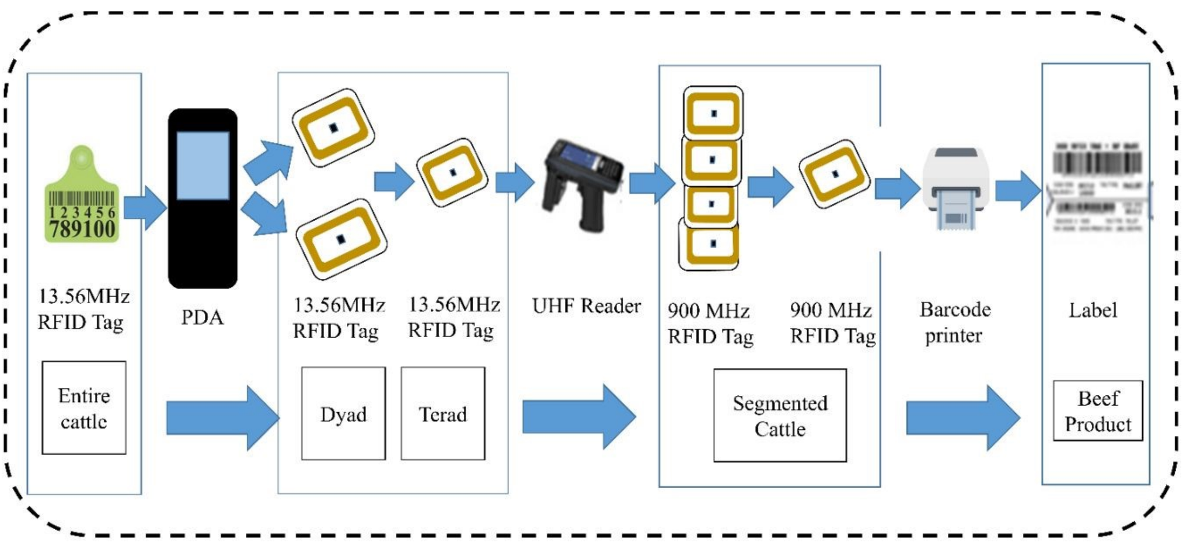


(a)



(b)

Figure 2. (a) Traceability system based on RFID and IoT-based sensors. Reprinted (reproduced) with permission from [28] Copyright © 2019 Elsevier. (b) The process of the data transformation and transmission between traceable units in RCBTS Adapted and modified from [30] Copyright © 2012 Elsevier

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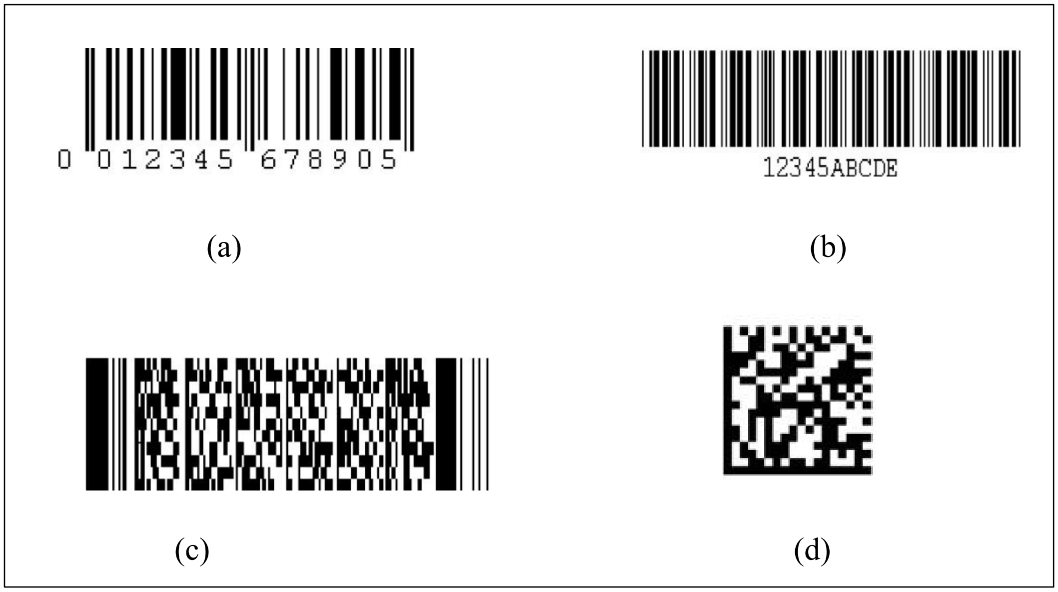

Figure 3. Different types of barcodes: (a) EAN- 13 (b) Code 39 (c) PDF-417 (d) Data Matrix code. Reprinted (adapted) with permission from [119] Copyright © 2006 Elsevier Ltd.

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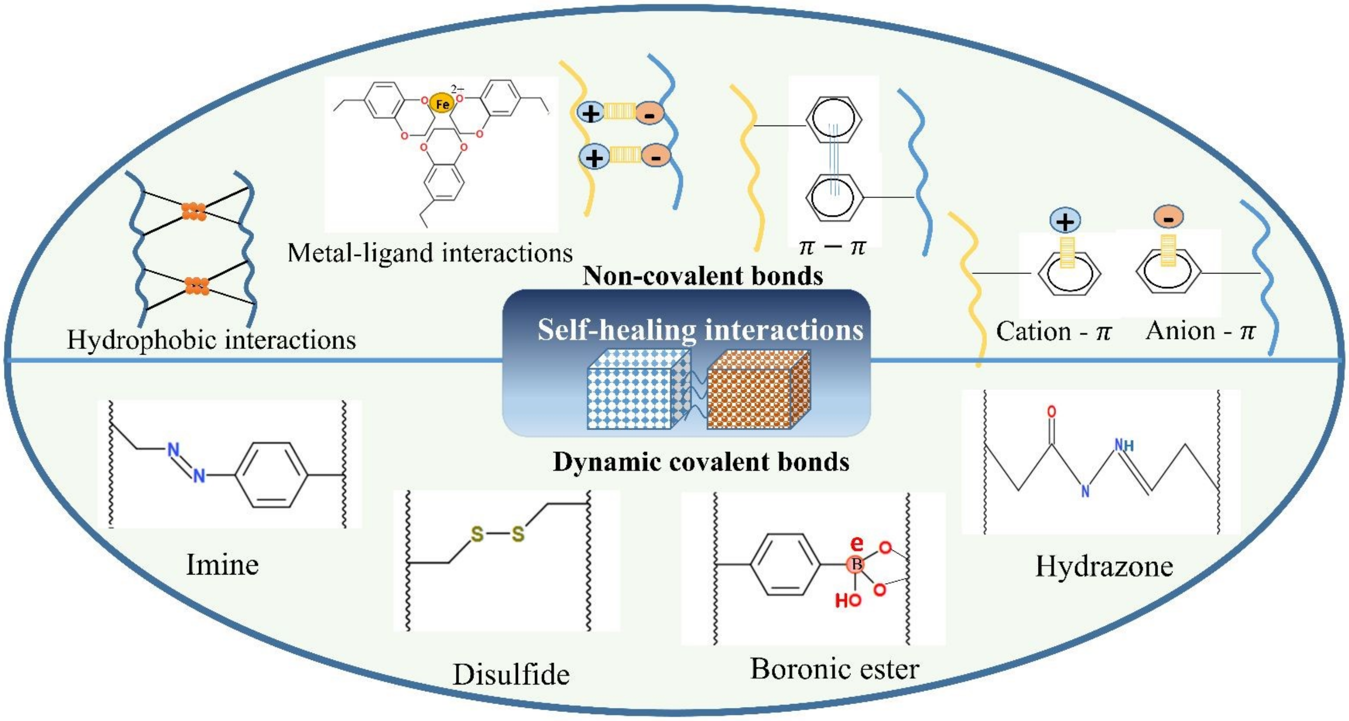
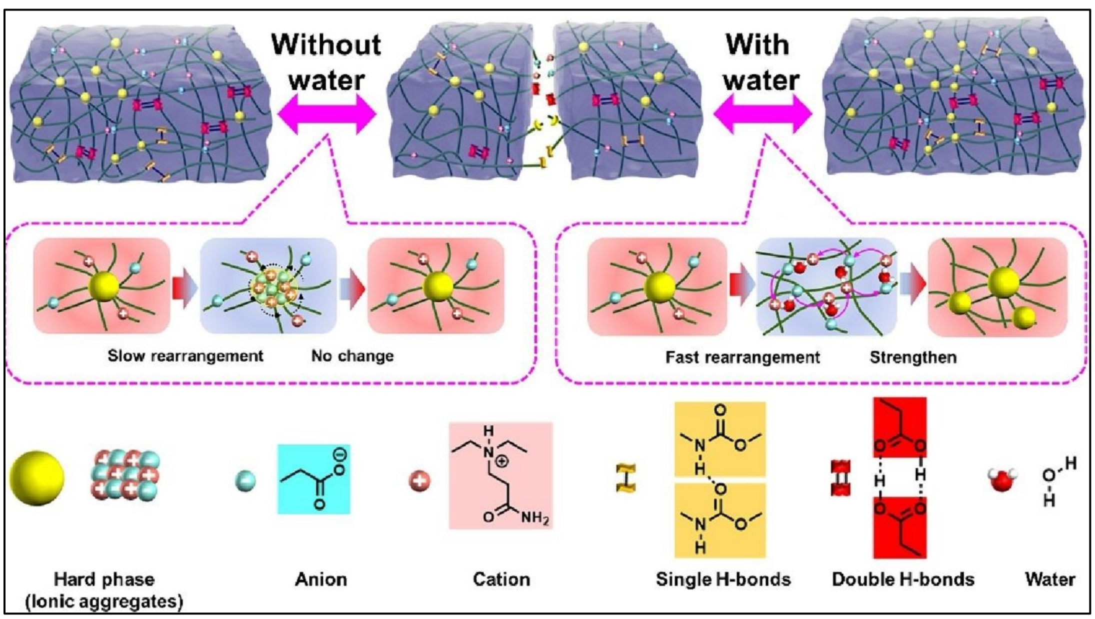


1076

1077 (a)



1078

1079 (b)

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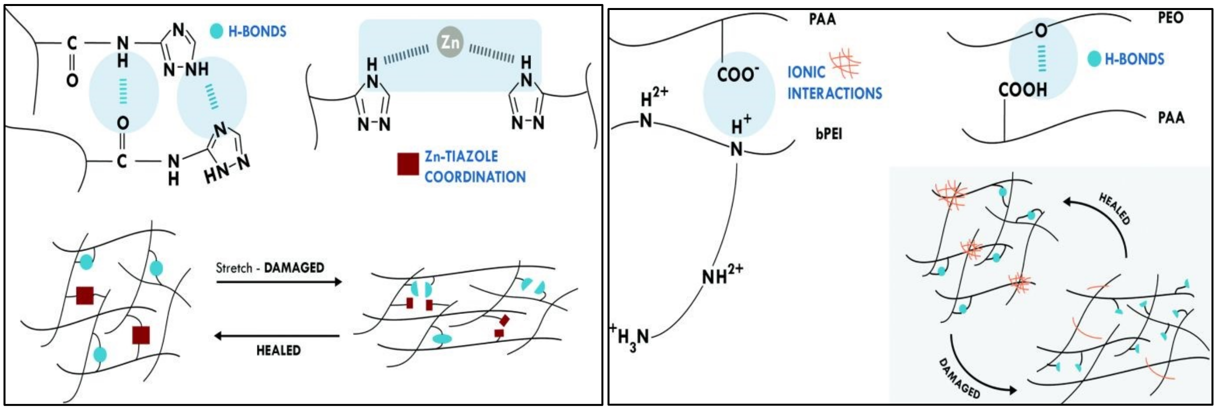

(c) (d)

Figure 4. (a) Representation of reversible dynamic covalent and non-covalent interactions for the preparation of self-healing hydrogels [48]. (b) Molecular behavior in self-healing process based on the rearrangement of H-bonds and interactions, exhibiting distinct molecular behavior during healing in the absence and presence of water. Reprinted (adapted) with permission from [56] Copyright © 2024 Elsevier. Schematic representation of (c) Combination between hydrogen bonds and metal-ligand coordination in poly(isoprene) (IR) Reprinted (reproduced) with permission from [64] Copyright © 2017 The Royal Society of Chemistry (d) Combination between hydrogen bonds and ionic interactions in bPEI/PAA/PEO. Reprinted (adapted) with permission from [57] Copyright © 2019 American Chemical Society

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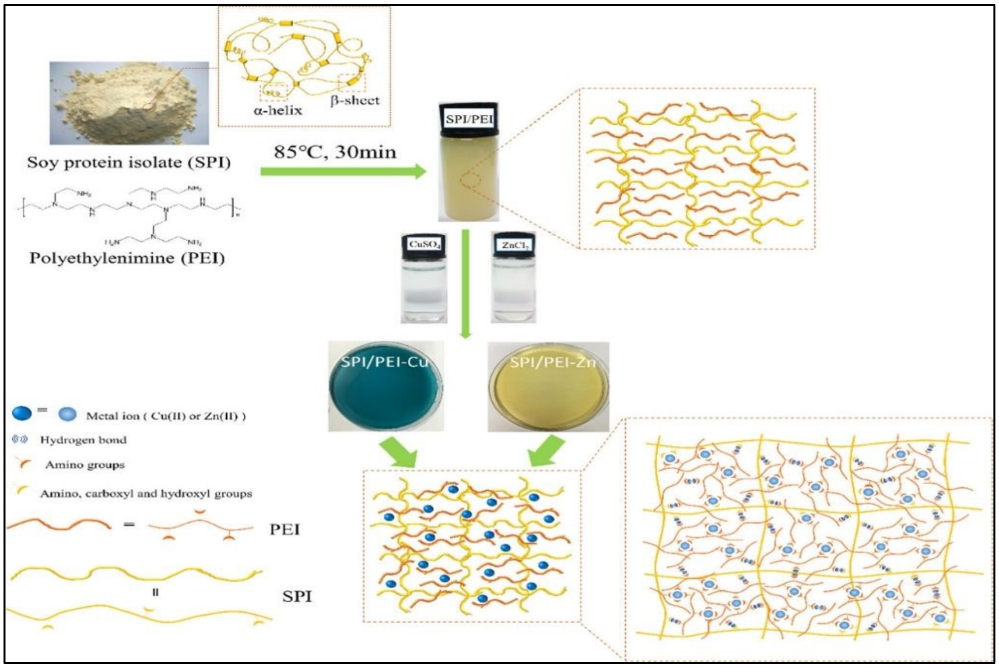
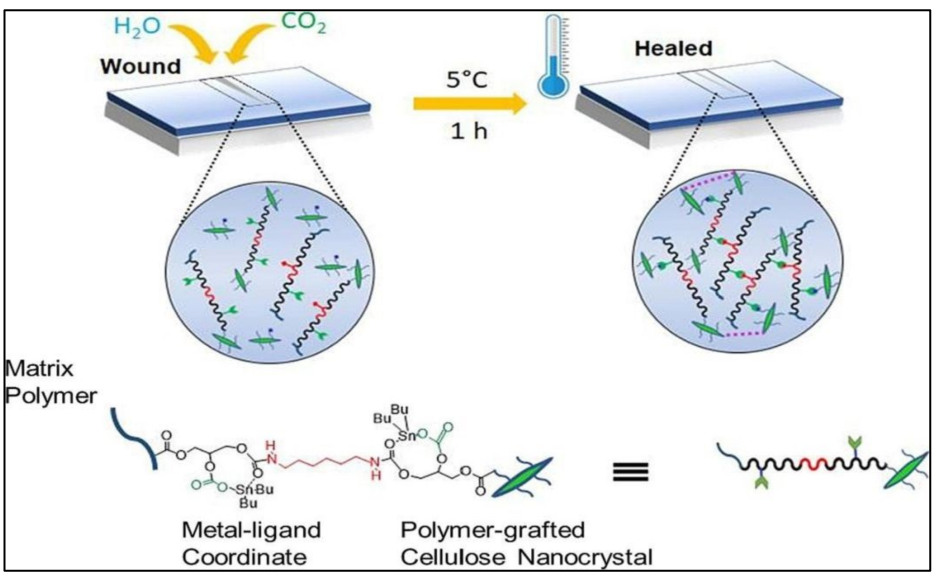


(a)



(b)

Figure 5. (a) Fabrication process and schematic of the SPI/PEI based films. Reprinted (reproduced) with permission from [82] Copyright © 2019 American Chemical Society Ltd. (b) Representation of self-healing achieved at low temperature in cellulose nanocrystal (CNC)/polymer nanocomposites. Reprinted (reproduced) with permission from [83] Copyright © 2022 Elsevier Ltd.

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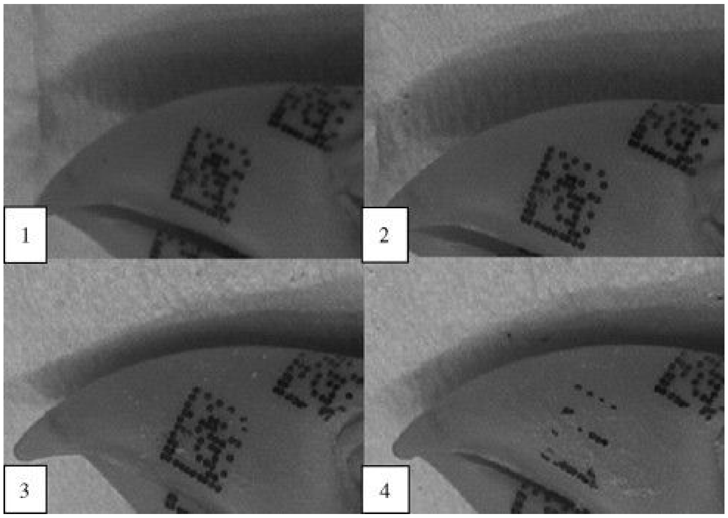
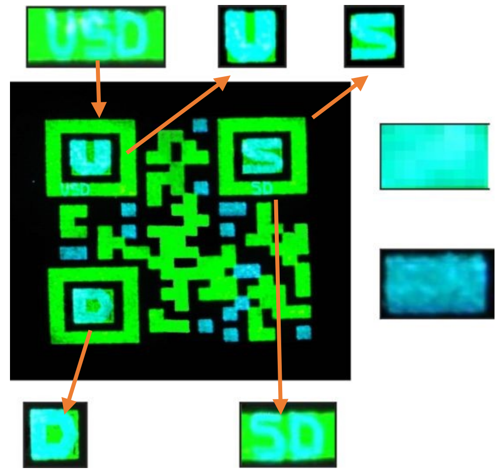
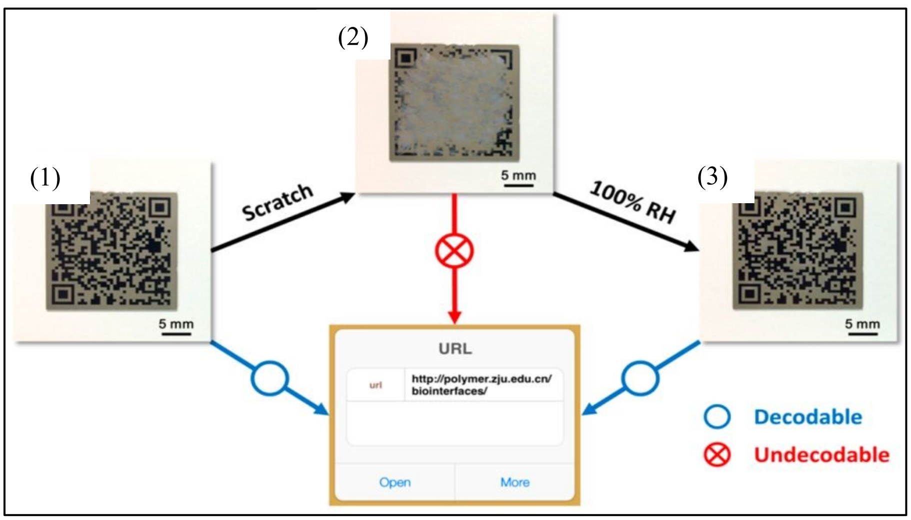




(a) (b)



(c)

Figure 6. (a) Sequence of deterioration of inkjet imprinted barcode by abrasion. Reprinted (reproduced) with permission from [45] Copyright © 2010 Elsevier. (b) Upconverting image of QR code which has the literal text 'USD'; 'U', 'S', and 'D'; and 'SD' inserted in the code image with blue upconverting ink. Reprinted (reproduced) with permission from [97] Copyright © 2012 IOP Publishing Ltd (c) Optical images showing the recovery process of a $(PEI/PAA\text{-}N_3)_{10}$ film, which was encoded with a QR code. (1) Film without any treatment. (2) Damaged film (3) Healed film after being exposed to 100% RH for 12 h. Reprinted (reproduced) with permission from [118]. Copyright © 2018 American Chemical Society.

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Data Availability

No data is generated for the present study.

Prof Poonam Mishra

Corresponding Author