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Recent Advances in Smart and Intelligent Packaging for food, Pharmaceuticals, and consumer goods

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Abstract

Radio-frequencyidentification(RFID)technologyhasprogressedbeyonditstraditionalrolein tracking and identification and is now increasingly integrated with sensing functions in smart food packaging. RFID-based sensing systems enable non-contact, real-time monitoring of critical parameters such as temperature, humidity, gas composition, and mechanical stress throughout the food supply chain. This review provides a comprehensive overview of recent developments in RFID-enabled smart packaging for food applications, with particular emphasis on sensing mechanisms, system architectures, and practical implementation strategies. Both passive and active RFID sensor platforms are discussed, highlighting their operating principles, performance characteristics, and suitability for different food products. The review also examines the integration of RFID sensors with data management systems, Internet of Things (IoT) frameworks, and cold-chain monitoring infrastructures. Key challenges related to sensor accuracy, cost, scalability, signal interference, and regulatory compliance are critically analyzed. In addition, emerging trends such as printable RFID sensors, battery-free sensing, and multifunctional smart labels are explored in the context of sustainability and large-scale adoption. Overall, RFID-based sensing is identified as a promising approach for enhancing food safety, quality assurance, and supply-chain transparency,althoughfurthertechnologicaloptimizationandstandardizationarerequiredfor widespread commercial deployment.

Keywords: Smart packaging; Food quality monitoring; Cold-chain management; Internet of Things

I. Introduction

Packaginghasalwaysbeenaquietbutessential partofhowproducts movefromproducersto market. The main thing is, packaging aims to protect goods from physical damage, contamination,andenvironmentalstressduringstorage andtransport (Marsh &Bugusu, 2007; Coles *et al.*, 2003).Formanyyears,itsrole hasexpandedtoincludecommunication,branding,andregulatorycompliance (Brody *et al.*, 2008).Still,ifwelook closely,mostconventionalpackagingsystemsremainpassivebydesign (Arvanitoyannis & Oikonomou, 2012).Theyprotect,butthey do not respond. They inform, but they do not truly reflect what is happening to the product inside. With supply chains becoming longer and more complex, this limitation is no longer easy to ignore(Müller *et al.*, 2017).

Thepharmaceuticalindustryfacesevenmorechallenges.Medicinessuchasvaccines,insulin, and protein-based formulations are highly sensitive to temperature, humidity, and light (Tiwari *et al.*, 2012). In practice,evenshortvariationsfromrecommendedstorageconditionscanchangedrugefficacy. Cold-chainfailuresduringtransportationremainaseriousconcern,particularlyinregionswith limitedinfrastructure (Yam*et al.*, 2022).Traditionalpharmaceuticalpackagingofferslittleindicationofwhether a product has experienced harmful conditions beforereachingthe patient. From experience in supply-chain discussions, it is clear that this lack of visibility makes post-distribution quality assessment both difficult and uncertain. As a result, there is growing demand for packaging systems that can actively monitor and communicate storage conditions throughout the product's journey (Roy *et al.*, 2022).

Intelligent packaging takes a different but complementary approach. Instead of changing the environment, it focuses on monitoring and communication (Yam *et al.*, 2005; Ghaani *et al.*, 2016). Indicators and sensors embedded in the package can track temperature exposure, freshness, or gas composition (Vanderroost*et al.*, 2014; Galvez *et al.*, 2018).Time– temperature indicators reveal whether a product has been exposed to unsuitable conditions (Kuswandi*et al.*, 2011; Mills, 2015), while freshness indicators respond to chemical changes linked to spoilage(Shao *et al.*, 2021). Gas sensors that detect oxygen or carbon dioxide levels further support real-time quality assessment (Huang *et al.*, 2019). When active and intelligent elements are combined, packaging systems become not only protective but informative and capable of supporting better decision-making across the supply chain.(Realini & Marcos, 2014).

Advances in sensor technologyhave made these systems more practical and accessible. Early indicator designs often lack accuracy or show weak connections with actual product quality (Vanderroost*et al.*, 2014). More recent developments use enzyme-based, polymer-based, and colorimetric sensing methodsthatrespondmorecloselytorealdegradationprocesses (Rodrigues *et al.*, 2021). Colorimetricindicators,in particular, stand out for their simplicity. A visible color change can communicate complex information without requiring specialized equipment, making quality assessment easier for bothretailersandconsumers (Souza *et al.*, 2019). Thisshiftfromdate-basedlabelingtocondition-basedevaluation represents a meaningful improvement in how shelf life is understood and managed (Souza *et al.*, 2020; Galvez *et al.*, 2018).

Digitaltechnologieshavefurtherexpandedthe roleofpackaging.ToolssuchasRFIDandNFC enable product identification, tracking, and authentication, which areparticularlyvaluable for pharmaceuticals and high-value goods (Chen *et al.*, 2020). Internet of Things–enabled packaging systems allow continuous monitoring of temperature, humidity, and handling conditions throughout the supplychain (Wang *et al.*, 2024)Whencombinedwithdataanalytics,thisinformationsupportsimprovedquality control, risk management, and logistics planning. Packaging, in this sense, becomes a source of data rather than just a physical container.

Sustainability has become a central consideration in the development of these technologies. Growing concerns over plastic waste and environmental impact have encouraged the use of biodegradablematerials,recyclablecomponents,andeco-friendlyindicators (Marsh &Bugusu, 2007; Marsh, 2016; Priyadarshi *et al.*, 2021).Whilethesesystems may involve additional materials, studies suggest that reductions in food waste and product loss can offset their environmental footprint.(Salgado *et al.*, 2021).

Overall, smart and intelligent packaging represents a significant shift in how packaging is viewed and used (Souza *et al.*, 2020; Palanisamy, 2025). By combining protection, monitoring, and communication, these systems offerpracticalsolutionstochallengesfacedacrossthefood,pharmaceutical,andconsumer goods industries. Continued research and responsible innovation will be essential to support their broader implementation. This review examines recent developments in smart and intelligent packaging, with particular emphasis on material innovations, sensing approaches, digital integration, and sector-specific applications.

II. Concepts, Definitions, and Classification of Smart and Intelligent Packaging

2.1 Evolution of Packaging Systems

Packagingdidnotevolveovernight.Itsdevelopmenthascloselyfollowedchangesinindustrial production, distribution practices, and consumer expectations. In its earliest form, packaging served a straightforward purpose: to protect products from physical damage, contamination, and environmental exposure during storage and transportation. At that stage, packaging systems were entirely passive. They neither interacted with the product nor responded to changes in the surrounding environment.For a long time, this approach was sufficient. However, as supply chains expanded and productsbegantravelinglongerdistances,limitationsbecamedifficulttoignore.Fromwhatis commonly observed in real distribution systems, products may remain visually intact while undergoing gradual quality loss due to temperature fluctuations, moisture exposure, or oxidative processes. Passive packaging simply cannot respond to such changes.This challenge became particularly evident for perishable foods and sensitive pharmaceutical formulations. As storage durations increased, the need for improved preservation strategies grew. Packaging systems gradually evolved to incorporate materials and designs aimed at extendingshelf lifeand improvingsafety. Eventually, attention shifted toward packagingthat could either interact with the product or provide information about its condition. Smart and intelligentpackagingrepresentsthemostrecentstageinthisevolution,combiningadvancesin material science, sensing technologies, nanotechnology, and digital communication to meet current industrial and consumer requirements (Shao et al., 2021). "The progressive evolution of packaging systems from passive protection to advanced smart packaging technologies is illustrated in Figure 1."

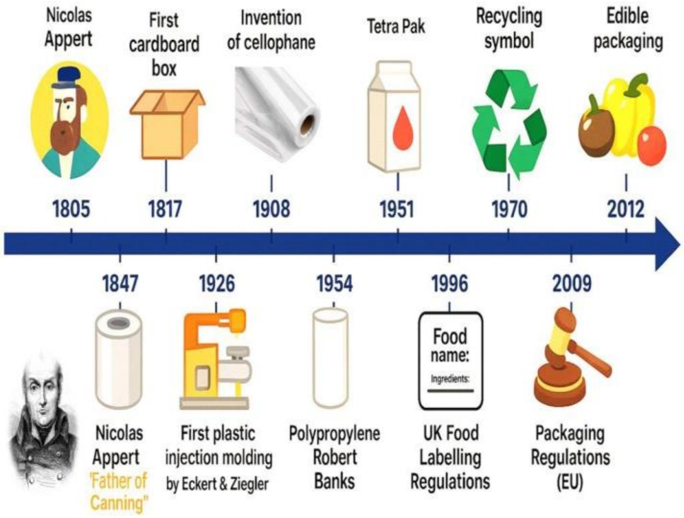

Figure 1. Evolution of packaging systems from conventional passive packaging to active, intelligent, and smart packaging technologies, highlighting the increasing levels of product interaction, monitoring, and digital communication (Shao et al., 2021)

2.2 Active Packaging

Active packaging refers to packaging systems that are intentionally designed to interact with the packaged product or its internal environment. Unlike conventional packaging, which acts onlyasabarrier,activepackagingmodifiesinternalconditionstoslowdeteriorationorenhance safety (Biji et al., 2015).

This interaction can occur through several mechanisms. Oxygen scavengers are commonly usedtoreduceoxidativereactionsthatcauserancidity,discoloration,andnutrientlossinfood products. Moisture absorbers help regulate humidity levels inside the package, limiting microbial growth and preventing texture deterioration. Ethylene absorbers are particularly important in fresh fruit and vegetable packaging, as ethylene accelerates ripening and senescence. Once ripening begins, quality decline is often rapid.

Antimicrobial packaging systems introduce another layer of protection. These systems incorporateagentssuchasorganicacids,enzymes,essentialoils,orantimicrobialnanoparticles that inhibit the growth of spoilage and pathogenic microorganisms (Heising et al., 2014). The principle is simple, but the impact can be significant.

In practice, active packaging has been widely adopted in the food industry for shelf-life extension. It is also relevant in pharmaceutical applications, especially for products sensitive to oxygen or moisture. That said, active systems raise important regulatory concerns. The potential migration of active substances into the product remains a key issue, making safety evaluation and regulatory approval essential before commercialization.

2.3 Intelligent Packaging

Intelligent packaging follows a different philosophy. Rather than changing the internal environment, it focuses on monitoring product conditions and communicating information related to quality, safety, or storage history (Rodrigues et al., 2021). Inrealsupplychainconditions,thisdistinctionmatters.Aproductmay bepackagedcorrectly yet still experience temperature abuse or unsuitable storage conditions during transport. Intelligent packaging addresses this gap by making such events visible. These systems typically rely on indicators or sensors that respond to factors such as temperature,time,gascomposition,ormicrobialactivity.Time–temperatureindicators(TTIs) are among the most widely used tools. They provide information on cumulative temperature exposure during storage and transportation and are particularly useful for cold-chain monitoringofperishablefoodsandtemperature-sensitivepharmaceuticalproducts(Shaoetal., 2021).

Freshness indicators operate bydetectingbiochemical changes associated with spoilage, such as pH variation or the formation of volatile nitrogen compounds in protein-rich foods. Gas sensors monitor headspace gases including oxygen, carbon dioxide, ammonia, and hydrogen sulfide,whichoftensignalproductdegradationbeforevisiblespoilageoccurs.Moreadvanced systems include biosensors designed to detect specific biological targets such as pathogenic microorganisms or toxins. While these technologies offer high sensitivity, challenges related to cost, stability, and large-scale implementation remain (Rodrigues et al., 2021).

2.4 Smart Packaging

Smart packaging represents an integrated approach that combines active and intelligent packaging functionalities within a single system. In many cases, it also incorporates digital connectivity,allowingpackagingtocommunicateinformationacrossthesupplychain(Restuccia et al, 2010).Technologiessuchasradio-frequencyidentification(RFID),near-fieldcommunication(NFC), andInternetofThings(IoT)platformsarecommonlyusedinsmartpackagingsystems.These tools enable real-time tracking, authentication, and data exchange related to product origin, handling conditions, and authenticity. In the pharmaceutical sector, smart packaging plays a critical role in anti-counterfeitingstrategies and cold-chain monitoring. In consumer goods, it supports brand protection while also enhancing consumer engagement through accessible product information.

2.5 ClassificationofAdvancedPackaging Systems

Advanced packaging systems are generally classified into three categories based on functionality:activepackaging,intelligentpackaging,andsmartpackaging.Activepackaging focusesonextendingshelflifethroughdirectinteraction withtheproductoritsenvironment. Intelligent packaging emphasizes monitoring and information delivery without influencing product conditions. Smart packaging integrates both approaches and adds digital communicationcapabilitiesintoaunifiedplatform(Palanisamy,2025).

2.6 ImportanceofClassification inPackagingResearch

Clearclassificationofpackagingsystemsisessentialforstructuredresearch,development,and commercialization.Distinguishingbetweenactive,intelligent,andsmartpackagingallowsfor more accurate assessment of performance, safety, and sustainability. It also simplifies regulatory processes by clarifying the functional role of each component within a packaging system.From a research perspective, proper classification supports the development of standardized testing methods and improves communication between scientists, manufacturers, and regulatoryauthorities. In practical terms, it reduces ambiguityand helps ensurethat advanced packaging technologies are applied responsibly and effectively (Mkhari et al., 2025).

III. Technologies Used in Smart and Intelligent Packaging

Smartandintelligentpackagingtechnologies havedevelopedovertimeinresponsetorepeated challengesrelatedtoproductspoilage,qualityloss,andlimitedvisibilityduringstorageandtransportation. Unlike conventional packaging, modern systems are designed not only to protect products but also to preserve quality, monitor surrounding conditions, and communicate relevant information throughout the supply chain. In practical distribution environments, packaging rarely experiences ideal or perfectly controlled conditions, making such technologies increasingly important.Smart packaging systems usually rely on a combination of approaches rather than a single solution.Temperaturefluctuations,handlingstress,and extendedstorageperiodsarecommon across supply chains (Palanisamy, 2025). To address these realities, smart and intelligent packaging technologies canbebroadlygroupedintosensorsandindicators,activepackagingsystems,nanotechnology-based materials, and digital or connected packaging solutions. Together, these technologies have expanded the functional role of packaging across food, pharmaceutical, and consumer goods industries.

3.1 SensorsandIndicatorsinIntelligentPackaging

Sensors and indicators form the foundation of intelligent packaging systems by enabling monitoring of environmental conditions and translating changes into information related to productqualityandsafety(Rodriguesetal.,2021).Dependingontheirdesign,thesetoolsmay provide real-time feedback or record cumulative exposure over a defined period.From what is commonly observed during storage and distribution, products can experience temperature or gas changes without showing visible signs of deterioration. Sensors and indicators help reveal these hidden changes by making environmental exposure measurable, even when physical appearance remains unchanged.

3.2 Time–TemperatureIndicators (TTIs)

Time–temperatureindicatorsareamongthemostwidelyappliedtoolsinintelligentpackaging. TTIs provide a visual or electronic record of the combined effects of time and temperature experienced by a product during storage and transportation. Since deterioration in many food and pharmaceutical products depends on both factors, TTIs often offer a more realistic assessment of product condition compared to fixed expiration dates.

These indicators are particularly valuable for cold-chain monitoring of chilled foods, frozen products, vaccines, and biologics (Shao et al., 2021). Even short temperature deviations can influence product stability, and TTIs help identify such events. Recent developments include enzyme-basedandpolymer-basedTTIsdesignedtobettermatchproduct-specificdegradation behavior. Improvements in printing techniques and reduced production costs have supported wider commercial adoption of these indicators (Palanisamy, 2025).

3.2.1 Freshness Indicators

Freshness indicators are designed to detect biochemical changes associated with product spoilage.Infoodpackaging,theseindicatorstypicallyrespondtochangesinpHortheaccumulation of volatile compounds such as ammonia, trimethylamine, or hydrogen sulfide.These compounds are produced during microbial degradation, particularly in protein-rich foods.Most freshness indicators rely on colorimetric responses that change visibly as spoilage progresses. This approach allows quality assessment without the need for specialized equipment (Shao et al., 2021). Recent research has focused on natural freshness indicators derived from plant-based pigments such as anthocyanins and curcumin. These materials are biodegradable, generally safe, and better aligned with sustainability goals in packaging development (Rodrigues et al., 2021).

3.2.2 Gas Sensors

Gas sensors are used in intelligent packaging to monitor the composition of gases within the package headspace. Common target gases include oxygen, carbon dioxide, ammonia, and hydrogen sulfide. Variations in these gases often indicate oxidation, respiration, or microbial activity during storage.Gas sensors may operate using electrochemical, optical, or colorimetric detection principles. Advances in miniaturization and low-power design have enabled integration into compact packaging formats without significantly increasing package size, supporting continuous monitoring of perishable products (Palanisamy, 2025).

3.2.3 Biosensors

Biosensors represent an advanced category of intelligent packaging technologies. These systems aredesigned to detect specific biological targets such as pathogenic microorganisms, toxins,orallergens.Typically,abiosensorcombinesabiologicalrecognitionelement,suchas anenzyme,antibody,oraptamer,withatransducerthatconvertsthebiologicalinteractioninto a measurable signal (Rodrigues et al., 2021).Although biosensors offer high sensitivity and specificity, their large-scale use in packaging remains limited. Challenges related to stability, cost, and integration into packagingmaterials continue to restrict commercial application. Ongoing research aims to improve durabilityand simplify biosensor incorporation without compromising performance.

3.3 ActivePackagingTechnologies

Activepackagingtechnologiesaredesignedtoextendshelflifeandimproveproductsafetyby directlyinteractingwith thepackaged product orits surrounding environment. Unlikepassive packaging systems, active packaging modifies internal conditions through controlled absorption or release mechanisms (Biji et al., 2015). This approach allows packaging to influence product stability rather than merely isolate it.

3.3.1 Antimicrobial Packaging

Antimicrobialpackagingincorporatesagentsthatinhibitthegrowthofspoilageandpathogenic microorganisms on product surfaces. Common antimicrobial agents include organic acids, essentialoils,enzymes,chitosan,andantimicrobialnanoparticlessuchassilverandzincoxide. These agents are incorporated into packaging films or coatings to provide sustained antimicrobial activity (Huang et al., 2019).Such systems are widely applied in food packaging to reduce contamination and extend shelf life.Inpharmaceuticalpackaging,antimicrobialmaterialsareparticularlyusefulforprotecting sterile products and moisture-sensitive formulations.

3.3.2 OxygenScavengers

Oxygenscavengersareactivepackagingcomponentsdesignedtoreduceoxygenlevelswithin packages. Bylimitingoxygen availability, these systems slow oxidative reactions responsible forspoilage, discoloration, and nutrient loss. Oxygen scavengersarecommonlyused in snack foods, processed products, and oxidation-sensitive pharmaceutical formulations (Biji et al.,2015).Modernoxygenscavengersareengineeredforcontrolledactivityandcompatibility with various packaging materials, improving reliability during storage.

3.3.3 MoistureandEthyleneAbsorbers

Moisture absorbers regulate humidity within packages, helping to prevent microbial growth and texture deterioration. Ethylene absorbers are particularly important in fresh produce packaging,asethyleneacceleratesripeningandsenescenceinfruitsandvegetables.Together, these absorbers contribute significantly to shelf-life extension, especially during prolonged storage and transportation (Palanisamy, 2025).

3.4 NanotechnologyinSmartPackaging

Nanotechnology has enhanced the functional performance of smart and intelligent packaging materials. Nanocomposites containing nano-clays, metal oxides, or polymeric nanoparticles exhibitimprovedmechanicalstrength,thermalstability,andbarrierpropertiesagainstoxygen and moisture. These improvements enable the development of thinner and lighter packaging films without compromising protection (Heising et al., 2014).Antimicrobial nanoparticles such as silver, titanium dioxide, and zinc oxide are effective against a wide range of microorganisms. At the same time, concerns regarding nanoparticle migration, toxicity, and environmental impact have increased regulatory attention. Current research focuses on improving nanoparticle immobilization and developing bio-based nanomaterials to enhance safety and sustainability.

3.5 DigitalandConnectedPackagingTechnologies

Digital technologies have transformed smart packaging into an interactive and data-driven system. Radio-frequency identification (RFID) and near-field communication (NFC) technologiesenableitem-leveltracking,authentication,anddatastorage,whichareparticularly valuable in pharmaceutical and high-value consumer goods packaging (Restuccia et al., 2018).InternetofThings–enabledpackagingsystemsallowcontinuousmonitoringofenvironmental conditionssuchastemperature,humidity, andmechanicalshockthroughoutthesupplychain. When integrated with data analytics, these systems support shelf-life prediction, logistics optimization, and risk management, allowing packaging to function as part of an information network rather than a passive container.

3.6 IntegrationofTechnologiesinSmartPackagingSystems

Modern smart packaging systems increasingly integrate sensors, active materials, nanocomposites, and digital communication tools within a single platform. This integrated approach supports comprehensive monitoring, preservation, and traceability while enabling data-driven decision-making across the supply chain. The convergence of these technologies representsakeydirectioninthefuturedevelopmentofsmartandintelligentpackagingsystems (Mkhari et al., 2025).

4 ApplicationsofSmartandIntelligentPackaging

Smartandintelligentpackagingtechnologiesarenowappliedacrossawiderangeofindustries, particularlyinfood,pharmaceuticals,andconsumergoods.Theiradoptionislargelydrivenby the need to improve product safety, maintain quality, enhance traceability, and strengthen consumertrust.Byintegratingsensingelements,active materials,nanotechnology,anddigital communication tools, packaging has gradually shifted from a passive protective role to a system that supports continuous quality management throughout the product life cycle.

4.1 ApplicationsintheFoodIndustry

The food industry represents one of the most significant application areas for smart and intelligent packaging technologies. Food products are inherently perishable, and factors such as microbial growth, oxidation, moisture loss, and temperature abuse contribute heavily to quality deterioration during storage and distribution. These challenges have increased the demand for packaging systems that can actively preserve food quality and provide reliable information about product condition (Shao et al., 2021).

Intelligent packaging tools are widelyused in food applications. Time–temperatureindicators arecommonlyappliedtochilledandfrozenfoodstomonitorcold-chainintegrity.Byproviding avisualindicationofcumulativetemperatureexposure,theseindicatorshelpidentifyproducts that may have experienced temperature abuse. Freshness indicators are frequently used for meat, seafood, and dairy products, where they respond to biochemical changes such as pH variationorthereleaseofvolatilenitrogencompoundsduringspoilage.Theseindicatorsoffer consumers a direct and easy wayto assess food qualityat the point of purchase (Rodrigues et al., 2021).

Active packaging technologies also play an important role in food preservation. Oxygen scavengers are used in snacks, bakery items, and processed foods to limit oxidative degradation, while moisture absorbers help maintain appropriate humidity levels to prevent microbial growth. Ethylene absorbers are extensively used in fresh fruit and vegetable packaging to delay ripening and extend shelf life. In addition, antimicrobial packaging systems incorporating natural extracts, enzymes, or antimicrobial nanoparticles inhibit microbial growth on food surfaces, thereby improving safety and extending product shelf life (Brody et al., 2008).

4.2 ApplicationsinthePharmaceutical Industry

In the pharmaceutical industry, packaging is critical for maintaining drug stability, ensuring patient safety, and preventing product tampering or counterfeiting. Many pharmaceutical productsarehighlysensitivetoenvironmentalfactorssuchastemperature,humidity,andlight. Smart and intelligent packaging technologies provide effective tools for monitoring these conditions throughout the supply chain (Rodrigues et al., 2021).

Time–temperatureindicatorsandelectronicdataloggersarecommonlyusedinpharmaceutical cold-chain management, particularly for vaccines, biologics, and insulin. These systems help detecttemperatureexcursionsthatcouldcompromisedrugefficacy.Intelligentpackagingisalso used for tamper detection through seals and indicators that provide visible evidence of unauthorized opening, thereby improving product security.

Anti-counterfeiting is another major application of smart packaging in the pharmaceutical sector. Technologies such as radio-frequency identification, near-field communication, and serialized barcodes enable item-level authentication and traceability. These systems allow manufacturers, regulators, and consumers to verify product authenticity and reduce the circulation of counterfeit medicines (Rhim et al., 2013).

Smartpackagingisadditionallyusedtosupportmedicationadherence.Smartblisterpacksand connected containers can record dosing events and provide reminders, which is particularly useful for chronic disease management and clinical trials. Such systems improve adherence monitoring and contribute to better therapeutic outcomes.

4.3 Applications in Consumer Goods

Smart and intelligent packaging technologies are increasingly adopted in consumer goods sectors including cosmetics, personal care products, electronics, and luxury items. In these markets, packaging serves not only a protective role but also an important function in brand communication and consumer engagement. Digital and connected packaging solutions such as QR codes, NFC tags, and augmented reality features enable direct interaction between brands and consumers. These tools provide access to product details, usage instructions, sustainability information, and promotional content through smartphones. Connected packaging enhances transparency and helps build consumer trust (Restuccia et al., 2010). Counterfeiting remains a significant concern in consumer goods, particularly for high-value and luxury products. Smart packaging technologies such as RFID and NFC support product authentication and supply-chain traceability, while tamper-evident seals provide visible signs of interference. Together, these features strengthen product security and protect brand reputation. Sustainability-oriented smart packaging solutions are also gaining importance in consumer goods. The use of bio-based materials, recyclable packaging components, and digital labels helps reduce environmental impact while maintaining functionality. In this way, smart packaging supports both sustainability goals and competitive market positioning.

4.4 Benefits of Application-Based Smart Packaging

Across food, pharmaceutical, and consumer goods sectors, smart and intelligent packaging technologies offer several shared benefits. These include improved product safety, better quality monitoring, reduced waste, and increased transparency throughout the supply chain. By providing access to real-time or condition-based information, these systems enable informed decision-making and support more efficient product distribution. Overall, application-driven smart packaging contributes to improved sustainability, reduced losses, and enhanced consumer confidence, reinforcing its growing importance in modern packaging systems (Mkhari et al., 2025).

5 Advantages of Smart and Intelligent Packaging

Smart and intelligent packaging technologies provide several advantages over conventional packaging systems by improving product safety, quality monitoring, supply-chain efficiency, and consumer interaction. By integrating active components, intelligent sensing systems, and digital communication tools, packaging is transformed from a passive protective layer into a dynamic system capable of supporting decision-making throughout the product life cycle. These advantages have led to the increasing adoption of smart packaging solutions across food, pharmaceutical, and consumer goods industries (Shao et al., 2021).

5.1 Improved Product Safety and Quality Assurance

One of the most significant advantages of smart and intelligent packaging is improved product safety and quality assurance. Intelligent packaging tools such as time–temperature indicators, freshness indicators, and gas sensors enable continuous or cumulative monitoring of environmental conditions that directly influence product quality. By detecting temperature abuse, spoilage-related biochemical changes, or variations in gas composition, these systems allow early identification of compromised products and reduce the risk of consumption of unsafe goods (Rodrigues et al., 2021; Shao et al., 2021).

Active packaging technologies further enhance safety by directly inhibiting spoilage mechanisms. Antimicrobial packaging systems reduce microbial growth on food surfaces, while oxygen scavengers and moisture absorbers slow oxidative and microbial degradation processes. Together, these technologies contribute to improved shelf life and reduced incidence of foodborne illness and pharmaceutical product degradation (Brody et al., 2008).

5.2 Extension of Shelf Life and Reduction of Product Waste

Shelf-life extension is a major advantage of smart and intelligent packaging, particularly in the food sector. Active packaging components such as ethylene absorbers and oxygen scavengers delay ripening and oxidation, while antimicrobial agents suppress the growth of spoilage microorganisms. At the same time, intelligent indicators allow shelf life to be assessed based on actual storage conditions rather than fixed expiration dates, enabling products to be used safely for longer periods (Palanisamy, 2025).By providing accurate, condition-based information on product quality, smart packaging reducesunnecessarydisposalofstill-usableproducts.Thiscontributestolowerfoodwasteand reduced economic losses, while also offering environmental benefits through improved resource efficiency and reduced emissions associated with discarded products (Mkhari et al., 2025).

5.3 EnhancedSupply-ChainMonitoringand Traceability

Smart packaging technologies significantlyimprove supply-chain monitoring and traceability through the use of digital identification and data transmission systems. Technologies such as radio-frequency identification, near-field communication, and Internet of Things platforms enable real-time tracking of products during storage and transportation. These tools allow stakeholderstomonitorenvironmentalconditions,identifycriticalcontrolpoints,andrespond quickly to deviations that may compromise product quality.In pharmaceutical and high-value consumer goods sectors, enhanced traceability supports regulatory compliance and efficient recall management. Item-level tracking enables rapid identificationofaffectedbatches,therebyreducingeconomicimpactandimprovingconsumer safety (Rodrigues et al., 2021).

5.4 Anti-CounterfeitingandProduct Authentication

Counterfeit products present serious risks to consumer safetyand brand integrity, particularly in pharmaceutical and luxury consumer goods markets. Smart packaging provides effective anti-counterfeiting solutions through the use of serialized identifiers, RFID tags, NFC chips, and digital authentication platforms. These technologies enable verification of product authenticityatmultiplepointsacrossthesupplychainas wellas attheconsumerlevel.Tamper-evident indicators and smart seals further strengthen product security by providing visibleevidenceofpackageinterference.Theuseofsuch systemsenhancesconsumertrustand supports efforts to combat counterfeit goods in global markets (Mkhari et al., 2025).

5.5 ImprovedConsumerEngagementand Transparency

Smart packaging also improves consumer engagement by enabling direct interaction between brandsandconsumers.DigitalfeaturessuchasQRcodes,NFCtags,andinteractiveinterfaces provide access to product information, usage instructions, origin details, and sustainability credentials. This transparency empowers consumers to make informed purchasing decisions and strengthens brand loyalty (Mkhari et al., 2025).Inaddition,intelligentindicatorsallowconsumerstovisuallyassessproductquality,increasing confidence in product safety. The ability to verify authenticity and access product history further enhances trust in smart-packaged products, particularly for high-risk or high-value items.

5.6 SupportforSustainabilityGoals

Smartandintelligentpackagingtechnologiessupportsustainabilitybyreducingproductwaste, improving resource efficiency, and enabling the use of environmentally friendly materials. Developmentsinbiodegradablepolymers,bio-basedindicators,andrecyclablecomponents align smart packaging innovations with circular economy principles. Studies suggest that reductions in product loss and improved logistics efficiency can offset the additional material and energy inputs associated with smart packaging systems (Realini et al., 2014; Mkhari et al., 2025).

5.7 Economicand OperationalBenefits

From an industrial perspective, smart packaging provides economic and operational benefits byreducingproductlosses,improvinginventorymanagement, andoptimizinglogistics.Real-time monitoring supports data-driven decision-making and enables predictive supply-chain management.Althoughinitialimplementationcostsmaybehigherthanthoseofconventional packaging,long-termbenefitssuchasreducedwaste,improvedcompliance,and enhanced brand value often outweigh these investments(Brody et al.,2008).

6 ChallengesandLimitationsofSmartandIntelligentPackaging

Despite the significant advantages and increasing interest in smart and intelligent packaging technologies, several challenges continue to limit their widespread adoption and commercialization. These limitations arise from a combination of technical, economic, regulatory, environmental, and consumer-related factors. Addressing these challenges is essential to enable the effective integration of smart packaging systems across food, pharmaceutical, and consumer goods industries (Marsh &Bugusu, 2007).

6.1 High CostofImplementation

One of the most prominent barriers to the adoption of smart and intelligent packaging is the high cost associated with advanced materials, sensors, and digital components. Technologies such as RFID tags, biosensors, and connected packaging systems often require specialized materialsandcomplexmanufacturingprocesses,which increaseoverallpackagingcosts.Asa result, smart packaging solutions are more frequently applied to high-value products, pharmaceuticals, and premium consumer goods, while low-margin products continue to rely on conventional packaging systems (Müller et al., 2017; Chen et al., 2020).Although technological advancements and large-scale manufacturing are expected to reduce costs over time, economic feasibility remains a major concern, particularly for small- and medium-scale manufacturers operating in cost-sensitive markets.

6.2 TechnicalComplexityandIntegrationIssues

Smart packaging systems typically involve the integration of multiple components, including sensors,activeagents,nanomaterials,anddigitalcommunicationtools.Ensuringcompatibility and stable performance of these components throughout the product shelf life presents significanttechnicalchallenges.Sensorsandindicators mayloseaccuracyovertime,while biosensors can experience reduced stability under fluctuating environmental conditions such as temperature and humidity (Vanderroost et al., 2014; Ghaani et al., 2016).Inaddition,integratingelectroniccomponentsintoflexibleorlightweightpackagingmaterials without compromising mechanical strength or barrier properties remains technically demanding. Power supply requirements for electronic sensors and data transmission further complicate system design and limit long-term reliability (Wang et al., 2024).

6.3 RegulatoryandSafety Concerns

Regulatory approval represents a major limitation for the commercialization of smart and intelligent packaging, particularlyin food and pharmaceutical applications. Active packaging systems that incorporate chemical or biological agents must undergo extensive safety assessmentstoevaluatepotentialmigrationintofoodor drugproducts.Similarly,nano-enabled packaging materials raise concerns related to nanoparticle migration, toxicity, and possible long-term health effects (Azeredo, 2013; Mihindukulasuriya& Lim, 2014).Regulatoryframeworks governingsmartpackagingtechnologiesdiffer acrossregionsand are often not fully harmonized. This lack of consistency creates uncertainty for manufacturers seeking global market access and can significantly delay product development and approval.

6.4 EnvironmentalandRecycling Challenges

Although smart packaging can reduce waste through improved shelf-life management, it also introduces environmental challenges related to material complexity and recyclability.The incorporation of electronic components, sensors, and multilayer materials can complicate recyclingprocessesandreducecompatibilitywithexistingwastemanagementsystems(Marsh, 2016).The generation of electronic waste from single-use smart packaging components is an emergingconcern.Developingrecyclable,biodegradable,oreasilyseparablesmartpackaging materialsremainsakeyresearchprioritytoensurealignmentwithcirculareconomyprinciples (Cappa & Pilati, 2022).

6.5 ConsumerAwarenessandAcceptance

Consumer understanding and acceptance play a crucial role in the successful implementation of smart packaging technologies. Many consumers remain unfamiliar with the function and interpretationofintelligentindicatorssuchasfreshnesslabelsortime–temperatureindicators. Misinterpretation of indicator signals can lead to confusion, distrust, or unnecessary disposal of products (Heising et al., 2014; Silva et al., 2021).Concerns related to data privacyand digital trackingmayfurther affect consumeracceptance, particularlyforconnectedpackagingsystemsthatcollectortransmitinformation.

6.6 ReliabilityandStandardizationIssues

The reliability and accuracy of smart packaging systems are particularly critical in safety-sensitive applications such as food and pharmaceuticals. Variability in sensor performance, lack of standardized testing procedures, and differences in indicator calibration can affect consistencyacrossproductsandmanufacturers.Theabsenceofuniversallyacceptedstandards for smart packaging evaluation and data interpretation further limits large-scale implementation and interoperability (Vanderroost et al., 2014).Developingstandardized testingprotocols and performancebenchmarks is essential to ensure reliability and regulatory acceptance of smart packaging technologies.

6.7 LimitedInfrastructureand Scalability

The effective deployment of connected smart packaging systems requires supporting digital infrastructure, including data management platforms, network connectivity, and trained personnel. In regions with limited technological infrastructure, implementing IoT-enabled packaging solutions may not be feasible. As a result, scalability across diverse markets and supply chains remains a significant challenge (Roy et al., 2022)

6.8 Summaryof Challenges

Insummary,whilesmartandintelligentpackagingtechnologiesoffersubstantialbenefits,their widespread adoption is constrained by high implementation costs, technical complexity, regulatory and safety concerns, environmental challenges, and limited consumer awareness. Overcoming these limitations will require continued interdisciplinary research, technological innovation,regulatoryharmonization,andclosecollaborationbetweenindustry,academia,and policymakerstosupportsafeandscalableimplementation(Realini&Marcos,2014;Cappa& Pilati, 2022).

7 SustainabilityandRegulatoryConsiderationsinSmartandIntelligent Packaging

Sustainability and regulatory compliance are key factors influencing the development and commercializationofsmartandintelligentpackagingtechnologies.Whilethesesystemsoffer clear benefits in terms of product safety, quality preservation, and waste reduction, they also introduce new environmental and regulatory challenges. Achieving a balance between technological innovation, environmental responsibility, and regulatory requirements is essential for the long-term success of smart packaging across food, pharmaceutical, and consumer goods industries (Marsh &Bugusu, 2007; Cappa& Pilati, 2022).

7.1 SustainabilityAspectsofSmartPackaging

Sustainability has become a central focus in packaging research due to growing concerns related to plastic pollution, climate change, and depletion of natural resources. Conventional packaging materials, particularly petroleum-based plastics, contribute significantly to environmental pollution and long-term waste accumulation. Smart and intelligent packaging technologiesofferopportunitiestosupportsustainabilityobjectivesbyreducingproductlosses, improving supply-chain efficiency, and enabling more accurate shelf-life management (Salgado et al., 2021).

One of the most significant sustainabilitybenefits of smart packaging is the reduction of food and product waste. Intelligent indicators such as time–temperature indicators and freshness sensorsallowqualityassessmentbasedonactualstorage conditionsratherthanfixedexpiration dates.Thiscondition-basedapproachenablessafeutilizationofproductsforlongerperiodsand reduces premature disposal of consumable goods. Several studies have shown that reductions in product waste achieved through smart packaging can offset the additional material and energyinputs required for advanced packaging components (Yam et al., 2005; Marsh, 2016).

7.2 Useof BiodegradableandBio-Based Materials

To address environmental concerns associated with conventional plastics, increasingresearch effortsarefocusedonbiodegradableandbio-basedmaterialsforsmartpackagingapplications. Biopolymerssuchaspolylacticacid,starch-basedpolymers,cellulosederivatives,andchitosan have been widely investigated as sustainable alternatives due to their renewability and biodegradability (Siracusa et al., 2008; Priyadarshi et al., 2021).

In addition, bio-based intelligent indicators derived from natural pigments such as anthocyanins and curcumin have gained attention because of their low toxicity and environmentalcompatibility.Thesematerialsareparticularlysuitableforfreshnessandquality indicatorsinfoodpackaging(Souzaetal.,2019).However,integratingsmart functionalities into biodegradable substrates remains challenging, as electronic components and sensors must also be designed for recyclability or safe disposal.

7.3 EnvironmentalImpactofElectronicandNano-EnabledComponents

Despite their sustainability potential, smart packaging systems may increase material complexityduetotheincorporationofelectroniccomponents,sensors,andnanomaterials.This added complexity can hinder recyclability and contribute to electronic waste if not properly managed. The use of single-use electronic elements in packaging raises concerns related to resource consumption and end-of-life disposal (Müller et al., 2017; Marsh, 2016).

Nanotechnology-based packaging materials, while offering improved mechanical and barrier properties,alsorequirecarefulenvironmentalassessment.Potentialissuessuchasnanoparticle migration,environmentalpersistence,andEcotoxicityremainimportantconsiderations.Life-cycleassessmentapproachesareincreasinglyappliedtoevaluatetheoverallenvironmental impact of nano-enabled smart packaging systems and to guide sustainable material selection and design strategies (Mihindukulasuriya& Lim, 2014; Scarfato et al., 2020).

7.4 RegulatoryFrameworkforSmartPackaging

Regulatory compliance is a major determinant of smart packaging adoption, particularly in food and pharmaceutical applications. Packaging materials intended for direct contact with food or drugs must meet strict safety requirements to ensure that harmful substances do not migrate into the product. Active packaging systems and intelligent indicators often require additional regulatory scrutiny due to their functional interaction with the packaged product (Restuccia et al., 2010; Arvanitoyannis & Oikonomou, 2012).Infoodpackaging,regulatoryauthoritiesrequire migrationstudies,toxicologicalassessments, and evidence of consumer safety before approving active or nano-enabled materials. In pharmaceuticalpackaging,smartsystemsmustcomply withgoodmanufacturingpracticesand guidelines related to product stability, traceability, and tamper evidence. Regulatory frameworks differ across regions, which complicates global commercialization and increases development timelines (Tiwari et al., 2012; Roy et al., 2022).

7.5 StandardizationandComplianceChallenges

The lack of standardized guidelines for evaluating the performance, safety, and reliability of smart packaging systems remains a major challenge. Differences in regulatory requirements, testingmethods, andsensorcalibrationproceduresacross countries canincrease development costs and delay market entry. Standardization is essential to ensure consistent system performance and regulatory acceptance (Vanderroost et al., 2014).Efforts are ongoing to develop harmonized standards for smart packaging technologies, including guidance on electronic data management, privacy protection, and environmental labeling. Collaboration among regulatory authorities, industry stakeholders, and academic researchers is necessary to support safe and scalable adoption of smart packaging systems (Wang et al., 2024).

7.6 RoleofSustainabilityandRegulationinFuture Adoption

Sustainability and regulatory considerations will play a decisive role in shaping the future of smart and intelligent packaging. Packaging solutions that successfully integrate advanced functionality with environmental responsibility and regulatory compliance are more likely to achieve widespread industrial and consumer acceptance. Continued research into recyclable smart materials, biodegradable electronic components, and globally harmonized regulatory frameworkswillbeessentialtoensurethatsmartpackagingcontributespositivelytolong-term sustainability goals (Cappa & Pilati, 2022; Salgado et al., 2021)

8 FutureProspectsandEmergingTrendsinSmartandIntelligentPackaging

Smart and intelligent packaging is a rapidly evolving field shaped by continuous advances in materials science, digital technologies, and sustainability-driven innovation. Future developmentsareexpectedtofurtherenhancethefunctionality,efficiency,andenvironmental compatibility of packaging systems across food, pharmaceutical, and consumer goods industries. Emerging trends indicate a clear shift toward connected, data-driven, and environmentally responsible packaging solutions that align with modern supply-chain requirementsandevolvingconsumerexpectations(Cappa&Pilati,2022).

8.1 IntegrationofInternetofThingsandArtificial Intelligence

One of the most important future directions in smart packaging is the deeper integration of InternetofThingstechnologieswithartificialintelligence.IoT-enabledpackagingsystemsare capable of continuously collecting data related to temperature, humidity, mechanical shock, andhandlingconditionsduringstorageandtransportation.WhencombinedwithAI-baseddata analytics, these systems can support predictive shelf-life estimation, early risk detection, and real-time logistics optimization (Chen et al., 2020).Predictive modelingusingartificial intelligence allows manufacturers and distributors to shift from reactive quality control toward proactive decision-making. For example, AI-driven systems can forecast spoilage events or cold-chain failures before theyoccur, enabling timely intervention and reducing product losses. Such developments are expected to significantly improve supply-chain efficiency and product safety in the coming years.

8.2 DevelopmentofBiodegradableandSustainableSmartMaterials

Future smart packaging systems are increasingly focused on sustainability through the development of biodegradable and bio-based materials that can support intelligent functionalities. Research efforts are directed toward incorporating sensors, indicators, and active components into compostable or recyclable substrates.Biopolymers such as polylactic acid, cellulose-based materials, starch derivatives, and chitosan are being explored as carriers for smart functions due to their renewability and environmental compatibility (Priyadarshi et al., 2021). Inparallel,progressisbeingmadetowardbiodegradable electronic componentsandprintable electronics that can reduce electronic waste associated with single-use smart packaging. Successfully integrating sustainability with intelligent functionality is expected to play a decisive role in the future scalability and acceptance of smart packaging technologies (Vilela et al., 2018).

8.3 AdvancesinPrintedandFlexibleElectronics

Printed and flexible electronics represent a promising area of innovation in smart packaging development. These technologies allow sensors, antennas, and electronic circuits to be fabricated directly onto flexible packaging materials using printing techniques. Advances in conductiveinks,flexiblesubstrates,androll-to-rollmanufacturingprocessesareexpectedto significantly reduce production costs and enable large-scale implementation (Mills, 2015).Printed electronics enable smart packaging systems to remain lightweight, flexible, and compatible with existing packaging formats. This is particularly important for food and consumer goods packaging, where cost efficiency and material flexibility are critical considerations for commercial adoption (Müller et al., 2017).

8.4 EnhancedBiosensingandReal-TimeSafety Monitoring

Future smart packaging systems are expected to incorporate more advanced bio sensing technologies for real-time detection of pathogens, toxins, and allergens. Ongoing improvements in biosensor stability, sensitivity, and selectivity are likely to enable more reliablemonitoringoffoodsafetyandpharmaceuticalquality.Theuseofsyntheticrecognition elements such as aptamers and molecularly imprinted polymers is anticipated to overcome limitations associated with traditional biological receptors (Poyatos-Racionero et al., 2018).Real-timebiosensingintegratedintopackagingcouldfundamentallychangequalityassurance practicesbyprovidingearlywarningsignalsofcontamination.Thiscapabilityhasthepotential to significantly reduce the incidence of foodborne illness and pharmaceutical product failure (Roy et al., 2022).

8.5 BlockchainandDigitalTraceabilitySystems

Blockchain technology is emerging as a complementary tool for improving traceability and transparency in smart packaging systems. When integrated with RFID, NFC, or QR code technologies,blockchainenablessecureandtamper-resistantrecordingofproductinformation across the supply chain. This approach is particularly relevant for high-value products, pharmaceuticals, and food items that require strict traceability and regulatory compliance.Blockchain-basedtraceabilitysystemscanenhancerecallmanagement,combatcounterfeiting, and strengthen consumer trust by providing verifiable information related to product origin, handling conditions, and authenticity (Silva et al., 2021).

8.6 Consumer-CentricandInteractivePackagingSolutions

Future smart packaging is expected to become increasingly consumer-centric, with a strong focus on usability, transparency, and engagement. Interactive features such as smart labels, augmentedrealityinterfaces, and personalized digital content are beingdevelopedto improve communication between brands and consumers. These technologies enable direct access to product information, sustainability credentials, and usage guidance through packaging interfaces (Heising et al., 2014; Müller et al., 2017). Enhancing consumer understanding of intelligent indicators and digital features will be essential for successful adoption. Intuitive design and targeted educational initiatives are expected to play an important role in ensuring correct interpretation and acceptance of consumer-facing smart packaging technologies (Aday & Yener, 2015).

8.7 OutlookforFutureAdoption

Overall, the future of smart and intelligent packaging is characterized by the convergence of advanced sensing technologies, digital connectivity, artificial intelligence, and sustainable materials.Astechnicalchallengesareaddressedandregulatoryframeworkscontinuetoevolve, smart packaging systems are expected to become more accessible and widely adopted across diverse product categories. Continued interdisciplinary collaboration among researchers, industry stakeholders, and regulatory authorities will be essential to translate emerging innovations into commercially viable, safe, and environmentally responsible packaging solutions (Cappa & Pilati, 2022).

9 Conclusion

Smartpackagingrepresentsamajoradvancementinpackagingscience,shifting conventionalpackagingfrompassiveprotectionto systems that preserve product quality, monitorenvironmental conditions, and enable informationexchange. Thisevolutionhas been driven by growing demands for food safety, pharmaceutical stability, product authentication, and sustainability. In the food sector, these technologies reduce spoilage, extend shelf life, and minimize food waste. Intelligent indicators, inducing time–temperatureand freshness sensors, support condition-based qualityassessment,allowingconsumersandretailerstomakeinformeddecisionsaboutproduct safety. Active packaging solutions, including antimicrobial films, oxygen scavengers, and ethylene absorbers,enhance preservation by slowing degradationand inhibitingmicrobialgrowth. Theseapproachesimprovefoodsafety,reduceeconomic losses, and strengthen consumer confidence. Within the pharmaceutical industry, smart packaging supports drug efficacy, patient safety, and regulatory compliance. Temperature-sensitive products like vaccines and biologics benefit from cold-chain monitoring using intelligent indicators and digital tracking technologies. Anti-counterfeiting measuresbasedonserialization,RFID,andNFCsupportsecureauthenticationandtraceability,protecting public health and reinforcing trust insupply chains. Smart adherence-monitoringsystemshighlightthepotentialofintelligent packagingto improve therapeutic outcomes and healthcare management. Consumer goods industries are adopting smart packaging to enhance brand protection,traceability,andconsumerengagement.InteractivefeaturessuchasQRcodes,NFC tags,anddigitallabelsenabletransparentcommunicationofproductinformation,authenticity verification,andsustainabilitycredentials.

Despitetheseadvantages,theadoptionofsmartpackagingremains constrainedbyhighimplementationcosts,technicalcomplexity, regulatory approval requirements, environmental concerns, and limited consumer awareness. The integration of electronic and nano-enabled components raises additional issues related to recyclability andelectronic waste.Addressingthese challengeswillrequireinterdisciplinaryresearch,regulatory harmonization, and improved consumer education.Looking forward, the future of smart and intelligent packaging lies in the convergence of advanced sensing technologies, digital connectivity, artificial intelligence, and sustainable materials.Innovationssuchasbiodegradablesmartsubstrates,printedandflexibleelectronics, AI-driven predictive analytics, and blockchain-enabled traceability are expected to further enhance packaging functionality while supporting environmental responsibility. Through responsible innovation and close collaboration among researchers, industry stakeholders, and regulatory authorities, has the potential to become a cornerstone of safe, sustainable, and transparent product distribution systems across food, pharmaceutical, and consumer goods industries.

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