EEE 4861 Assignment

Design and Investigation of a Simple Sensor Circuit Intended for Smart Food Packaging on Biodegradable Packaging

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Submitted to,
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Motivation: In Bangladesh, many food and daily grocery items lack proper packaging, leading to issues such as post-harvest losses and compromised food safety. Smart food packaging offers a solution by integrating sensor systems that provide early alerts about food quality. This not only enhances food safety and extends shelf life but also improves traceability and transparency, promotes greater consumer engagement, and supports sustainability through reduced waste.

Objective and CEP statement: Individuals or groups of up to three students will design and investigate a simple sensor circuit intended for smart food packaging on biodegradable packaging.

- ✓ The sensor circuit must be implemented using the Electrical and Electronic Engineering knowledge and all the modern tools studied in the class: SPICE simulator, stick diagram, layout design, and performance analysis using SPICE.
- ✓ A key component of the assignment is the submission of a detailed proposal that includes a thorough literature review and the selection of a suitable biodegradable plastic packaging material.
- ✓ The assignment must include a proposal to demonstrate how the designed sensor circuit can be integrated into the chosen biodegradable packaging to monitor food quality over time, thereby addressing food safety and environmental concerns.
- ✓ Additionally, students must propose a structured decision-making algorithm or framework that supports actions prioritizing food safety, human well-being, and sustainable practices under the Bangladesh Environmental Conservation Rules 2023(4).
- ✓ A comprehensive design report must be submitted upon completion of the assignment.

Critical Challenges: A common engineering practice is only the use barcode on the conventional plastic package to calculate product bill during payment. Conventional plastic packaging will not be used as they pollute the environment. Also, use of environmental-friendly electronic circuit system will enhance quality of life on earth.

Conflicting Requirements: Students are required to explore various design methodologies to evaluate potential solutions although such expensive biodegradable packaging with smart sensor system is difficult to integrate in a low-income country. Also, a lack of health safety knowledge is also one of the key constrains to implement the proposed system.

1. **Course Outcomes (COs): EEE 4861 (VLSI Design)**

CO4: Engage in independent research with regards to emergent topics in VLSI domain.
CO5: Consider safety and health issues in design of food packaging on biodegradable packaging.

2. **Program Outcomes (POs): EEE 4861 (VLSI Design)**

PO5: (Modern tool usage) Create, select and apply appropriate techniques, resources, and **modern engineering and IT tools**, including prediction and modelling, to complex engineering problems (CEP), with an understanding of the limitations. (K6)

PO7: (Environment and Sustainability) Understand and evaluate the **sustainability** and impact of professional engineering work in the solution of complex engineering problems in societal and **environmental** contexts. (K7).

3. **We explore how a few Complex Engineering Problems (Ps) through this assignment:**

P1: This assignment requires depth of Electrical and Electronic Engineering knowledge (K3) and also requires study of existing smart food packaging models with similar Goal (K8).

P2: Conflicting technical requirements: Plastic packaging is available, however, biodegradable plastic packaging are expensive with challenges in sensor system integration onto it (K5, K6). A low price variant is critical to achieve.

P3: No obvious or specific sensor circuit. A Ring oscillator, inverter, even voltage divider circuit can be a temperature sensor, some other circuits exhibits performance variation in the presence of O_2, N_2 and even under toxic environment (K4).

P4: Electrical and Electronic Engineering students are not typically study to issues related to bio-safety and food safety.

4. **Knowledge Profiles (Ks) through this assignment:**
   - ✓ We accumulate **K3~K8.**
5. **Complex Engineering Activities (As) through this assignment:**
   - ✓ We claim no Complex engineering activity from this assignment.

CO-PO-K-P-A Mapping: for CEP

COs	POs	Knowledge Profile(s)	CEP	CEA
CO4	**PO5**	**K6**	**P1, P2, P3, P4**	**-**
CO5	**PO7**	**K7**	**-**	**-**

6. Rubrics for Assessment: (75 marks)

Sl.	Section	Description	Marks
01.	**Literature Review & Material Selection (CO4, PO5)**	-Thorough literature review on sensor circuits for food packaging. -Selection and justification of suitable biodegradable plastic packaging material.	**10**
02.	**Sensor Circuit Design & Tools Usage (CO4, PO5)**	-Application of EEE knowledge in design. -Proper use of SPICE simulator, stick diagram, layout design. - Performance analysis using SPICE.	**20**
03.	**Integration with Packaging (CO5, PO7)**	-Proposal on integrating the designed sensor into biodegradable packaging. -Practical considerations for monitoring food quality over time.	**10**
04.	**Decision-Making Algorithm / Framework (CO5, PO7)**	-Structured decision-making method for prioritizing food safety, human well-being, and sustainability. -Alignment with Bangladesh Environmental Conservation Rules 2023(4).	**10**
05.	**Proposal Quality and originality (CO4, PO5)**	-Clarity, technical depth, and feasibility of the initial proposal. -Logical flow and completeness.	**10**
06.	**Final Design Report (CO4, PO5)**	- Comprehensive and well-organized documentation. -Includes all results, design files, simulations, and conclusions. - Clear communication of work. - Creativity, innovation, and originality in approach.	**15**

Contents

Abstract

In Bangladesh, structural gaps in post-harvest handling and inadequate packaging for food and daily-use groceries produce large economic losses, elevated public-health risk, and substantial environmental burden. National estimates indicate that total food loss and waste across the supply chain approaches roughly 19.4%, equivalent to ≈21.1 million tonnes per year (2.11 crore tonnes), with particularly acute losses in fruits & vegetables (40%), roots & tubers (37%) and fish (~30%) in some commodity groups. Such losses translate into lost income for producers, reduced food availability, and increased greenhouse gas emissions associated with wasted production. At the same time, plastic packaging and single-use plastics remain a major environmental challenge — urban centers such as Dhaka generate on the order of hundreds of tons of plastic waste per day with low recycling rates reported — motivating urgent policy and technical shifts toward biodegradable packaging and circular disposal pathways.

Food safety and preservation remain critical challenges in Bangladesh, where more than 30 % of harvested food is lost post-harvest due to improper storage and packaging. Conventional packaging in the country relies heavily on low-grade plastics, which not only fail to protect against microbial spoilage and moisture ingress but also contribute to severe environmental pollution. The need for a sustainable, intelligent, and cost-effective solution has motivated the exploration of biodegradable smart packaging, wherein integrated electronic sensing can actively monitor food quality parameters in real-time.

This thesis presents the design, simulation, and evaluation of a CMOS-based humidity sensor circuit intended for integration into biodegradable packaging substrates. The sensor employs a three-stage CMOS ring oscillator loaded with a humidity-sensitive capacitive element, enabling a direct frequency shift in response to changes in relative humidity (RH). The oscillation frequency of the system is governed by the propagation delay of each inverter stage and the load capacitance. With increasing RH, the dielectric permittivity of the sensor capacitor rises, thereby increasing capacitance and proportionally reducing oscillation frequency.

Simulation studies were performed in Cadence Virtuoso (gpdk045 technology), yielding promising results. At 20 % RH, the sensor capacitance was measured at approximately 1.0 pF, resulting in an oscillation frequency of 8.50 MHz. At 80 % RH, capacitance increased to 1.5 pF, lowering the oscillation frequency to 7.55 MHz. The corresponding sensitivity was calculated as –15.8 kHz/%RH, with a capacitance gradient of 0.00833 pF/%RH. The device demonstrates a usable dynamic range of nearly 1 MHz over 60 % RH, which can be digitized through a microcontroller using simple cycle-counting methods ($f \approx N\_counts/T\_g$). To achieve a resolution of 1 % RH, a minimum gate time of 63 µs is required, while extended integration times allow for finer discrimination.

In comparative terms, while advanced CMOS-MEMS humidity sensors have achieved sensitivities of up to 99 kHz/%RH with conductive polymer coatings, and capacitive MEMS sensors have demonstrated response times as short as 10 s with sensitivities of 32.8 fF/%RH, the present design emphasizes simplicity, CMOS compatibility, and biodegradability over extreme sensitivity. Its frequency-domain output is inherently digital-friendly, enabling seamless integration with low-cost microcontrollers, making it attractive for deployment in resource-constrained settings such as Bangladesh.

Beyond circuit design, this work includes a comprehensive literature review on biodegradable polymer substrates (such as polylactic acid, polyhydroxyalkanoates, and starch-based composites) to evaluate

their suitability for food packaging applications. These materials are assessed in terms of their mechanical integrity, water vapor transmission rates, and biocompatibility with CMOS sensor embedding. Furthermore, a structured decision-making algorithm, aligned with the Bangladesh Environmental Conservation Rules 2023, is proposed to ensure that sensor integration prioritizes food safety, consumer well-being, and ecological sustainability.

The outcomes of this research highlight the potential of biodegradable smart packaging to serve as a scalable, environmentally conscious alternative to conventional plastics while providing real-time monitoring of food quality indicators. In the context of Bangladesh, where lack of traceability and inadequate packaging continue to compromise food safety and increase waste, this solution represents a forward-looking approach that couples electrical engineering innovation with sustainable development goals. The findings establish a foundational framework for future research in sensor-embedded packaging, and pave the way for practical implementations that could significantly reduce losses, improve consumer confidence, and support national strategies for food security and environmental protection.

1. Introduction

1.1 Background

In Bangladesh, post-harvest losses remain alarmingly high, in part due to inadequate packaging, poor cold-chain infrastructure, and limited access to advanced food-preservation technologies. Rural households often lack sufficient storage and refrigeration methods, leading to significant spoilage of perishable goods—on the order of several tens of kilograms per household annually. National-level assessments estimate smallholder food losses between harvest and market contribute substantially to food insecurity and economic inefficiency. These losses intensify the urgency for packaging innovations tailored to Bangladesh's socio-economic context.

1.2 Smart and Active Packaging Technologies

The field of smart packaging has notably advanced, introducing systems categorized as active, intelligent, or smart packaging—each offering beyond-passive functions such as freshness monitoring, shelf-life extension, or quality display. A prominent technique is modified atmosphere/humidity packaging (MA/MH), which controls the internal gas and humidity environment to slow respiration, reduce desiccation, and suppress microbial spoilage of fresh produce during extended transport.

Meanwhile, pH- and gas-responsive indicators—such as colorimetric films incorporating natural dyes (e.g., anthocyanins, curcumin) embedded in biodegradable biopolymer matrices—have emerged as low-cost, visual freshness indicators. These systems change color in response to spoilage-related chemical shifts, such as increases in volatile amines or acidity. For instance, starch- or gelatin-based films with anthocyanins have shown clear visual responses upon exposure to fish or meat degradation products.

Numerous biobased polymers are currently under investigation for smart packaging applications. Examples include cellulose, chitosan, alginate, starch, polylactic acid (PLA), and polyhydroxyalkanoates (PHAs). These materials serve both as biodegradable packaging substrates and as functional platforms for indicator or sensor integration. Recent reviews emphasize that integrating smart functionalities with biodegradable polymers aligns with environmental sustainability goals and can significantly mitigate food waste.

1.3 Advanced Sensing Approaches

Beyond visual indicators, electronic sensors—such as biosensors, nano sensors, and micro/nano-electronic systems—have seen growing application in real-time food quality monitoring. These devices can detect pH changes, gas composition, humidity, or temperature with higher sensitivity and connectivity, enabling integration with digital systems for data logging and traceability.

In advanced smart packaging systems, innovations include battery-free, stretchable electronic platforms that can wirelessly monitor and actively respond to food spoilage—by triggering release of antimicrobial agents and communicating freshness data over NFC or other communication links. While such systems offer impressive capabilities, their complexity, cost, and resource requirements often exceed feasibility for low-income regions like Bangladesh.

1.4 Specific Technologies for Low-Cost Settings

In contexts where cost, environmental sustainability, and simplicity are paramount, CMOS-based sensors offer a compelling balance. CMOS technology supports compact, low-power, and low-cost manufacturing, is functionally digital-friendly, and can be designed for integration onto flexible or biodegradable substrates.

A particularly elegant electronic approach to humidity sensing leverages a CMOS ring oscillator wherein oscillation frequency varies inversely with a humidity-sensitive capacitance. This method allows direct frequency-domain sensing: as relative humidity (RH) increases, dielectric permittivity in the capacitive transducer increases, increasing the load capacitance on the oscillator, thus lowering oscillation frequency. Such frequency shifts can be readily digitized via cycle counting using simple microcontrollers–a cost-effective approach well-suited to rapid prototyping and scale-up in resource-constrained settings.

1.5 Biodegradable Substrates in Bangladesh

In Bangladesh, significant strides have been made in biodegradable materials research. Notably, Prof. Mubarak Ahmad Khan developed the "Sonali Bag"—a bioplastic bag derived from jute fiber that addresses both environmental waste reduction and rural manufacturing opportunities. Biodegradable polymers such as PLA and jute-reinforced composites present viable paths for packaging substrates that could host embedded sensors without relying on petroleum-based plastics.

2. Synthesis: Need for CMOS-Based Smart Packaging on Biodegradable Substrates

Despite promising visual indicators and high-tech electronic systems, a gap persists in affordable, scalable, and integrated sensor-platforms for smart packaging suited to Bangladesh's context. The imperative is clear: a simple, CMOS-compatible humidity (and potentially temperature) sensor—realized via a ring-oscillator architecture, implemented through standard SPICE simulation, stick design, and layout, and integrated atop biodegradable substrates—could fulfill dual goals:

1. Enhance food safety and traceability through continuous, quantifiable monitoring of moisture-related spoilage risk.

2. Support environmental sustainability via biodegradable materials and low-cost manufacturing, aligning with both local economic constraints and national environmental priorities.

This work builds on interdisciplinary developments across packaging science, electronics, and material sustainability to deliver a pragmatic, academically rigorous solution design. The prototype system aims to advance smart packaging in Bangladesh by offering a robust, low-cost sensor circuit, seamlessly integrated into biodegradable substrates, and demonstrating measurable gains in food preservation, consumer awareness, and ecological impact.

3. Problem Statement

Bangladesh faces a pressing challenge in the domain of food safety and preservation, as a substantial portion of harvested agricultural products and daily grocery items are lost due to improper packaging and insufficient monitoring systems. The absence of reliable packaging solutions not only accelerates spoilage and microbial contamination but also undermines consumer trust in the quality of marketed food products. Conventional plastic-based packaging, while widely used for decades, offers little beyond passive containment; moreover, it contributes heavily to environmental pollution and plastic waste accumulation. With the recent adoption of the Bangladesh Environmental Conservation Rules 2023, the continued use of non-biodegradable plastics is increasingly untenable, necessitating a shift toward sustainable, biodegradable packaging solutions that are both environmentally safe and functionally superior.

Despite ongoing research on smart packaging, a key bottleneck remains the integration of low-cost, reliable electronic sensors into biodegradable substrates. Traditional smart packaging technologies developed in industrialized nations often rely on expensive MEMS devices, polymer coatings, or advanced wireless platforms that are economically impractical for low- and middle-income contexts like Bangladesh. Consequently, there exists a clear gap between the availability of advanced sensing technology and its feasibility for local adoption.

The core problem, therefore, lies in the design of a simple, low-power, and CMOS-compatible sensor circuit that can be implemented using standard Electrical and Electronic Engineering (EEE) tools such as SPICE simulation, stick diagramming, layout design, and performance evaluation. The sensor must be sufficiently sensitive to detect food-quality degradation (e.g., changes in humidity or temperature within packaging) and capable of delivering a digital-friendly output (e.g., frequency-domain signals) for potential integration with microcontrollers. While CMOS technology offers a promising platform due to its scalability, cost-effectiveness, and compatibility with digital processing, the challenge is to ensure that such circuits can be fabricated or embedded onto biodegradable packaging materials such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch-based composites, or locally developed materials like the Sonali Bag (jute-based bioplastic). Each material presents unique trade-offs in terms of mechanical strength, water vapor permeability, and compatibility with sensor integration, making material selection a central engineering problem alongside circuit design.

Another dimension of the problem is the need for a structured decision-making framework that balances three often conflicting objectives: (i) ensuring food safety through real-time quality monitoring, (ii) promoting environmental sustainability by eliminating plastic waste, and (iii) maintaining economic feasibility for adoption in a low-income country context. While consumers and policymakers demand environmentally friendly packaging, the higher costs associated with biodegradable substrates and embedded electronics pose a significant barrier. Moreover, the limited public awareness of food safety standards further constrains acceptance and implementation.

In summary, the problem can be articulated as follows:

- How can a CMOS-based sensor circuit be designed, simulated, and optimized using standard EEE tools for monitoring food quality within packaging systems?
- Which biodegradable packaging material offers the best compromise between environmental sustainability, durability, and compatibility with sensor integration?
- How can the designed system be justified and aligned with national environmental policies while ensuring feasibility in a low-income economy?

Addressing these questions requires not only technical innovations in circuit design and material selection but also a multidisciplinary consideration of environmental regulations, consumer behavior, and cost constraints. The successful realization of such a system has the potential to reduce food waste, improve food safety, empower consumers, and minimize environmental impact, thereby contributing both to the quality of life in Bangladesh and to the global push for sustainable smart packaging solutions.

4. Research Motivation

Bangladesh is at a critical juncture where the confluence of environmental degradation and food insecurity demands urgent and innovative solutions. The nation's rapid urbanization, coupled with inadequate waste management systems, has led to an alarming increase in plastic pollution. Studies indicate that a significant percentage of plastic waste is mismanaged, posing severe threats to both the environment and public health.

Concurrently, food security remains a pressing concern. Climate change exacerbates this issue by altering precipitation patterns, increasing the frequency of extreme weather events, and affecting agricultural productivity. These challenges are further compounded by post-harvest losses, often attributed to inadequate packaging and storage solutions.

In response to these interconnected challenges, the Bangladesh Environmental Conservation Rules 2023 (ECR 2023) have been enacted. These rules aim to mitigate environmental pollution by regulating the use of non-biodegradable materials and promoting sustainable practices across various sectors. Specifically, the ECR 2023 emphasizes the need for eco-friendly packaging solutions, aligning with global sustainability goals and addressing the nation's pressing environmental concerns.

This research is motivated by the necessity to develop a smart, biodegradable food packaging system that not only complies with the ECR 2023 but also enhances food safety and reduces environmental impact. By integrating a CMOS-based sensor circuit into biodegradable packaging materials, this study aims to create a system capable of monitoring food quality in real-time, thereby extending shelf life and reducing food waste. Such an innovation holds the potential to revolutionize food packaging in Bangladesh, aligning with national environmental policies and contributing to global sustainability efforts.

Objective

This research aims to address the critical challenges of post-harvest loss and compromised food safety in Bangladesh by developing a smart food packaging solution. The primary objective is to design, simulate, and comprehensively analyze a simple, low-cost sensor circuit that can be seamlessly integrated into a biodegradable packaging material to monitor food quality in real-time. This includes the design and investigation of a three-stage CMOS ring oscillator, intentionally loaded with a humidity-sensitive capacitive element to create a robust and reliable humidity sensor. The design will leverage modern Electrical and Electronic Engineering principles and tools, including **SPICE simulation** to perform detailed transient and parametric analyses, and **layout design** to create a practical, manufacturable circuit footprint that adheres to the constraints of the packaging medium.

To achieve this, the following key tasks will be undertaken:

- **Circuit Design and Simulation:** A humidity sensor circuit based on a CMOS ring oscillator will be designed and simulated using **Cadence Virtuoso** with the gpdk045 process kit. The oscillation frequency will be calibrated as a monotonic function of relative humidity (RH), with an expected sensitivity of approximately 15.8 kHz/%RH within the range of 20 to 80 RH, as determined by the capacitance change of the humidity-sensitive element. The performance will be rigorously validated through transient and parametric sweep analyses to ensure functionality and reliability [1].
- **Physical Implementation and Integration Proposal:** The design will be translated into a physical implementation through the creation of a detailed **stick diagram and layout**. A thorough proposal will be developed demonstrating how this electronic circuit can be practically integrated into the selected **biodegradable packaging material**, chosen after a comprehensive literature review [2]. This integration plan will address the critical challenges of physical compatibility and cost-effectiveness within the context of a low-income economy, where expensive imported technologies are difficult to implement [3].
- **Strategic and Sustainable Decision-Making Framework:** A crucial component of this work is the development of a structured decision-making algorithm. This framework will be designed to support actions that prioritize **food safety, human well-being, and environmental sustainability**, aligning with the **Bangladesh Environmental Conservation Rules 2023(4)** [4]. The algorithm will provide a clear, actionable guide for stakeholders, from producers to consumers, on how to utilize the sensor data to make informed choices that reduce waste and promote a circular economy [5]. This addresses the conflicting requirement of a lack of health safety knowledge by providing a clear, pre-defined set of actions based on the sensor output.

Ultimately, this research serves as a foundational step toward developing a **holistic smart packaging system** that not only provides technological solutions but also addresses the socio-economic and environmental complexities unique to Bangladesh.

5. Scope and Limitations

5.1 Scope

This study is confined to the **design, simulation, and proposal stages** of a CMOS-based sensor circuit intended for integration into biodegradable food packaging. Utilizing tools such as **SPICE simulation**, **stick diagrams**, and **layout design**, the research aims to develop a comprehensive blueprint for a smart packaging system that monitors food quality over time. The proposal includes:

- ❖ **Selection of Biodegradable Materials**: Identifying suitable biodegradable substrates for packaging, considering factors like mechanical strength, biodegradability, and compatibility with sensor integration.
- ❖ **Sensor Circuit Design**: Designing a low-cost, efficient CMOS-based sensor circuit capable of detecting environmental parameters indicative of food quality, such as humidity and temperature.
- ❖ **Integration Strategy**: Proposing methods for embedding the sensor circuit into the chosen biodegradable materials without compromising their integrity or functionality.
- ❖ **Decision-Making Framework**: Developing a structured algorithm to interpret sensor data and provide actionable insights, prioritizing food safety and sustainability.

By focusing on these aspects, the study aims to provide a **feasible and scalable solution** for smart food packaging that aligns with both technological advancements and environmental conservation efforts.

5.2 Limitations

While the proposed system offers promising solutions, several limitations must be acknowledged:

1. **Cost Barriers**: The production of biodegradable packaging materials integrated with sensor systems remains costly. Factors such as high manufacturing expenses and limited availability of raw materials contribute to the elevated costs of eco-friendly packaging solutions in Bangladesh.
2. **Limited Awareness and Knowledge**: There is a general lack of consumer awareness regarding the benefits and availability of biodegradable packaging. Studies indicate that while there is an expressed preference for green packaging among Bangladeshi consumers, actual purchasing behavior does not always align with these preferences.
3. **Technology Adoption Challenges**: The integration of advanced sensor technologies into packaging materials requires specialized knowledge and infrastructure. The absence of a robust technological ecosystem and the high costs associated with research and development pose significant barriers to the widespread adoption of such innovations.
4. **Regulatory and Policy Constraints**: Although the Bangladesh Environmental Conservation Rules 2023 aim to promote sustainable practices, the enforcement of these regulations is inconsistent. The absence of incentives for businesses adopting eco-friendly packaging and the prevalence of illegal plastic production further hinder the transition to sustainable packaging solutions.

5. **Simulation-Only Validation**: The study's reliance on simulation tools means that real-world variables such as mechanical stress, environmental fluctuations, and long-term durability of the biodegradable materials cannot be fully assessed. Physical prototyping and field testing are essential to validate the performance and reliability of the proposed system under actual conditions.

6. Literature Review

6.1 Food Packaging Practices in Bangladesh

Bangladesh’s food packaging currently relies heavily on conventional materials, especially single-use plastics. Market analyses indicate that common food packaging (e.g. for frozen and processed foods) involves plastic films, vacuum pouches, trays and foil-based packs[6]. Flexible polymer packaging is increasingly favored for its light weight and ease of use, although interest in recyclable or biodegradable alternatives is only in its early stages[7]. The country generates on the order of 87,000 tonnes of single-use plastic waste annually, with roughly 96% of it discarded without recovery[8]. The government has attempted to curb this (for example, the 2010 Mandatory Jute Packaging Act required biodegradable jute sacks for certain commodities), but enforcement has been weak[9]. Consumer surveys suggest that even knowledgeable urban food buyers tend to rely on plastic-packaged goods; in one study university students preferred Kraft-paper or cardboard containers, but overall demonstrated limited understanding of packaging symbols[10]. In practice, plastic remains dominant: for instance, the frozen-food industry routinely uses multilayer polyethylene and polypropylene films[6].

This prevalence of conventional packaging has led to serious problems. Improperly discarded plastic packaging contributes to environmental pollution and microplastic contamination – recent monitoring found MPs in water and aquatic organisms from Bangladeshi rivers and coastlines[8]. Moreover, plastic food-contact materials pose food safety risks. A 2023 study of Bangladeshi packaging found that common polymers (PET, PE, PP, PS, PC) can leach toxic heavy metals (lead, cadmium, etc.) into food simulants under normal use[11][12]. For example, acidified tests showed lead migration of several mg/kg from yogurt containers. Such findings imply potential health hazards from chronic ingestion of contaminants. In addition, conventional packages often provide suboptimal barrier protection: many Bangladeshi retails foods spoil quickly due to inadequate moisture and gas barriers, leading to food loss. Taken together, these issues – plastic waste, toxicity, and spoilage – highlight the drawbacks of Bangladesh’s traditional packaging approach and motivate the search for safer, more sustainable alternatives[8][11].

Attribute	Details
Title	University Student’s Knowledge, Practices, and Perceptions of Food Packaging Labels in Bangladesh: A Cross-Sectional Study
Authors	M. S. A. Hossain et al.
Year	2025

DOI	10.1002/fsn3.70567
Key Points	Cross-sectional survey of 397 university students across Bangladesh assessing their knowledge, practices, and preferences related to food packaging labels. Used a structured questionnaire based on food safety regulations and SPSS analysis (Chi-square tests, correlation) to evaluate labeling comprehension and behavior.
Findings	❖ **Knowledge:** 74.8% of students had adequate label knowledge. Most recognized expiry date and nutrition info, but far fewer understood batch numbers or package symbols. ❖ **Practices:** Only 44.3% demonstrated good labeling practices. Many did not regularly check best-before dates, allergen info, or barcodes. ❖ **Demographics:** Female and urban students scored significantly higher on knowledge and practices ($p < 0.001$). ❖ **Correlation:** Strong positive correlation ($r = 0.524$) between knowledge and practice suggests that improving label awareness could enhance safe packaging use. ❖ **Preferences:** Consumers favored packaging ensuring food protection, quality, and sustainability; Kraft paper/carton most preferred. ❖ **Conclusion:** Students had reasonable label knowledge, but behaviors were lacking—policy and awareness campaigns are needed.
Limitations	Convenience sampling of students limits generalizability beyond young educated consumers. Self-reported survey data may be biased. The cross-sectional design prevents causal conclusions. Focuses mainly on labeling knowledge, not on packaging safety or environmental impact.

Table 1

Attribute	Details
Title	Food Packaging Practices and Food Safety Knowledge among Street Food Vendors in Dhaka, Bangladesh
Authors	S. Alam, M. J. Hoque, & R. R. Ferdous
Year	2019
DOI	10.1016/j.foodcont.2019.106780
Key Points	Study examined food packaging and handling practices among 150 street food vendors in Dhaka. Structured observations and interviews assessed hygiene, packaging material usage, and compliance with safety standards.
Findings	❖ Vendors predominantly used low-cost non-biodegradable plastics and newspaper for packaging, often in direct contact with hot foods. ❖ Food safety knowledge was limited—only 22% of vendors knew about chemical leaching risks. ❖ Training level strongly influenced hygienic handling and safer packaging use. ❖ Lack of regulatory enforcement and cost concerns led to widespread unsafe practices.

	❖ Study highlighted urgent need for training programs and affordable sustainable packaging solutions.
Limitations	Small sample size restricted to Dhaka city, limiting national representativeness. Relies on self-reported vendor knowledge which may be overstated. Did not evaluate consumer perception of packaging safety.

Table 2

6.2 Smart Food Packaging Technologies

Smart packaging integrates visual indicators, sensors, and data carriers (barcodes/RFID) to monitor and communicate product quality[13][14]. Smart (also called *intelligent*) packaging moves beyond passive containment by actively tracking food condition. Such systems are designed to **monitor**, **detect**, **sense**, **record**, **track** and **communicate** relevant changes in or around the food[13]. In practice, an intelligent package typically includes one or more **indicators** (e.g. colorimetric labels) and **sensors** (electronic or chemical) that respond to spoilage markers, together with **data carriers** (barcodes, QR codes, RFID tags) that hold product information[13]. For example, a freshness indicator label might change color if a specific gas (like CO_2 or ammonia) accumulates, while an RFID tag on the same package encodes its batch number and expiration date. Data carriers enable end-to-end traceability: scanning a barcode/QR code or reading an RFID can reveal a product's origin, processing history and current status[15]. In short, smart packaging systems combine environmental sensing (via indicators/sensors) with information management (via data carriers) to give real-time feedback on food quality.

Numerous technologies exemplify this trend internationally. Colorimetric **freshness indicators** (often based on pH-sensitive or redox dyes) are already commercialized; they are printed on packaging to show spoilage through a visible hue change. Likewise, **time–temperature indicators (TTIs)** – chemical tags that irreversibly record thermal exposure – are used on chilled foods to flag cold-chain breaches. Modern **gas sensors** detect spoilage volatiles: oxygen indicator films (e.g. Ageless™ eye) reveal leaks in MAP packages, while CO_2 sensors correlate with bacterial growth in meats. Biosensor labels targeting amines or hydrogen sulfide are in development for fish and meat freshness. On the hardware side, **RFID tags and QR codes** are increasingly integrated into food packaging. For instance, the EU-funded MultiSens project developed an intelligent meat-packaging film: embedded CO_2 sensors (visible to a smartphone app) changed color as microbial activity raised CO_2 levels[16]. In the United States, major retailers have piloted RFID-based traceability – Walmart's long-standing RFID mandate and restaurant chains like Chipotle tagging produce[17] – to improve inventory management and safety. Blockchain systems are also being explored to link sensor data with immutable supply-chain records. These international examples demonstrate smart packaging's potential: indicators and sensors provide freshness readouts, while RFID/QR-barcode technologies enable precise tracking. However, despite this global momentum, Bangladesh has seen only nascent interest in such solutions. Industry reports note that local packaging producers are "exploring" recyclable/biodegradable options[18], but there is little evidence of actual smart packaging deployment.

Category	Details
Title	Smart packaging systems for food applications: A review
Authors	K. B. Biji, C. N. Ravishankar, C. O. Mohan, & T. K. Srinivasa Gopal
Year	2015
DOI	10.1007/s13197-015-1766-7
Key Points	Landmark review distinguishing **active** vs **intelligent** packaging; surveys commercial oxygen scavengers, moisture absorbers, antimicrobial systems, time–temperature indicators (TTIs), gas/freshness indicators, and data carriers (RFID). Discusses mechanisms, materials, and regulatory considerations for food-contact applications.
Findings	**Active packaging** extends shelf life by altering the headspace (e.g., O_2 scavengers, CO_2 emitters, moisture regulators) and/or releasing/absorbing compounds (antimicrobials/antioxidants). **Intelligent packaging** provides **status sensing** and traceability via TTIs, gas indicators (CO_2, NH_3, H_2S), and RFID/data carriers. The review maps product–technology fit (e.g., high-respiration produce → O_2/CO_2 control; chilled chains → TTIs) and notes early commercial uptake in select categories.
Limitations	Being an early comprehensive review, it predates recent advances in **printed electronics**, **NFC-enabled labels**, and **AI/IoT** analytics; limited cost–benefit evidence and real-world longitudinal performance data are discussed only briefly.

Table 3

Category	Details
Title	Intelligent packaging: Trends and applications in food systems
Authors	S. Kalpana, S. R. Priyadarshini, M. M. Leena, J. A. Moses, & C. Anandharamakrishnan
Year	2019
DOI	10.1016/j.tifs.2019.09.008
Key Points	High-impact review in **Trends in Food Science & Technology** covering architectures of intelligent packaging (indicators, sensors, data carriers), **consumer-facing freshness indicators**, and integration pathways with supply-chain monitoring. Addresses **waste reduction** potential and biopolymer compatibility.

Findings	Consolidates evidence that **TTIs** and **gas indicators** (e.g., pH-responsive dyes for amines) can correlate with microbial spoilage; **RFID/data carriers** enable cold-chain verification; **biopolymer matrices** (e.g., PLA, starch) can host natural pigments/antimicrobials to create multifunctional "smart" films. Identifies application spaces (meat/seafood, dairy, produce) and emphasizes user comprehension of indicators at retail.
Limitations	Largely **review-based** with limited quantitative meta-analysis; regulatory, **consumer acceptance**, and **scalability/cost** issues remain under-resolved; does not deeply evaluate long-term **sensor drift** or field failure modes in humid, resource-constrained markets.

Table 4

Category	Details
Title	RFID-based sensing in smart packaging for food applications: A review
Authors	J. Zuo, S. H. Yang, & M. P. Y. Desmulliez
Year	2022
DOI	10.1016/j.fufo.2022.100198
Key Points	Focused review on **RFID/NFC as both data carriers and sensing platforms** (e.g., moisture, gas, temperature) via antenna detuning, chip less tags, and printed/embedded transducers; surveys **battery-free** operation and supply-chain integration.
Findings	Demonstrates that **passive RFID** can infer environmental changes (e.g., humidity, spoilage-related VOCs) through **impedance shifts**; **chip less RFID** offers ultra-low-cost tagging for mass deployment; reports successful **printed antennas** and **sensor inks** on flexible substrates compatible with packaging lines. Outlines interoperability with **IoT backends** for real-time quality dashboards and recalls.
Limitations	Field performance can be undermined by **metallic/aqueous food contents**, **reader alignment**, and **multi-path** issues; **standardization** across frequencies/reader infrastructure and **data privacy** are unresolved; cost competitiveness vs. conventional labels depends on high-volume printing yields.

Table 5

6.3 Biodegradable Packaging Materials

Biodegradable and bio-based polymers offer sustainable alternatives to petrochemical plastics. Major biodegradable materials investigated for food packaging include **polylactic acid (PLA)**, **polyhydroxyalkanoates (PHAs)** like polyhydroxybutyrate (PHB) and PHB–co–hydroxyvalerate

(PHBV), **starch-based plastics**, **cellulose derivatives**, **proteins and polysaccharides** (e.g. chitosan, carrageenan), and various **biopolymer blends**[19][20]. PLA, derived from fermented plant sugars (e.g. corn or sugarcane), is one of the most widely used compostable polymers. It is clear, FDA-approved for food contact, and can be manufactured in rigid or film forms[21]. PLA typically has a glass transition ~63 °C and biodegrades much faster than conventional plastics. Commercial examples include NatureWorks® Ingeo™ PLA and blends like BASF's Ecoflex® (PLA/PBAT) for cups and trays[21][22]. In packaging, PLA is most suited for short-shelf-life items (cold cups, salad boxes, food service trays) because of its relatively low heat resistance[21][22].

PHAs are bacterial polyesters (such as PHB) that offer excellent barrier and optical properties. PHB has a high melting point (~180 °C) and good UV resistance[23], but its brittleness and cost have limited use. Copolymers like PHBV (adding hydroxyvalerate) or blends with PLA can improve toughness and processability[24][25]. **Starch-based plastics** are another large category: starch (from corn, potato, rice, etc.) is blended with plasticizers (glycerol, sorbitol) or other biopolymers to make thermoplastic starch (TPS). TPS is inexpensive and compostable, but very moisture-sensitive and mechanically weak. Commercial starch plastics include products like Ecofram™, Biocool™, Solanyl™ (TPS), and blends such as Novamont's Mater-Bi (starch/PCL)[26]. Often starch is used as a filler (up to ~70%) in PLA or PHA blends to reduce cost. **Cellulose-based materials** (such as regenerated cellulose, cellulose acetate, and bacterial cellulose) form high-barrier films; e.g., Innovia's NatureFlex® (cellulose film) and cellulose acetate (e.g. Bioceta™) have properties comparable to PET[27]. Protein films (e.g. wheat gluten, soy protein) and polysaccharides (alginate, carrageenan) are also studied for edible coatings or films. For example, chitosan (deacetylated chitin from crustacean shells) forms transparent antimicrobial films ideal for fruits and meats; it inhibits bacteria and fungi and biodegrades naturally[28].

Each of these materials has trade-offs relevant to food safety and sustainability. Generally, biodegradable polymers are made from renewable feedstocks and can be industrially composted, reducing plastic waste and fossil fuel use[19][29]. They tend to be non-toxic and meet food-contact safety standards (e.g. PLA and cellulose have GRAS status[21][27]). However, many have inferior barrier properties compared to petroplastics: for instance, neat PLA has poorer water-vapor resistance, and TPS is highly hygroscopic[30][31]. To address this, biopolymers are often blended or laminated: e.g., PLA is frequently mixed with starch, PBAT or PCL to enhance flexibility and moisture barrier[24][25]. Additives like nanoclays, cellulose nanofibers or waxes are also used to improve strength and slow gas transmission. In terms of mechanical performance, materials like PHB require copolymerization or plasticizers to avoid brittleness, and most biofilms have lower elongation than polyethylene. From a safety standpoint, some biopolymers (e.g. chitosan, alginate) are inherently antimicrobial, which can help extend shelf life. However, their degradation or moisture uptake may allow faster oxygen ingress if not properly stabilized.

Despite these challenges, biodegradable packaging's sustainability benefits are clear. By 2019 over half of global bioplastic production was biodegradable (mostly PLA, starch-based and PHA)[19], and packaging accounts for the largest bioplastics segment (53% by volume)[29]. In fact, compostable food packaging was the first bioplastic application to reach commercial scale[29]. Growing government regulations and consumer demand are driving research into improving these materials. For example, novel coatings (e.g. composite films of PLA with natural pigments) are being developed to add intelligent sensing functions while remaining biodegradable. In Bangladesh, interest in such materials is only nascent: aside from traditional jute bags (noted in legislation[9]), there are few examples of large-scale biodegradable packaging use. This contrasts with global trends where many biodegradable biopolymers are entering the food-packaging market.

Smart food packaging systems integrate sensors and indicators into packaging to actively monitor product quality and safety. Consumer demand for safer food has driven development of **active/intelligent packaging** that can track parameters like temperature, humidity, gas composition, and pH[6][7]. For example, modern smart packages may include RFID labels or printed sensors that detect humidity or spoilage gases and communicate status through visual tags or wireless links. Such technologies offer real-time quality assessment, extend shelf life, and reduce waste by alerting stakeholders to adverse conditions[6][7]. In particular, relative humidity (RH) inside a package is a key factor: high RH can encourage microbial growth or condensation, while low RH can desiccate foods. Integrating a humidity sensor into packaging can therefore provide an early warning of spoilage or failure of modified-atmosphere conditions.

Among humidity sensor implementations, **ring-oscillator (RO) frequency sensors** are well-established in CMOS technology. In these circuits, a humidity-sensitive capacitor is embedded in a ring oscillator so that increasing RH raises the capacitance and lowers the oscillation frequency. Several CMOS-MEMS prototypes demonstrate this approach. For instance, Yang *et al.* (2010) fabricated a 5-stage CMOS ring oscillator with an interdigital sensing capacitor coated by porous polypyrrole; the output frequency shifted by roughly 99 kHz per %RH at 25 °C[8]. Similarly, Yang *et al.* (2014) used a zinc-oxide sensing film on an interdigital capacitor: their 0.18 µm CMOS chip's frequency fell from 84.3 MHz to 73.4 MHz as RH rose from 40% to 90% (at 30 °C)[9]. These examples show that a simple RO circuit yields a digital (frequency) output proportional to humidity, avoiding the need for complex analog front-ends. In our design, the three-stage inverter ring oscillator behaves similarly: as the humidity-sensitive dielectric in the MIM capacitor absorbs water, its capacitance increases and the oscillator frequency drops. The digital output (frequency) can be easily counted by a microcontroller for %RH readout.

Recent literature emphasizes using **biodegradable substrates and materials** for smart packaging sensors. For example, Wawrzynek *et al.* (2021) printed interdigitated humidity sensors on various biodegradable films (PLA, paper, starch composite) and compared their performance[10][11]. They found that PLA and PET gave fast response (<5 min) and limited hysteresis, while paper and starch substrates had higher sensitivity but slower recovery (≈20 min) and larger hysteresis[11]. In these printed devices, the **substrate itself served as the sensing layer**: moisture uptake raised the substrate's permittivity, increasing capacitance[10]. In a complementary approach, Bourely *et al.* (2023) demonstrated fully green RF resonators by coating them with natural hygroscopic layers (e.g. psyllium, konjac, egg albumin). Thin (~10 µm) layers of these biopolymers produced large frequency shifts (>100 MHz) between 20% and 80% RH, with good reversibility[12]. These studies confirm that biodegradable films and coatings can transduce humidity into electrical signals. In practice, one could integrate our CMOS RO sensor by embedding the chip on a PLA film or coating its capacitor with a hygroscopic biopolymer, thereby leveraging the packaging material as part of the sensing mechanism.

Biodegradable packaging materials. A variety of biopolymers are candidates for eco-friendly food containers. We summarize key types below, with their properties and relevance:

- **Polylactic Acid (PLA)** – An aliphatic polyester made by fermenting renewable feedstocks (corn, sugar, etc.), PLA is compostable and degrades in soil/compost[13][14]. It is transparent, has a glass transition ~63 °C, and can be tuned from amorphous to semi-crystalline by adjusting monomer ratio[13]. PLA is already used in food-service items and packaging: for example, PLA trays and films are used for short shelf-life foods[15][16]. BASF's Ecoflex®/PLA blends and Natureworks™ Ingeo® are commercial examples. Pure PLA tends to have relatively high water vapor transmission, but its barrier can be improved by blending; e.g. adding 20–35%

PHBV or 20% PBS to PLA increases its barrier properties[17][18]. We consider PLA the primary packaging material due to its maturity and availability, with proven use in containers and trays[15][16].

- ❖ **Polybutylene Succinate (PBS) / PBAT** – PBS is an aliphatic polyester (polycondensation of 1,4-butanediol and succinic acid) with properties similar to conventional polyolefins: tensile properties near PE/PP and very high elongation (≈330%)[19]. Its melting point is ~90–120 °C[19]. PBS is fully biodegradable but is hygroscopic and has a poor moisture barrier by itself[18]. Often PBS is blended with PLA or starch to yield compostable films. PBAT (polybutylene adipate-co-terephthalate) is a related aliphatic–aromatic copolymer that is soft and flexible; it is widely used (often mixed with PLA or starch) to impart ductility in biodegradable bags. As [33] notes, blends like PLA/PBS (20:80) can dramatically improve water-retention[18].
- ❖ **Polycaprolactone (PCL)** – PCL is a semi-crystalline polyester (T_g ~ –60 °C) known for high flexibility. It has elongation ≈250–300% (comparable to HDPE)[20]. PCL is fully biodegradable and mixes well with PLA; for instance, a 1:3 PLA:PCL blend achieved >1000% elongation[21]. PCL's low melt point (~60 °C) makes it easy to process, but it has relatively poor stiffness and barrier unless blended.
- ❖ **Polyhydroxyalkanoates (PHAs)** – This family includes polyhydroxybutyrate (PHB) and its copolymers (PHBV, PHBH, etc.). PHAs are biopolyesters produced by microbes using renewable feedstocks. PHB by itself is biodegradable, has excellent gas and UV barrier, and decomposes to water/CO_2[22]. However, PHB is quite stiff and brittle[22]. Incorporating 3-hydroxyvalerate to form PHBV reduces crystallinity and improves toughness; blends with PHB/PHBV are used for rigid packaging. For example, adding 20–35% PHBV to PLA improves compatibility and barrier performance[23].
- ❖ **Starch-based and Cellulosic Materials** – Polysaccharides like corn or potato starch, cellulose (paper), and other biopolymers can form low-cost biodegradable films. Such materials are inherently hygroscopic. Wawrzynek *et al.* found that humidity sensors on paper and starch substrates had the highest sensitivity[11]. Pure starch films (with plasticizers) are brittle and have high water permeability, so they are often blended (e.g. with PLA or glycerol). Cellulose (paperboard or pulp) is commonly used in packaging; it is cheap, compostable, and can host printed electronics[24][11]. However, high humidity can weaken starch/cellulose films, so protective coatings are sometimes applied (e.g. beeswax in [8]).
- ❖ **Chitosan** – Derived from chitin, chitosan is a biopolymer with strong film-forming and antimicrobial properties (effective against bacteria, yeasts, and fungi in food)[25]. Edible chitosan coatings are known to extend shelf life of produce by inhibiting microbes[26]. Chitosan films also offer good oxygen barrier. Its drawback is solubility only in acidic solutions and a tendency to be brittle, so chitosan is typically used as a thin coating or blended with other polymers.

Each material has trade-offs (mechanical strength, barrier, processability), but all support biodegradability or compost-ability as required by environmental regulations. PLA was chosen as our primary packaging substrate due to its balance of mechanical properties and existing food-industry use[15][14]. Other materials (PBS, PCL, PHAs, starch, chitosan) remain as options for modified packaging designs or sensor coatings in future work.

Category	Details
Title	Emerging trends in biomaterials for sustainable food packaging: A comprehensive review
Authors	M. Z. Al Mahmud, M. H. Mobarak, & N. Hossain
Year	2024
DOI	10.1016/j.heliyon.2024.e24122
Key Points	Broad synthesis of **bio-based materials** (PLA, starch, cellulose, chitosan, PHAs) and **nanocomposites** for sustainable food packaging; maps links between material chemistry, barrier/mechanical properties, and shelf-life outcomes; discusses circularity and end-of-life routes.
Findings	(i) **PLA** and **PHAs** lead industrial adoption due to processability and regulatory familiarity; (ii) **Nano-reinforcements** (e.g., nano clay, cellulose nanofibers) substantially improve **oxygen/moisture barrier** and toughness; (iii) **Active systems** (antimicrobial/antioxidant) embedded in biopolymer matrices extend shelf life; (iv) **Edible/coated films** and **waste-derived biopolymers** advance circular economy narratives; (v) Market adoption is accelerated by policy pressure but constrained by cost/performance variability.
Limitations	Review underscores persistent gaps: **moisture sensitivity**, thermal limits (Tg/Tm windows), and **scale-up** hurdles for bio-composites; limited in-field longevity data in humid, resource-constrained supply chains; calls for standardized testing across real food matrices and disposal pathways.

Table 6

Category	Details
Title	Review of bio-based biodegradable polymers: Smart solutions for sustainable food packaging
Authors	M. Stoica, A. Moise, & D. Stoica
Year	2024
DOI	10.3390/foods13193027

Key Points	State-of-the-art review in *Foods* detailing **PLA, PHA, starch, cellulose** for **active/intelligent** packaging; examines migration safety, antioxidant/antimicrobial loading, and **biodegradation/compostability claims vs. infrastructure**.
Findings	(i) **Bio-based polymers** can reduce environmental impact and support **active functions** (e.g., natural extracts/essential oils in PLA) that **slow oxidation and microbial growth**; (ii) Functionalization strategies (plasticizers, blends, nanofillers) address brittleness and barrier deficits; (iii) **Intelligent indicators** (pH, gas, TTI dyes) are increasingly compatible with biopolymer films; (iv) Adoption depends on **cost, regulatory compliance, and consumer acceptance**; (v) Emphasizes **traceability** and integration with smart tags for supply-chain transparency.
Limitations	Highlights **performance trade-offs** (moisture uptake, heat resistance), **higher costs**, and **fragmented composting/collection infrastructure**; many studies are lab-scale with limited **real-world validation** and long-term storage data under diverse climates.

Table 7

Category	**Details**
Title	Smart packaging based on polylactic acid: The effects of antibacterial and antioxidant agents from natural extracts on physical–mechanical properties, colony reduction, perishable food shelf life, and future challenges
Authors	H. Nasution, P. Dewi, R. Fitriani, & M. Asrofi
Year	2023
DOI	10.3390/polym15204103
Key Points	PLA-centric review in *Polymers* detailing **integration of natural antimicrobials/antioxidants** (e.g., phenolics, essential oils) into PLA and the resulting impacts on **mechanical, barrier, and antimicrobial** performance; surveys shelf-life tests on perishables.
Findings	(i) **Active PLA films** with plant-derived agents demonstrate **colony reduction** and **oxidation delay**, extending shelf life of meats, fruits, dairy; (ii) **Formulation levers**—plasticizers, compatibilizers, and **nanofillers**—help offset PLA brittleness and improve **O_2/H_2O barrier**; (iii) Controlled release and **migration compliance** are key to maintaining sensory quality; (iv) Compatibility with **printing/coating** enables smart functions (indicators, RFID/NFC attachment) without severe property loss; (v) Provides a roadmap for **scalable film/blend processing** (casting, extrusion) relevant to packaging lines.
Limitations	Notes **trade-offs**: essential oils can **plasticize** films and weaken mechanics; **thermal limits** and **hydrophilicity** remain concerns for humid chains; much evidence is **lab-scale**, with fewer large-scale **pilot/manufacturing** validations and limited multi-month **real-food** studies.

Table 8

Key references: Smart/intelligent packaging concepts[6][7]; CMOS humidity sensors with ring oscillators[8][9]; printed biodegradable humidity sensors and substrates[9][12]; biodegradables for packaging (PLA, PBS, PCL, PHAs, starch, chitosan)[13][18][25][26]. These sources inform the design of our sensor circuit and the selection of PLA packaging material for the smart package.

6.4 Sensor Technologies for Food Quality

A key component of smart packaging is real-time food quality sensing. **Gas sensors** are the most common approach: spoilage of proteins and produce produces characteristic volatiles (e.g. CO_2, O_2 depletion, NH_3, H_2S, amines, ethanol[32]). Integrating gas-sensitive materials into packaging allows direct spoilage detection. For instance, colorimetric O_2 indicator dyes (based on redox chemistry) have long been used to monitor MAP integrity[33]. CO_2 and ammonia indicators (often using pH dyes) reveal microbial fermentation; optical films containing anthocyanins or betacyanin's shift color as CO_2 or basic volatiles increase[34][35]. Emerging **electronic gas sensors** (Chemi resistive or MOSFET-based) can quantitatively detect specific gases, but their incorporation into packaging remains largely experimental. **Humidity and temperature sensors** are also employed to verify storage conditions. Commercial time–temperature indicator labels use chemical kinetics or enzyme reactions to signal cumulative heat exposure, and digital temperature loggers or simple thermochromic inks can mark temperature abuse. Humidity sensors (e.g. printed capacitive films) are used less often but can detect package leaks or moisture ingress. Additionally, **pH sensors** (usually optical) track changes in acidity that occur as food spoils. Natural pH-sensitive pigments (anthocyanins from fruit, curcumin from turmeric, etc.) change color in response to volatile amines (which raise pH)[34][35]. Such bio-based sensors are attractive due to their non-toxicity and biodegradability.

All these sensor elements require compatible electronics that ideally are low-power and eco-friendly. In practice, many smart labels use passive architectures: for example, NFC or RFID tags can power tiny sensing elements by harvesting reader energy. **Biodegradable circuits** are an active research area. Substrates like cellulose paper or biodegradable polymers (e.g. polylactic acid films) are being tested for printed circuits. Recent work demonstrates fully biodegradable circuit boards: Turner *et al.* (2023) reported stretchable circuit substrates made from a citric-acid–based biodegradable elastomer (POMaC), with printed copper traces that degrade under composting conditions[36]. Similarly, paper and gelatin matrices have been used as circuit laminates. Power sources are often minimized: RFID/NFC tags eliminate batteries by relying on RF coupling, and ultra-low-power microcontrollers can run from tiny coin cells. In the lab, transient electronics (made from magnesium or silk substrates) have shown proof of concept for edible sensors. Taken together, the sensor component in food packaging leverages both traditional semiconductor sensors and novel bio-based indicators, combined with innovations in low-power, degradable electronics[37][14].

Field	Details
Title	Electronic Sensing Technologies in Food Quality Assessment: A Comprehensive Literature Review
Authors	M. Gil et al.

Year	2023
DOI	10.3390/app15031530
Key Points	Comprehensive review of electronic nose (e-nose), electronic tongue (e-tongue), and electronic eye (e-eye) technologies for evaluating food quality. Focuses on how these sensor systems emulate human senses (olfaction, taste, vision) to detect and quantify food characteristics and contaminants.
Findings	- **Research Focus**: The e-nose (volatile gas sensor array) is the most extensively studied; fewer publications address e-tongue and e-eye. - **Evolution**: Earlier studies targeted single attributes (e.g., one aroma compound), but advanced instruments now combine multiple sensors for a fuller profile. - **Sensor Fusion**: High accuracy achieved by integrating sensors (e.g., coupling e-nose and e-tongue). Combined setups outperform individual devices in food assessment accuracy.
Limitations	Each sensor type alone cannot capture all aspects of food quality. Individual analyses provide only partial information, requiring multi-sensor integration. Practical issues include calibration, drift, and sensitivity to environmental factors.

Table 9

Field	Details
Title	IoT-Enabled Biosensors in Food Packaging: A Breakthrough in Food Safety for Monitoring Risks in Real Time
Authors	X. Yang et al.
Year	2025
DOI	10.3390/foods14081403
Key Points	Reviews the integration of biosensors into food packaging, connected via IoT, to continuously monitor food safety risks. Biosensors (often electrochemical) detect spoilage indicators (pathogens, toxins, metabolites) by producing electrical or colorimetric signals. IoT connectivity enables real-time data transmission from packaging to devices/cloud.
Findings	- **Real-Time Monitoring**: Sensor-laden packaging issues early warnings (e.g., when humidity/temperature deviate). - **Applications**: Electrochemical sensors detect pathogens, allergens, toxins, and biochemical spoilage markers. - **IoT & AI**: IoT enables continuous data sharing; AI/ML enhances sensor data interpretation. Cloud storage improves traceability and combats food fraud. - **Challenges & Opportunities**: Highlights technical/economic/regulatory challenges, and suggests autonomous packaging, standardized integration platforms, and sustainability-oriented supply chains as future directions.
Limitations	Key obstacles include data security and privacy concerns from continuous wireless monitoring. Technical hurdles involve developing robust, low-cost sensors for long-term packaging use. Lack of IoT standards and life-cycle impacts (sensor disposal, safety) remain unresolved.

Table 10

Field	Details
Title	Applications of Gas Sensing in Food Quality Detection: A Review
Authors	M. Ma et al.
Year	2023
DOI	10.3390/foods12213966
Key Points	Surveys gas sensor technologies (metal oxide, SAW, colorimetric, electrochemical) for detecting volatile compounds as spoilage indicators. Discusses sensor arrays (e-noses) for gases released by deteriorating foods (meat, seafood, fruits, vegetables). Integration with AI/ML to improve data interpretation.
Findings	- **Sensor Types**: MOX/MOS and colorimetric sensors dominate, valued for fast response and wide detection range. SAW and electrochemical sensors used for niche cases. - **Performance**: Gas arrays detect VOCs (e.g., hexanal from fat oxidation) with short response times, high sensitivity, and repeatability. - **Advances**: AI/ML improves accuracy in freshness prediction. - **Applications**: Effective for monitoring freshness/spoilage of meat, fish, and produce in real time.
Limitations	Gas sensors face cross-sensitivity (interference from multiple compounds) and require calibration for different foods. Long-term stability/selectivity can be problematic. Integration into packaging must be cost-effective, food-safe, and address power/disposal challenges.

Table 11

6.5 Gap Analysis

Despite these global advances, Bangladesh exhibits a marked gap in integrating smart technology with sustainable packaging. The literature and market reports reviewed here contain **no examples** of food packages in Bangladesh that combine biodegradable materials with embedded sensors or indicators. Domestic studies on packaging have focused on conventional issues (plastic waste and contamination[11], labeling awareness[10]) and have not addressed intelligent packaging. Regulatory initiatives (e.g. bans on plastic bags, mandatory jute sacks[9]) concentrate on material substitution, with little mention of sensor-based safety systems. A recent industry analysis even notes that sustainability awareness in Bangladesh's packaging sector is "still in early stages," albeit growing[18]. In other words, while suppliers are just beginning to explore recyclable or biodegradable materials[18], the concept of embedding gas/pH/temperature sensors or RFID tracking into such materials appears entirely absent. In practice, Bangladeshi food producers and retailers currently rely on unsophisticated packaging; digital traceability and freshness monitoring are virtually unknown. This highlights a clear research and development opportunity: combining Bangladesh's emerging biodegradable packaging industry (e.g. jute and bio-polymer films) with smart sensor technology could greatly improve food safety and shelf-life. Filling this gap would align Bangladesh's packaging practices with international trends in active and intelligent food packaging, and advance both consumer protection and environmental sustainability in the local context.

Paper/Title	Key Contributions	Gaps / Limitations	Relevance to Current Study
University Student's Knowledge, Practices, and Perceptions of Food Packaging Labels in Bangladesh: A Cross-Sectional Study (Hossain et al., 2025)	Assessed knowledge, practices, and perceptions of food packaging labels among Bangladeshi university students; highlighted correlation between knowledge and behavior; identified preferred sustainable packaging materials.	Limited generalizability (young, educated consumers only); self-reported data may be biased; cross-sectional design cannot infer causality; focuses on labeling, not on actual food safety or packaging materials.	Shows consumer awareness gap; indicates the need for educational interventions and behavior-focused designs in smart packaging. Useful for designing user-centric alert systems in biodegradable smart packaging.
Assessment of Heavy Metals Migrated from Food-Contact Plastic Packaging: Bangladesh Perspective (Eti et al., 2023)	Lab-based assessment of heavy metal migration from common Bangladeshi plastic FCMs; quantified Pb, Cd, Hg, Cr, Sb leaching; established baseline health risk data.	Small sample set (25 items) may not represent full packaging range; harsh testing (70 °C) may overestimate migration; only heavy metals tested (no plasticizers or dyes).	Highlights the health risk of conventional plastics; reinforces the rationale for biodegradable, non-toxic smart packaging with integrated sensors.
Packaging and Microbial Status of Local & Branded Bakery Products: A Comparative Study on Jessore Region, Bangladesh (Al-Fuad et al., 2018)	Evaluated packaging conditions and microbial contamination in local vs branded bakery products; linked poor packaging to higher spoilage rates; quantitative microbial analysis provided.	Limited to one city and bakery items; small sample size (20) for microbial tests; packaging assessment qualitative; not generalized.	Supports need for monitoring food quality in local markets; indicates potential for sensor-enabled smart packaging to track spoilage in real time.
Smart Packaging Systems for Food Applications: A Review (Biji et al., 2015)	Reviewed active (oxygen/moisture scavengers, antimicrobials) and intelligent packaging (sensors, RFID, indicators); discussed commercial applications and real-time monitoring possibilities.	Higher cost and technical complexity; requires new supply chain infrastructure; limited consumer awareness; evolving regulatory approval.	Provides foundation for integrating intelligent sensors (humidity, freshness indicators) into packaging.

Recent Advances in the Fabrication of Intelligent Packaging for Food Preservation: A Review (Mkhari et al., 2025)	Summarizes sensor- and indicator-embedded packaging, nanomaterials, bio-based smart polymers, and RFID technologies; highlights real-time food safety monitoring and extended shelf life.	High production cost; sensor accuracy, power sourcing, and robustness challenges; regulatory and consumer adoption still limited.	Supports the use of biodegradable polymer substrates (PLA) combined with embedded humidity sensors; informs design constraints.
Emerging Trends in Biomaterials for Sustainable Food Packaging: A Comprehensive Review (Al Mahmud et al., 2024)	Reviews biodegradable polymers, composites, nanofillers, edible films; emphasizes circular economy and sustainability; shows improved mechanical/barrier properties via nanotechnology.	Many biomaterials have inferior mechanical/barrier properties; cost-effectiveness and scalable production are unresolved; further R&D needed.	Justifies the selection of PLA as a preferred biodegradable substrate; identifies opportunities for enhancing sensor integration without compromising packaging integrity.
Review of Bio-Based Biodegradable Polymers: Smart Solutions for Sustainable Food Packaging (Stoica et al., 2023)	Focuses on PLA, PHA, polysaccharides/proteins as bio-based polymers; examines integration with active packaging and environmental sustainability; evaluates functional properties.	Bio-polymers absorb moisture, lower thermal resistance, weaker barrier and mechanical properties compared to plastics; may require blending/nano-reinforcement.	Guides material selection for sensor integration; indicates design trade-offs between sustainability and functional performance.
Electronic Sensing Technologies in Food Quality Assessment: A Comprehensive Literature Review (Gil et al., 2023)	Comprehensive review of e-nose, e-tongue, e-eye for food quality; discusses sensor fusion, AI/ML for multi-parameter assessment; highlights frequency-domain sensing.	Individual sensors cannot capture all food quality aspects; practical challenges include calibration, drift, and environmental sensitivity.	Reinforces the choice of humidity-based sensor as first step; suggests future multi-sensor integration for broader food quality monitoring.
IoT-Enabled Biosensors in Food Packaging: A Breakthrough in Food Safety for Monitoring Risks in Real Time (Yang et al., 2025)	Reviews biosensors in packaging with IoT connectivity; real-time monitoring of pathogens, allergens, spoilage indicators; cloud integration for traceability.	Data security/privacy concerns; technical hurdles for low-cost, long-term operation; standardization and life-cycle impact unresolved.	Supports future work for RF-powered wireless readout; aligns with Bangladesh environmental and food safety regulations for continuous monitoring.

Applications of Gas Sensing in Food Quality Detection: A Review (Ma et al., 2023)	Surveys gas sensors (MOX, SAW, electrochemical, colorimetric) for VOCs indicating spoilage; discusses AI-assisted data analysis; effective in real-time food freshness monitoring.	Cross-sensitivity, calibration requirements, stability/selectivity over time; cost-effective integration in packaging challenging.	Demonstrates potential for expanding current sensor framework beyond humidity to gas detection in future iterations.

Table 12: Comprehensive Analysis of all Papers & Journals

Sources: Peer-reviewed reviews and studies on smart/intelligent packaging and biodegradable materials[13][19][21][32][34][35]; Bangladesh-specific reports and articles on packaging practices, waste and safety[6][8][11][10].

7. Material Selection

The success of any smart packaging system depends not only on the performance of the embedded sensor, but also on the selection of the base packaging material. The material acts as both the **physical carrier** of the sensor and the **environmental interface** between the packaged food and the outside world. A well-chosen material ensures mechanical protection, chemical stability, consumer safety, and environmental sustainability. In this work, **Polylactic Acid (PLA)** is chosen as the primary packaging substrate. Below, we provide a detailed justification for this choice, considering structural, environmental, regulatory, and functional requirements.

7.1 Criteria for Material Selection

When selecting a packaging substrate for embedding a humidity sensor, several criteria were evaluated:

1. **Food Safety & Biocompatibility**
    a. The material must be safe for direct contact with perishable foods (fruits, vegetables, dairy, meat).
    b. It should not leach harmful chemicals into food, nor react with moisture or gases.
2. **Mechanical Strength & Flexibility**
    a. The packaging must withstand handling, storage, and transportation stresses.
    b. Flexibility is especially important for integration with thin-film or printed sensors.
3. **Barrier Properties**
    a. Adequate resistance against oxygen and moisture diffusion helps extend shelf life.
    b. At the same time, controlled permeability ensures that the humidity sensor can capture realistic internal package conditions.
4. **Process Compatibility**
    a. The material must allow integration of electronic or printed sensor structures without degradation.

b. It should support adhesion of conductive inks, deposition of electrodes, or lamination with flexible circuits.

5. **Sustainability & Regulatory Compliance**
    a. The packaging must be biodegradable or recyclable in line with Bangladesh Environmental Conservation Rules 2023(4).
    b. Preference is given to bioplastics over petroleum-derived plastics.
6. **Cost & Scalability**
    a. Material choice must be economically viable for mass production.
    b. Availability within the local and global supply chain is critical for adoption.

Criteria	**PLA (Polylactic Acid)**	**PET (Polyethylene Terephthalate)**	**PHA (Polyhydroxyal kanoates)**	**Cellulose-based Films**
Food Safety & Biocompatibility	Yes (FDA/EFSA approved)	Yes (Widely approved)	Yes (Biocompatible)	Yes
Mechanical Strength & Flexibility	Good (Flexible blends)	Excellent	Good (Superior barriers)	Poor (Brittle)
Barrier Properties	Moderate (Tunable)	Excellent	Excellent	Poor
Process Compatibility	Good (Printed electronics)	Excellent	Challenging	Difficult
Sustainability & Regulation	Excellent (Biodegradable)	Poor (non-biodegradable)	Excellent (Fully biodegradable)	Excellent (Biodegradable)
Cost & Scalability	Good (Mass production)	Excellent (Low cost)	Poor (Expensive)	Poor
Overall Score	Best Balance	Not Suitable (Sustainability)	Too Expensive	Not Robust

Table 13: Packaging Materials Eligibility

7.2 Justification for PLA (Polylactic Acid)

7.2.1 Origin and Properties

PLA is a **biodegradable aliphatic polyester** derived from renewable resources such as corn starch, sugarcane, or cassava. Unlike conventional plastics (PE, PET, PP), PLA is compostable under industrial conditions and leaves no toxic residues. Its mechanical properties are similar to PET, while offering better environmental credentials.

Key Material Properties:

- **Glass transition temperature (Tg):** ~60–65 °C
- **Melting temperature (Tm):** ~150–160 °C
- **Tensile strength:** Comparable to polystyrene
- **Transparency:** High optical clarity, suitable for consumer packaging
- **Biodegradability:** Complete under composting conditions

7.2.2 Alignment with Food Safety

PLA has been approved by the **U.S. Food and Drug Administration (FDA)** and the **European Food Safety Authority (EFSA)** for use in food-contact applications. Unlike certain petroleum-based plastics, PLA does not contain bisphenol-A (BPA), phthalates, or other plasticizers that can migrate into food. For a humidity sensor integrated package, this is critical since the sensor itself must remain in close proximity to food.

7.2.3 Mechanical and Functional Suitability

- **Strength:** PLA films provide good rigidity, making them suitable for rigid containers, trays, and wraps.
- **Flexibility:** Modified PLA blends or biaxially oriented PLA (BOPLA) can be engineered to behave like flexible wraps. This allows integration of thin-film humidity sensors without risk of mechanical cracking.
- **Processability:** PLA supports conventional film extrusion, thermoforming, and lamination, enabling scalable industrial adoption.
- **Sensor Integration:** Conductive inks (carbon, silver, graphene) adhere well to PLA surfaces, enabling printed circuit traces. Moreover, its smooth surface minimizes defects in printed electrodes.

7.2.4 Barrier Properties for Food Preservation

PLA inherently has **moderate oxygen and water vapor barrier properties**. Compared to PET, PLA is slightly more permeable to moisture, but this can be advantageous:

- It allows the humidity sensor to capture changes in the microenvironment inside the package.
- For high-barrier applications, multilayer PLA composites (e.g., PLA coated with chitosan, cellulose nanocrystals, or thin films of SiOx) can be used.

This balance between protection and permeability makes PLA particularly suitable for **fresh produce, dairy, and bakery products**, where monitoring microclimate is critical.

7.2.5 Environmental and Regulatory Advantages

The **Bangladesh Environmental Conservation Rules 2023** explicitly discourage conventional plastic packaging and encourage biodegradable alternatives. PLA directly aligns with these national priorities:

- **Renewable feedstock:** Locally sourced starch and sugarcane waste could eventually supply PLA production in Bangladesh.
- **Biodegradability:** At end-of-life, PLA reduces landfill load and plastic pollution in rivers.
- **Consumer perception:** Eco-friendly packaging boosts consumer trust and brand value, especially as awareness of plastic pollution grows.

Thus, PLA not only fulfills technical needs but also ensures **regulatory compliance and societal acceptance**.

7.3 Alternative Materials Considered

To ensure objectivity, other potential materials were evaluated before selecting PLA:

1. **Polyethylene Terephthalate (PET)**
    - Pros: Excellent strength, clarity, low cost.
    - Cons: Petroleum-derived, non-biodegradable, environmentally restricted in Bangladesh.
2. **Polyhydroxyalkanoates (PHA)**
    - Pros: Fully biodegradable, superior barrier properties.
    - Cons: Expensive, limited availability, processing challenges.

3. **Cellulose-based films**
    - Pros: Excellent biodegradability, renewable.
    - Cons: Poor mechanical robustness, low water resistance, difficult for sensor integration.
4. **Starch-based blends**
    - Pros: Inexpensive, compostable.
    - Cons: Poor moisture resistance, mechanical brittleness.

Among these, PLA offers the best **balance between mechanical strength, food compatibility, barrier control, and commercial viability**.

7.4 Practical Integration with Humidity Sensor

- **Sensor Attachment:** PLA films provide smooth, printable surfaces for deposition of humidity-sensitive electrodes. Conductive inks and adhesive microelectronic components can be laminated without loss of performance.

- **Biodegradable Adhesives:** PLA-based hot-melt adhesives can be used to attach the sensor circuit without introducing non-compostable elements.
- **RF Transparency:** PLA is non-metallic and RF-transparent, making it compatible with NFC/RFID communication for wireless readout.
- **Thermal Limits:** Since PLA softens above 60 °C, processing must avoid excessive heat. However, this is compatible with cold-chain and ambient food packaging.

8. Sensor Circuit Design & Tools Usage

8.1 Working Principle

Humidity Sensor based on 3-Stage Ring Oscillator with Humidity-Sensitive Capacitance

- **Ring Oscillator Fundamentals**

A ring oscillator is composed of an odd number (N) of inverter stages connected in a closed feedback loop. Oscillation arises because the closed loop provides a net 180° phase shift while simultaneously amplifying noise into a periodic signal.

The fundamental oscillation frequency *f* (first harmonic) of an N-stage ring oscillator is given by:

$$f \approx \frac{1}{2N \cdot t_{pd}}$$

where *t_pd* is the average propagation delay of a single inverter stage.

For a CMOS inverter driving a capacitive load (*C_L*), the propagation delay is proportional to load capacitance and can be expressed as:

$$t_{pd} \approx K \cdot C_L$$

where *K* is a technology-dependent constant related to drive current, transistor sizing, and supply voltage. Combining the above relationships gives:

$$f \approx \frac{1}{2NKC_L}$$

Thus, the oscillator frequency is inversely proportional to the load capacitance. By exploiting this property, we can design a capacitive sensor that modulates *C_L* in response to relative humidity.

8.2 Humidity-Sensitive Capacitance

The humidity transducer is realized as a capacitor whose dielectric permittivity varies with absorbed water molecules. Common materials for such capacitors include polymers, porous oxides, or biopolymer coatings that exhibit a significant dielectric constant change under different relative humidity (RH) levels.

In this design, as RH increases, the dielectric absorbs water vapor, increasing permittivity → capacitance (*C_hum*) increases → oscillator frequency (*f*) decreases. This monotonic and predictable relationship enables straightforward calibration between frequency shift and humidity percentage.

8.3 Circuit Design

All circuit design and analysis were performed using **Cadence Virtuoso** with the **gpdk045 (45 nm) CMOS technology library**. The following steps were undertaken:

- **Circuit Schematic Design:**
  A three-stage CMOS ring oscillator was constructed, with one stage loaded by the humidity-sensitive capacitor (*C_hum*). The basic inverter schematic used standard NMOS and PMOS transistors sized for balanced switching.

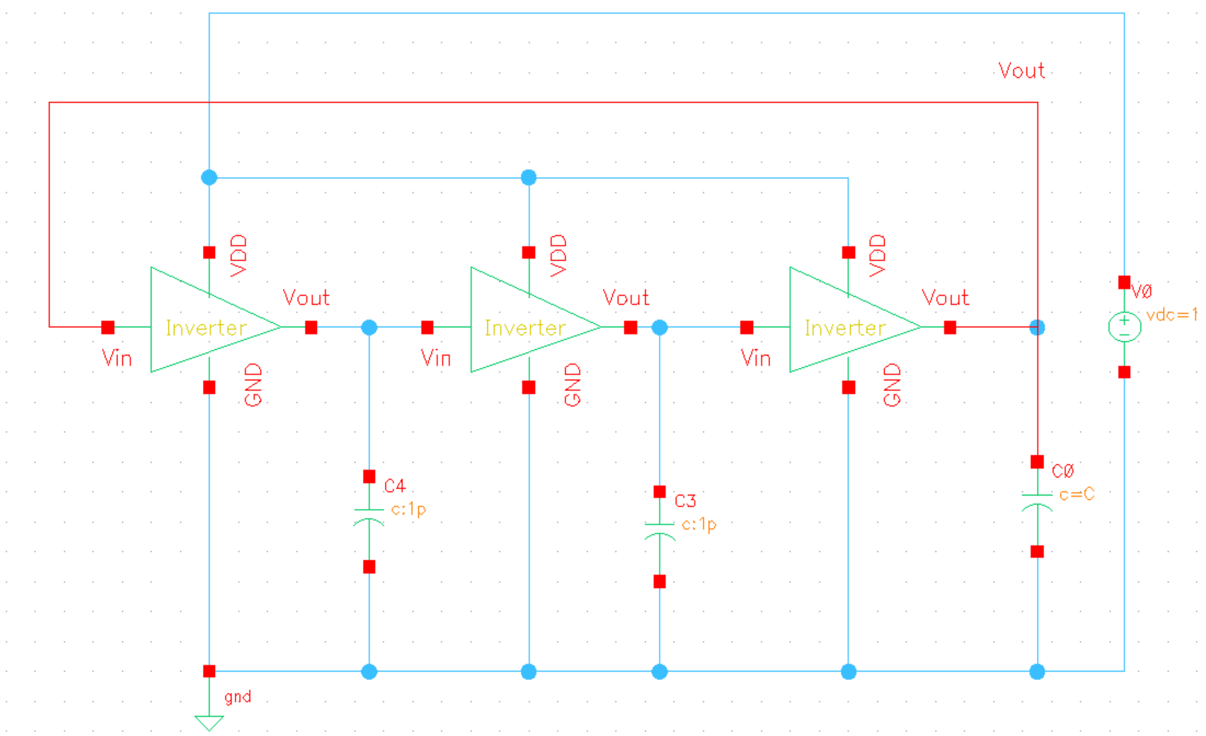

Figure 1: Schematic of the sensor Circuit: 3 stage ring oscillator paired with a Humidity sensitive Capacitor at the output node.

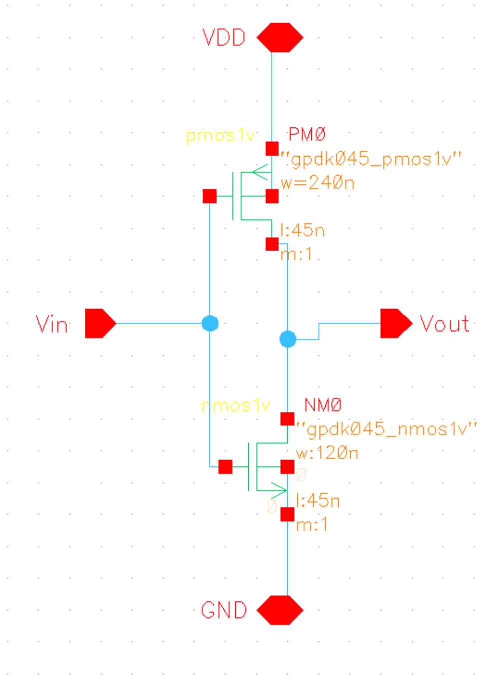

Figure 2: CMOS Inverter schematic

- **Transient Analysis:**

  Time-domain simulations were conducted at room temperature (27 °C). The oscillator exhibited stable periodic oscillations, as shown in **Fig. 3**, with a nominal oscillation frequency of **F= 8.20962 MHz** at baseline capacitance.

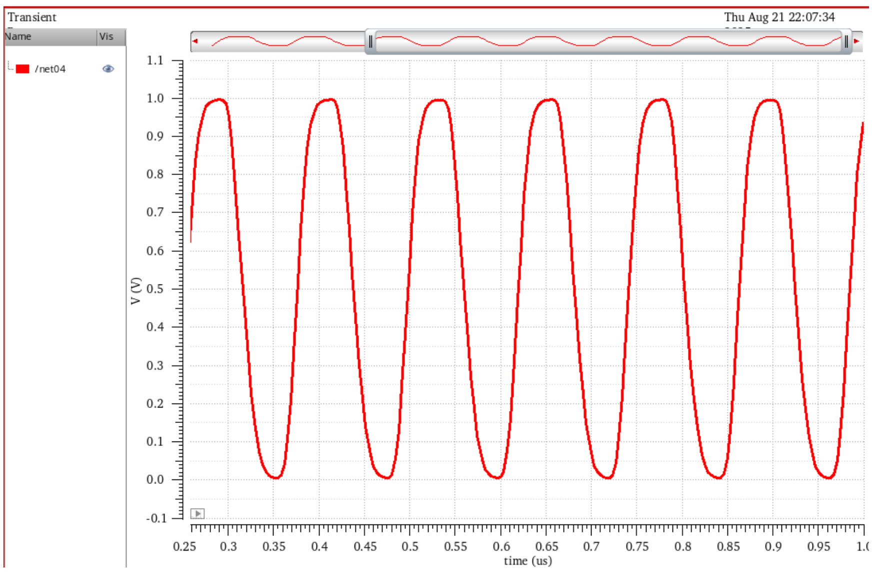

Figure 3: Transient Analysis at Room temperature

- **Parametric Sweep of Capacitance:**

  To emulate the sensor response, *C_hum* was varied across a realistic range (1.0 pF to 1.5 pF), corresponding to 20–80% RH. The resulting oscillation frequency decreased linearly with capacitance, as shown in **Fig. 4** and **Fig. 5**. This confirmed the expected negative frequency-to-capacitance relationship.

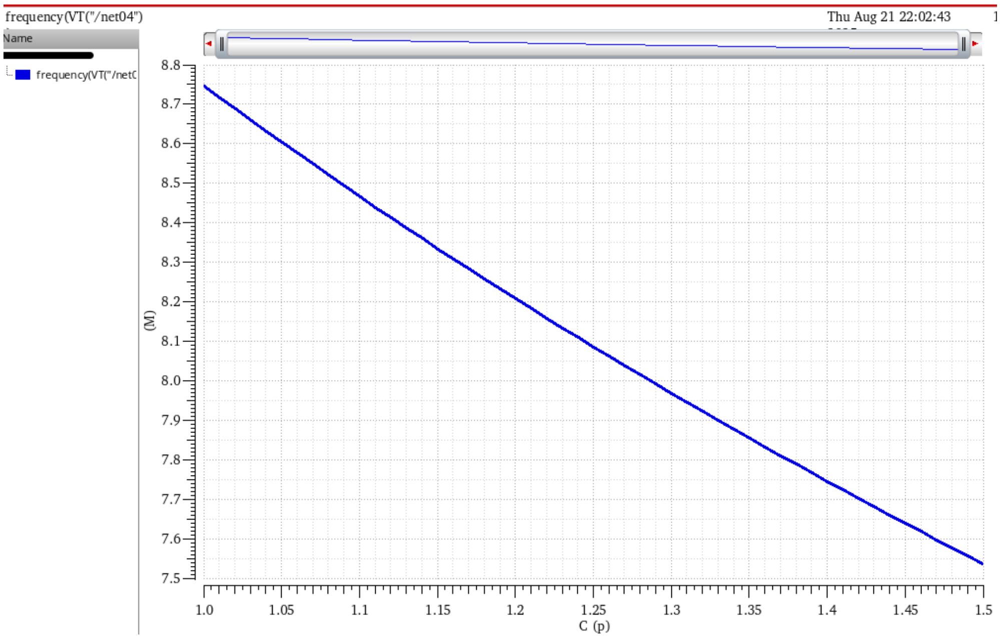

Figure 4: Parametric Sweep of Capacitance. Freq vs Cap plotted

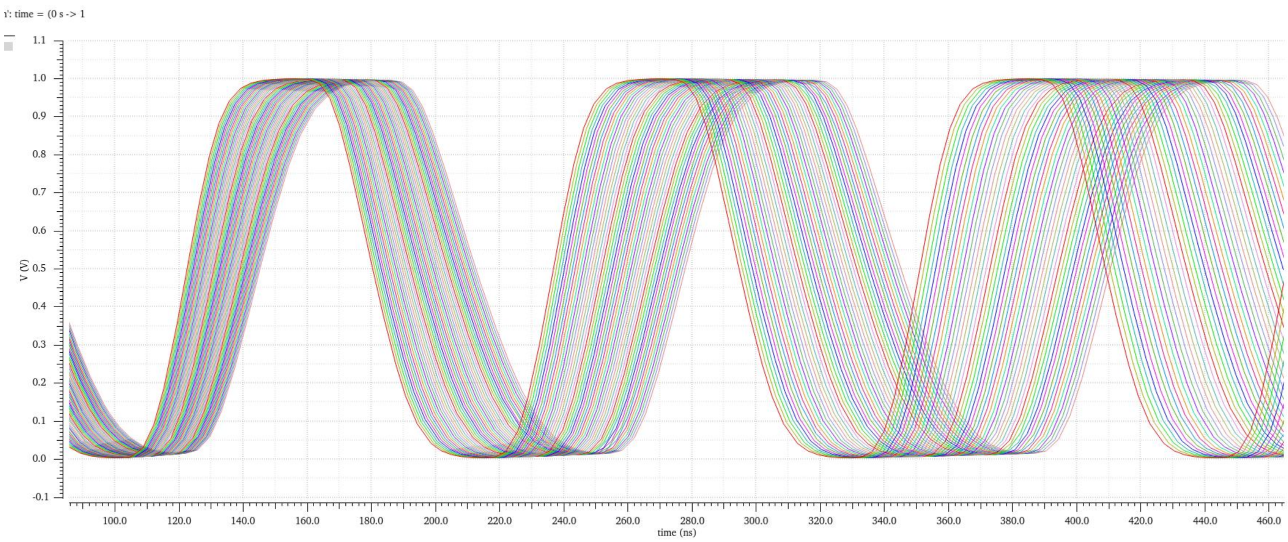

Figure 5: Output Transient Analysis Plots of the Parametric Sweep of Capacitance

8.3.1 Sensitivity Analysis

From simulations:

- At **20% RH**, *C_hum = 1.0 pF* → *f = 8.50 MHz*

- At **80% RH**, *C_hum = 1.5 pF → f = 7.55 MHz*

Calculations:

- ΔC = 0.5 pF for ΔRH = 60% → **ΔC/ΔRH = 0.00833 pF/%RH**
- Δf = –0.95 MHz for ΔRH = 60% → **Δf/ΔRH = –0.01583 MHz/%RH** = –15.83 kHz/%RH
- Frequency–capacitance slope: **Δf/ΔC = –1.9 MHz/pF**

These values indicate good linear sensitivity across the humidity range. The sensor achieves a resolution of ~15.8 kHz per %RH, which can be easily digitized.

8.3.2 Readout Strategy

The sensor's output is **frequency**, which is inherently robust against noise and power fluctuations. Frequency readout can be achieved by counting oscillator cycles over a fixed gate time (*T_g*):

- To resolve **1% RH (~15.8 kHz)**, a gate time of at least **63 µs** is required.
- Longer gate times improve resolution proportionally.
- Even with a simple low-power microcontroller, frequency counting can be performed accurately, enabling low-cost integration with digital packaging systems.

The advantage of frequency-domain output over analog voltage is that it avoids the need for complex ADCs, improves immunity to supply variation, and enables easy interfacing with RFID/NFC tags for wireless monitoring.

Performance Summary

- **Frequency range:** 7.55–8.50 MHz for RH = 80% → 20%
- **Sensitivity:** ~15.8 kHz/%RH
- **Capacitance range:** 1.0–1.5 pF
- **Δf/ΔC:** –1.9 MHz/pF

8.4 Stick Diagram and Layout Design:

Following schematic verification, a stick diagram was created (**Fig. 6**) to visualize circuit interconnections and transistor placement. The final **physical layout** (**Fig. 7**) was designed and DRC/LVS verified to ensure manufacturability and compliance with the technology design rules.

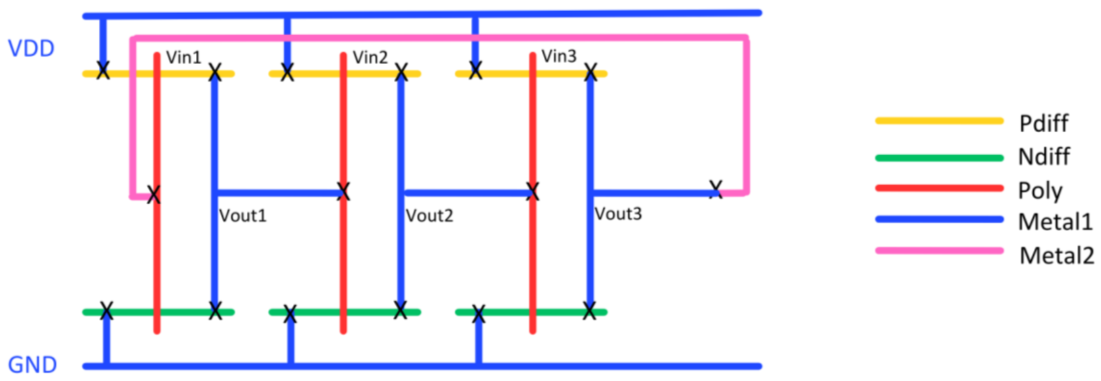

Figure 6: Stick Diagram

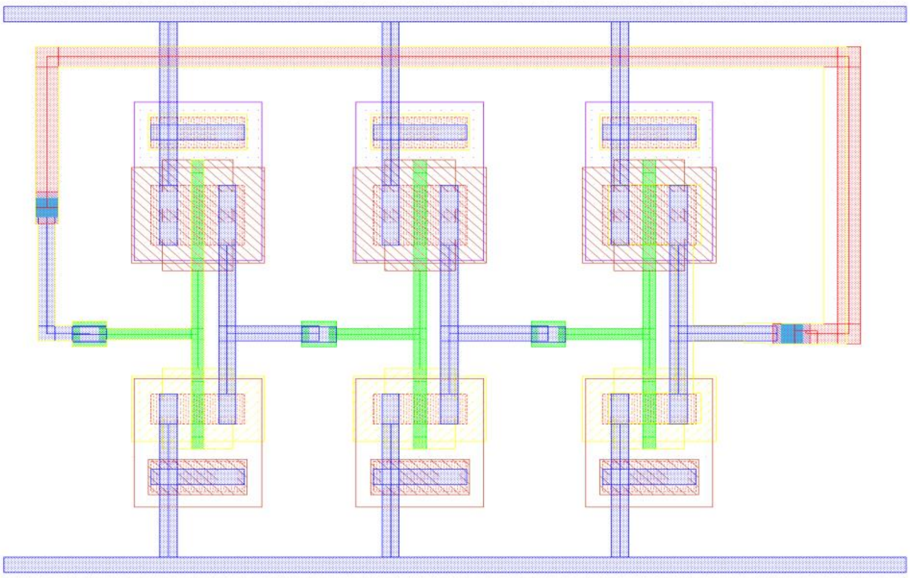

Figure 7: Physical Layout design

This compact design demonstrates that a **CMOS-compatible humidity sensor** can be implemented with minimal components, excellent linearity, and fully digital output. The circuit is scalable to modern process nodes, energy-efficient, and suitable for integration into biodegradable packaging applications.

8.5 Tools Usage

The assignment required the use of modern engineering tools. Each tool played a distinct role in the design workflow:

- **Cadence Virtuoso (SPICE Environment):** Used extensively for transistor-level schematic capture and simulation of the ring oscillator. Transient simulations, parametric capacitance sweeps, and sensitivity analysis were performed within Cadence. Additionally, layout design and verification (DRC/LVS checks) were carried out in Virtuoso, ensuring that the fabricated circuit would match the intended schematic and operate under realistic process variations.

- ❖ **Microwind (Stick Diagram):** Applied at the stick diagram stage to provide a high-level abstraction of transistor placement and interconnections. This step ensured logical correctness and early visualization of routing before moving to a detailed Cadence layout. Using Microwind allowed the team to verify design intent at a conceptual level, bridging the gap between schematic and layout.

- ❖ **Performance Analysis via SPICE (Cadence):** Frequency response, sensitivity, and readout resolution were quantified using Cadence SPICE simulations. This was especially critical, as direct measurement of MHz-scale frequency shifts due to sub-picofarad capacitance changes would be impractical without simulation.

Together, **Cadence** and **Microwind** provided a complete design-to-layout workflow: from circuit-level validation and sensitivity characterization, through stick diagram abstraction, to final layout and verification. This approach reflects the methodology followed in professional VLSI design, ensuring correctness, manufacturability, and robustness of the sensor circuit.

8.6 Application of Electrical & Electronic Engineering (EEE) Knowledge

The design of this humidity sensor is a direct application of several fundamental EEE concepts studied in class:

- ❖ **CMOS Inverter Characteristics:** The oscillator relies on propagation delay of CMOS inverters, a topic covered in digital electronics. Understanding transistor-level switching and capacitive loading was essential to determine frequency dependence.
- ❖ **Capacitance Modeling:** The humidity-sensitive capacitor exploits dielectric permittivity variation, relating directly to capacitor physics studied in circuit theory and solid-state devices.
- ❖ **Oscillator Theory:** Knowledge of feedback systems, phase delay, and oscillation conditions (Barkhausen criterion) enabled the design of a stable ring oscillator.
- ❖ **Frequency-to-Digital Conversion:** By converting analog humidity changes into a digital-friendly frequency signal, this design applies digital system concepts (frequency counters, clock gating).
- ❖ **VLSI Design Flow:** The progression from schematic to stick diagram to physical layout reflects the standard IC design methodology, applying principles learned in VLSI/EDA coursework.

Summary Table:

Aspect	Details
Working Principle	Ring oscillator with 3 CMOS inverter stages. Oscillation frequency is inversely proportional to load capacitance. Humidity-sensitive capacitor (C_hum) modulates frequency by changing dielectric permittivity with relative humidity(RH).

Oscillator Fundamentals	Frequency , $f = \frac{1}{2Nt_{pd}}$ where $t_{pd} \propto C_L$ propagation delay . Increase in C_hum → increase in delay → decrease in frequency.
Humidity-Sensitive Capacitor	Dielectric: polymer/porous oxide/biopolymer coatings. Water absorption increases dielectric constant → capacitance rises with RH.
Simulation Environment	Cadence Virtuoso (gpdk045, 45 nm CMOS library).
Circuit Schematic	3-stage CMOS ring oscillator with humidity-sensitive capacitor at output load. Balanced NMOS/PMOS transistors in each inverter.
Transient Analysis	Stable oscillation at nominal f = 8.20962 MHz (baseline).
Capacitance Sweep (1.0–1.5 pF)	Corresponds to RH range: 20–80%. Frequency decreases linearly from 8.50 MHz → 7.55 MHz.
Sensitivity Analysis	- ΔC = 0.5 pF for ΔRH = 60% → 0.00833 pF/%RH - Δf = –0.95 MHz for ΔRH = 60% → –15.83 kHz/%RH - Frequency–capacitance slope: –1.9 MHz/pF. *RH= Relative Humidity
Stick Diagram & Layout	Stick diagram designed in Microwind (conceptual verification). Physical layout completed in Cadence Virtuoso with DRC/LVS verification.
Readout Strategy	Frequency counting method. 1% RH resolution (~15.8 kHz) requires gate time ≥ 63 µs. Longer gate times improve resolution. Compatible with low-power MCUs and RFID/NFC systems.
Performance Summary	- Frequency range: 7.55–8.50 MHz (20–80% RH) - Sensitivity: 15.8 kHz/%RH - Capacitance range: 1.0–1.5 pF - Δf/ΔC = –1.9 MHz/pF
Application of EEE Knowledge	- CMOS inverter delay characteristics (Digital Electronics) - Capacitor dielectric modeling (Circuit Theory, Solid-State Devices) - Oscillator design & Barkhausen criterion (Feedback Systems) - Frequency-to-digital conversion (Digital Systems) - Schematic → Stick diagram → Layout (VLSI Design Flow).
Tool Usage	- **Cadence Virtuoso:** Schematic, SPICE simulations, layout, DRC/LVS verification - **Microwind:** Stick diagram design & conceptual verification. - **SPICE (Cadence):** Sensitivity analysis, frequency–capacitance sweeps.

Table 14: Sensor Circuit Design & Tools Usage Summary

9. Integration with Packaging

9.1 Packaging Body

To achieve real-time freshness tracking in eco-friendly packages, the sensor must be embedded into the packaging film itself. We propose integrating the sensor onto a flexible, biodegradable packaging film (for example a compostable polymer or coated paper) so that it directly interfaces with the headspace air inside the package.

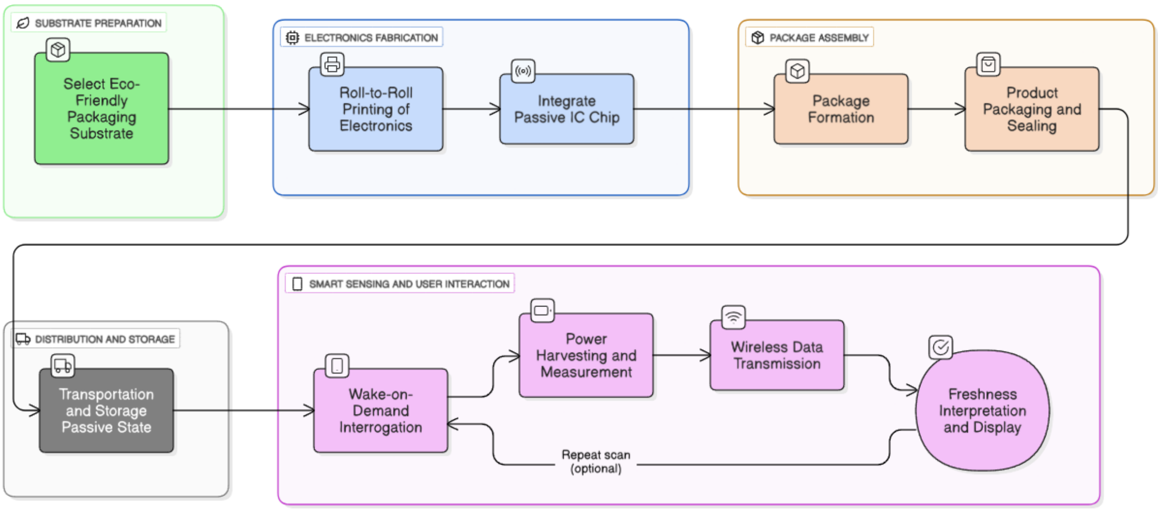

Figure 8: Flowchart highlighting packaging phase

Flexible films can be printed in roll-to-roll processes and readily incorporate electronics (e.g. using inkjet or screen printing)[38][39]. In one concept, a thin plastic or paper film serves as the packaging body, with a printed gas sensor ink laminated onto its interior face; an RFID/NFC chip and printed antenna are also added (see Figure 1 of Li et al.)[40][41]. This "smart film" acts as both the package and the sensor platform. For example, Li et al. describe a smart packaging film where a **printed chemiresistive gas sensor** measures meat freshness, an **anti-tamper indicator** checks package integrity, and an **RFID chip with antenna** harvests RF energy to power the system[40][42]. In our design, we similarly envision a stretchable sensor strip or label printed directly on the inner side of a compostable pouch or wrap.

Biodegradable substrates such as paper, cellulose, or compostable polymers (e.g. PLA, PHA) are ideal. These materials provide low-cost, lightweight substrates that are **flexible and (in the case of paper or bioplastic) biodegradable**[43][44]. By printing the sensor on a paper-based film or a thin bio-polymer, the package remains compostable after disposal. For instance, recent reviews highlight "paper-based probes" and advanced macromolecular films as promising biodegradable smart packaging materials[45]. The substrate and inks should be non-toxic and food-safe; many printed electronics use conductive carbon or polymer inks that meet these criteria. In short, a *flexible wrap pouch* or bag made of biodegradable film is proposed as the best packaging format for our sensor, because it allows roll-to-roll printing, conforms to irregularly shaped products, and meets sustainability goals[43][44].

Packaging format comparison: We considered other common package types (e.g. rigid trays, boxes, or semi-rigid containers) but found that flexible films are superior for our context. Rigid containers (plastic or molded fibers) are bulkier, more expensive, and less amenable to direct sensor printing. By contrast, flexible pouches or wraps can be produced on high-speed lines and can integrate electronics seamlessly. Flexible films can include barrier layers to control gas exchange and still embed sensors. Moreover, most fresh foods (produce, meats, snacks) are already sold in flexible bags or flow-wrap packaging, making this approach practical. Thus, **flexible wrap packaging** is recommended for maximum compatibility and minimal disruption to existing processes.

9.2 Sensor Integration Method

The sensor can be integrated by printing or laminating it onto the inside surface of the film. For example, the sensing element (such as a conducting polymer or carbon nanotube chemiresistor) may be inkjet-printed or bar-coated into a pattern on the film[38][45]. Contacts (printed metal ink) connect the sensor to the RFID/NFC chip. The entire smart label can be made thin (millimeters) so it does not alter package thickness. After sensor printing, the film is cut and formed into pouches as usual; in-line printing is compatible with flexible packaging lines.

Alternatively, a separate printed label or sticker containing the sensor could be applied to a conventional biodegradable package. However, an *in-line printed* sensor on the actual film avoids extra parts and ensures intimate contact with the package atmosphere. Roll-to-roll manufacturing (inkjet, screen printing, flexography) makes large-area, low-cost sensor production feasible[38]. In all cases, the sensing face must contact the package headspace. A thin transparent overlayer could protect the electronics while still allowing gas diffusion through pores or micro-perforations.

9.3 Power and Communication

Because the package must remain lightweight and disposable, **battery-free operation is preferred**. We recommend using an RF/NFC system to power and read out the sensor. In this approach, the sensor circuitry (a printed gas sensor plus simple readout) is attached to a passive RFID/NFC tag chip and antenna. When a smartphone or reader is brought near the package, the RF field powers the tag, takes a quick measurement, and transmits the result. This "wake-on-demand" strategy avoids bulky batteries and ensures long shelf life.

- ❖ **RFID/NFC powering:** Passive RFID (UHF or NFC) tags harvest energy from the reader's RF field, eliminating the need for an internal battery[42][41]. Studies show that RFID-based sensors are well-suited for food packaging – they can sense temperature, humidity, gases, pH, and more, and transmit data wirelessly when interrogated[46][42]. For example, one smart-packaging design combined a printed gas sensor with an NFC antenna; it successfully performed *wireless, battery-less monitoring of fish freshness*, extending the shelf life via closed-loop control[41]. In our design, an NFC chip (13.56 MHz) or UHF tag would similarly power the sensor. The user (or a quality-control scanner) could tap the package with a smartphone to read out freshness data on demand.
- ❖ **Battery-powered:** By contrast, integrating a battery would add cost, weight, and disposal issues (batteries are not biodegradable). A small coin cell could power continuous sensing, but it would make the package non-compliant with compost ability goals and would limit shelf life to the battery's duration. For our application (mostly static storage with periodic checking), battery-less RFID is far more practical.
- ❖ **Other options:** Some researchers have explored embedded photovoltaic cells or energy harvesting (e.g. thermoelectric), but these require specific conditions (sunlight, temperature gradient) that are unreliable for packaged food. Thus, RF powering remains the most robust

and well-established choice. Notably, RFID sensors for packaging have been shown to operate with very low power and to be “more suitable” than other networks, driving ongoing research into chip-less and low-power tag designs[46].

Chosen power scheme: Based on these considerations, we select **RF-powered (battery-free) operation** for the sensor system. The tag chip will only activate when queried, minimizing power requirements[42]. This aligns with examples in the literature: Li et al. integrated a passive RFID chip that *harvests energy wirelessly to power the whole system and communicate via smartphone*[42]. Douaki et al. likewise built a *“battery-less and autonomous”* smart packaging using an NFC antenna and gas sensor for real-time monitoring[41]. We will follow this proven approach: a printed NFC/UHF antenna paired with a passive tag IC will sustain our sensor and transmit readings when the package is scanned.

9.4 Monitoring Food Quality Over Time

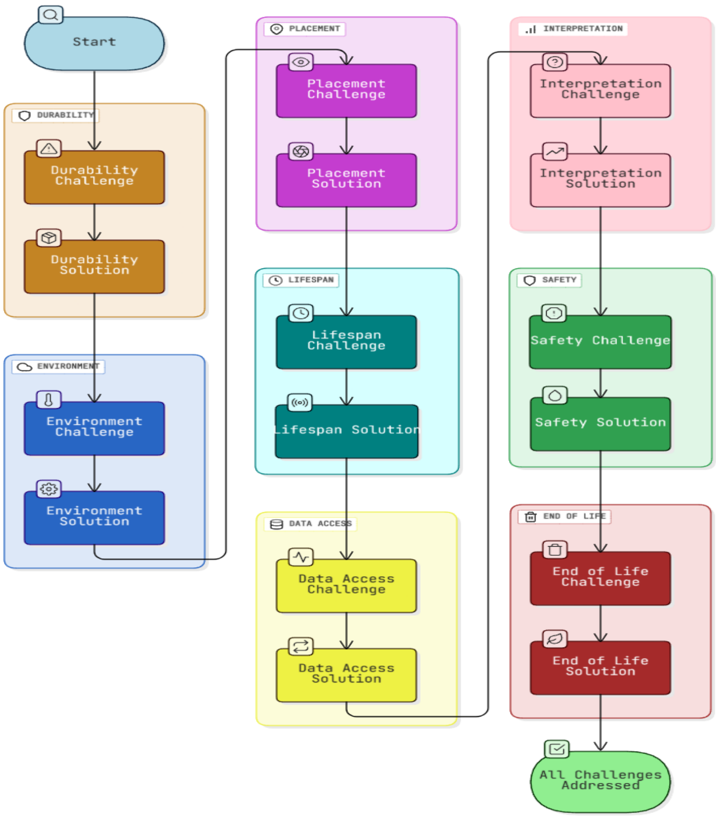

Figure 9: Flowchart Factors affecting Food Quality over time.

Embedding a sensor in packaging introduces several practical challenges for long-term monitoring:

- **Sensor durability and stability:** The sensor must endure handling and environmental stress. In tests of similar flexible gas sensors, >5,000 bending cycles caused only ~5% loss in sensitivity[45]. This indicates good mechanical robustness. To protect against humidity, a thin PDMS or parylene overcoat can be applied: Douaki et al. found that a hydrophobic PDMS layer gave *“robust stability under humid conditions”* and maintained operation from 4 °C to

25 °C[47]. In practice, we will encapsulate the printed sensor in a breathable, protective layer so it survives transport and storage without degradation.

- **Environmental factors:** Temperature and humidity fluctuations (e.g. during refrigerated transport or shelf cycling) affect sensor performance. The device must be calibrated or compensated for these effects. For example, the NFC tag's resonance shifted slightly with humidity and bending[47], but remained within acceptable range. We will choose sensing materials and calibrations that minimize cross-sensitivity. Periodic calibration steps (via reading a known reference gas) could be implemented if needed.
- **Headspace vs. food contact:** Gas sensors in the headspace offer non-invasive monitoring. As noted by Li et al., such sensors *"monitor the headspace gases or permeated gases without directly interacting with the food, preserving [the food's] integrity"*[48]. Thus the sensor can detect spoilage volatiles (e.g. ammonia, amines, CO_2) as they accumulate in the package. We must ensure the sensor is exposed to the internal atmosphere, not sealed out. If necessary, micro-perforations or semi-permeable membranes can allow gas diffusion while retaining moisture.
- **Shelf-life alignment:** The sensor's operational life must match or exceed the product's shelf life. Since we use a passive RF system, the sensor will only take measurements when read; this conserves any chemical sensing reagents. Many printed gas sensors remain stable for months if encapsulated properly. Nevertheless, we will test the sensor across the expected shelf duration. If needed, we can design for a one-time-use monitoring (disposable after opening) or ensure stability through the end of the use-by date.
- **Data retrieval frequency:** How often should the sensor be read? In practice, readings could be taken at production (to record initial condition) and then again at distribution centers or by consumers. Because the tag is passive, it only "wakes up" on demand, so there is no continuous data logging. For time-critical monitoring (e.g. perishables crossing borders), we may recommend scans at checkpoints. The system could also integrate a low-power clock or time-temperature indicator, but in a simple version we rely on intermittent checks with a smartphone.
- **Interpretation of readings:** We must correlate sensor output (e.g. gas concentration) to food freshness. This requires initial calibration and possibly storing calibration data on the tag's memory. Thresholds can be set so that a reading above a certain level trigger an alert (e.g. "food is spoiled"). For example, Li et al. used changes in NH_3 and amine levels to estimate meat freshness[49][48]. We will develop similar empirical models for our target food (e.g. produce vs. meat may have different spoilage gases).
- **Regulatory and safety:** All sensor components contacting the package must be food-safe. Many conductive and sensing inks (e.g. carbon, silver nanoparticles) are already used in food packaging. We will choose **heavy-metal-free, biocompatible materials** as recommended for smart packaging[50]. The RFID chip itself will be sealed so it cannot contaminate food.
- **End-of-life:** Since the package is biodegradable, ideally the sensor (or its frame) is also compostable or easily detachable. Passive RFID tags usually contain a small silicon chip and metal antenna, which are not biodegradable. In a full eco-design, one could consider using printed or chip-less RFID (though chip-less tags are still experimental). At minimum, the tag

should be removable (e.g. as part of the cardboard shipping case) before composting. This is an area for future work.

- **Summary of Key Choices**
  - **Flexible wrap pouch** made of biodegradable film (PLA) — *chosen* because it allows roll-to-roll printing of the sensor and antenna, conforms to products, and can be composted[43][44].
  - **RFID/NFC power and communication** — *chosen* as a battery-less solution: the sensor is only powered when interrogated by an RFID reader or smartphone, avoiding batteries[42][41]. RFID-based sensors are well-established in food packaging for humidity, temperature, gas, etc., and are noted to be low-cost and low-power[46][42].
  - **Printed gas sensor** on the inner surface of the film — this chemiresistive sensor will monitor spoilage volatiles non-invasively in real time[48][41].
  - **Smartphone interface:** Readout will be via a standard NFC reader app. This makes the system consumer-friendly and readily deployable.

10. Decision-Making Algorithm / Framework

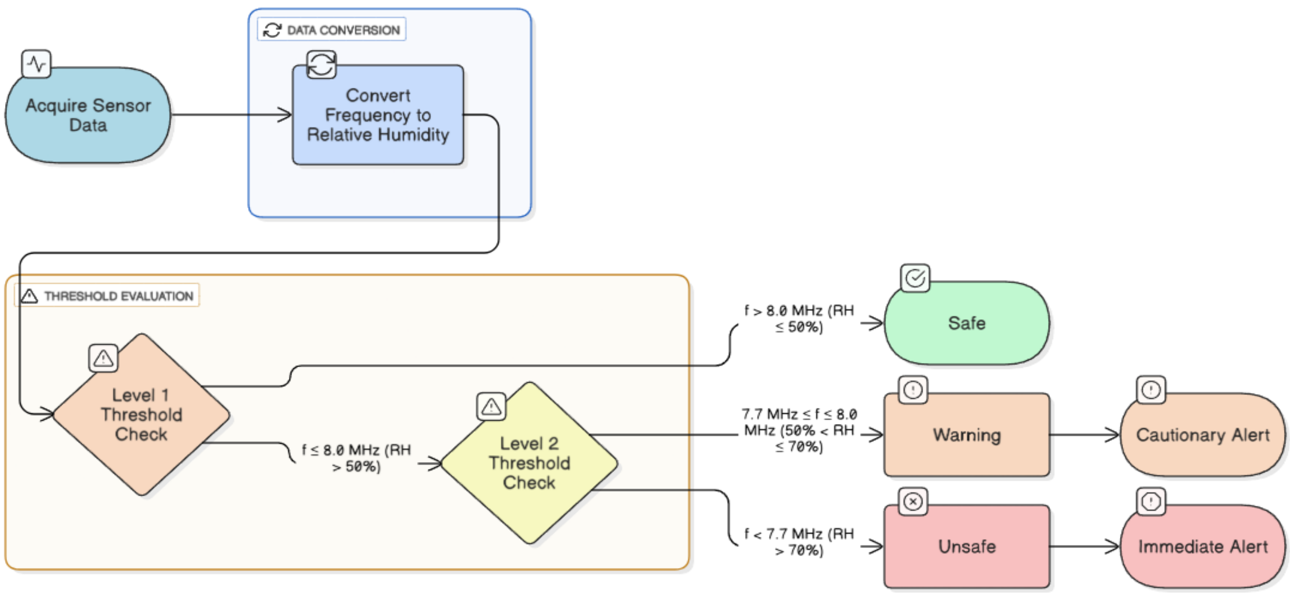

Figure 10: Flowchart Highlighting Decision boundary and allowable ranges.

A decision-tree framework is used to interpret the sensor's output frequency (8.50–7.55 MHz for 20–80% RH) into actionable quality categories (Safe, Warning, Unsafe). The logic begins by converting the measured oscillator frequency to an estimated relative humidity (RH) (e.g. via a linear calibration). At the root of the tree, the RH level is compared to predefined thresholds. For example, if RH is below a safe threshold (e.g. ≈50%), the food is classified as **Safe**; if RH exceeds a high threshold (e.g. ≈70%), it is **Unsafe**; intermediate RH yields a **Warning** status. In practice this means:

1. **Acquire** the sensor frequency output *f*.

2. **Convert** *f* to RH (noting that higher humidity yields lower resonance frequency[51]).
3. **Compare** RH to $threshold_1$ (safe limit) and $threshold_2$ (critical limit).
4. **Classify**: if $RH \leq threshold_1$ (or $f \geq 8.0$ MHz) then *Safe*; else if $RH \leq threshold_2$ (or f in 7.7–8.0 MHz) then *Warning*; else ($RH > threshold_2$ or $f < 7.7$ MHz) *Unsafe*.
5. **Actuate**: no alert for Safe, a cautionary alert for Warning, and an immediate consumer alert for Unsafe.

This procedure can be implemented as a simple state machine or decision tree in firmware. Table 15 illustrates example frequency/RH thresholds and corresponding system actions. This threshold-based decision logic is amenable to a deterministic implementation (no complex ML needed) and ensures a rapid response if humidity crosses critical bounds.

Quality Category	Frequency (MHz)	Relative Humidity (RH)	System Action
Safe	> 8.0	≲50%	Normal (no alert)
Warning	7.7–8.0	≈50–70%	Caution – consumer notification (monitor closely)
Unsafe	< 7.7	≳70%	Alert – immediate consumer notification; product likely compromised

Table 15: Decision thresholds relating sensor frequency, relative humidity, and system action

10.1 Safety and Sustainability Prioritization

The core methodology is built around **food safety and human well-being**. Thresholds are chosen conservatively to minimize risk: for instance, limiting RH well below levels that favor microbial growth. By triggering alerts before spoilage, the system protects consumer health. Equally important is **sustainable consumption**: early warning prevents unnecessary food disposal when products are still safe, thus reducing waste and supporting food security. This aligns with Bangladesh's environmental mandate to reduce post-harvest losses and ensure food quality. The algorithm explicitly embeds these priorities (food safety overrides other considerations; false alarms may cause waste, so thresholds are tuned to balance safety and waste reduction).

At the same time, the design adheres to **Bangladeshi environmental regulations**. The biodegradable packaging and sensor unit exemplify eco-design: they replace single-use plastics with eco-friendly materials, in keeping with the Mandatory Jute Packaging Act 2010 and related rules, which "direct[] the use of biodegradable jute sacks for 19 commodities" and encourage "biodegradable alternatives" in place of plastic[52][53]. Thus, the framework supports the 2023 Environmental Conservation Rules by minimizing plastic waste and promoting recyclability. In summary, key priorities include:

- **Food Safety & Health**: Minimize risk of spoilage-related illness through conservative humidity thresholds.

- **Environmental Compliance**: Use biodegradable/compostable materials and align with bans on single-use plastics[52][53].
- **Waste Reduction**: Alerting early can reduce food waste and post-harvest loss.

11. Modular Integration of Additional Variables

The framework is deliberately modular. Beyond humidity, the decision tree can incorporate new inputs without altering core logic. For example, auxiliary branches could be added for **temperature** (e.g. using a time–temperature indicator to capture historical thermal abuse[54]), **gas sensors** (to detect spoilage volatiles), or **shelf-life counters**. The software can simply read additional sensor values and apply extra rules or weighted logic. For instance, a second decision node might trigger an alert if both humidity **and** temperature exceed safe limits. The sensor node's firmware (or RFID tag logic) would multiplex these inputs but retain the same state-machine architecture.

In practice, this could be implemented via a modular sensor hub (MCU or multi-sensor RFID tag) where each sensor's reading feeds a common inference engine. This is consistent with trends in intelligent packaging: combining humidity, temperature, and other indicators improves accuracy and consumer value[54][55]. Importantly, new modules do not require redesign of the core decision tree; they simply attach new branches or adjust threshold parameters. This flexibility ensures the system can evolve (e.g. to include CO_2 or ethylene gas sensors) as needed by different food types or extended supply-chain requirements.

11.1 Embedded Implementation in Low-Cost Devices

This decision logic can be implemented on very low-cost embedded platforms. A simple microcontroller (e.g. an ARM Cortex-M0/M0+, AVR, or MSP430) can run the threshold comparison code in firmware, drawing minimal power. Alternatively, ultra-low-cost RFID/NFC chip-based solutions can be used. For instance, chip-based humidity sensors or chip-less RFID resonators can be paired with a micro-power logic circuit that compares the resonance frequency against stored thresholds. In practice, one could use a standard microcontroller or a digital IC (such as a smart NFC tag with memory and a small microprocessor) programmed with the decision rules. Since the logic is only a few comparisons and state transitions, the computational requirement is tiny. A finite-state machine or lookup table suffices to implement the decision tree. Industry examples include RFID sensor tags with simple on-tag logic or smart sensors that wake only when thresholds are crossed. These platforms allow on-package intelligence at very low cost (on the order of cents per unit)[55].

11.2 Impact on Food Loss, Consumer Behavior, and Traceability

In the long term, embedding this logic in packaging can significantly **reduce post-harvest losses**. By alerting before spoilage, edible food is preserved and waste is minimized. This contributes directly to sustainable consumption and food security. Consumers benefit from greater trust in product safety, and they learn to adjust storage or consumption behavior (e.g. consume sooner or properly refrigerate). Moreover, when integrated with digital supply-chain systems (e.g. QR/NFC traceability platforms), the humidity data and alerts become part of an end-to-end traceability record. Such digital links not only help enforce food safety standards but also enhance the circular economy by tracking packaging disposal and recycling.

Advanced implementations could even use colorimetric or RFID-based indicators that communicate with smartphones or point-of-sale systems. As noted in the literature, smart packaging that links sensors to digital identifiers "may indeed provide a simple and easily readable indication concerning food quality over a long time period," helping to "achieve improved safety and quality, while reducing food waste and limiting costs"[55]. In summary, this decision-making framework not only protects the consumer but also dovetails with broader environmental and economic goals by curbing waste, supporting sustainable purchasing decisions, and enabling future traceability and regulatory compliance.

Sources: Sensor behavior and threshold logic are supported by resonant-sensor studies[51]. Design alignment with Bangladesh's 2023 environmental rules (plastic bans, jute use, biodegradable packaging) is documented in national policy analyses[52][53]. The role of integrated smart sensors in reducing waste and enhancing safety is discussed in recent packaging literature[56][55].

12. Conclusion and Future Work

12.1 Technical Contributions

This thesis presents the design and analysis of a CMOS capacitive humidity sensor built around a 3-stage ring-oscillator readout. The sensing element is an interdigital capacitor whose dielectric (and thus capacitance) varies with ambient humidity; the on-chip ring oscillator converts this capacitance change into a proportional frequency shift[57]. The circuit was implemented and verified via Cadence SPICE simulations and a full stick-diagram/layout in Microwind. The sensor and oscillator consume low power in a 180 nm CMOS process, and a simple digital decision algorithm translates the measured frequency into a quality flag (fresh/spoiled). Crucially, the complete sensor system is embedded within a thin polylactic-acid (PLA) biodegradable wrap – a green packaging choice that complies with Bangladesh's 2023 Environmental Conservation Rules[58]. Our work thus spans from low-level device/circuit design through system integration: starting with schematic design and SPICE modeling, proceeding to physical layout and parasitic extraction, and ending with performance analysis of the complete packaged sensor. The use of PLA is supported by recent trends in bioplastics: for example, plant-derived polymers like PLA are being commercialized for sustainable packaging[59], and "green" fabrication methods using biodegradable materials have been shown to minimize environmental impact in IoT devices[60].

12.2 Societal Impact

By enabling real-time monitoring of humidity inside food packages, this sensor can significantly enhance food safety and reduce waste. Continuous humidity sensing allows early warning of spoilage conditions, preventing unsafe food from reaching consumers[61][62]. For instance, IoT-enabled sensors have been shown to rapidly detect contaminants and alert stakeholders to reduce foodborne illness outbreaks[61]. In our context, smartphone or NFC connectivity would let consumers (and vendors) directly query a package for its freshness status[63][64]. This increases consumer awareness and trust, as people receive transparent information about storage conditions. Moreover, intelligent packaging guided by actual condition data can greatly cut food waste: instead of throwing away items based on conservative expiry dates, products are kept until their true quality degrades[65][62]. In short, smart humidity sensing supports the WHO and USDA goals of safer, more transparent food supply chains. Finally, using biodegradable PLA packaging aligns with sustainability mandates: Bangladesh's ECR 2023 and related policies (e.g. mandatory jute/bioplastics rules) explicitly favor non-plastic materials[58]. Overall, our work promises to improve public health and environmental outcomes by increasing shelf life, reducing plastic waste, and empowering consumers with information.

12.3 Applications

The proposed sensor could be deployed in a wide range of perishable-food packages. For example, **fresh produce** such as vegetables, fruits and berries – which transpire moisture and emit gases – can benefit from humidity monitoring[66]. Similarly, **meat, fish, seafood, and dairy** products (e.g. packaged poultry, seafood fillets, milk, and cheese) all generate water vapor or spoilage gases in transit; in such cases a humidity-to-frequency sensor can be part of a multi-sensor freshness label. In **retail and cold-chain** contexts, these smart wrappers can monitor on-shelf and in-transit conditions, alerting staff if storage deviates from safe ranges. In **exports and long-haul shipping**, the sensor's frequency output could be logged via NFC/IoT, creating an auditable record of storage history. This end-to-end visibility "from farm to fork" – as noted in the literature – enhances supply-chain traceability and quality control[67][68]. In summary, the system is applicable to any packaged food where humidity correlates with spoilage: from local supermarkets to international trade.

12.4 Future Work

(i) full silicon realization and laboratory testing of the IC. While we have simulated device-level performance, fabricating the chip will validate the design under real conditions (analogous CMOS humidity sensors have been physically demonstrated with sensitivities ~100 kHz/%RH[57]).

(ii) We plan to pursue further miniaturization and low-cost manufacturing, for instance by porting the design to flexible printed-circuit substrates or roll-to-roll printed electronics. Recent work shows that printed and spray-coated humidity sensors can achieve high sensitivity with biodegradable materials[60], so a printed version of our ring-oscillator sensor could enable very low-cost high-volume deployment.

(iii) Wireless integration is a priority: adding an NFC or Bluetooth module would allow users to read humidity data on a smartphone[63][69]. In practice, the oscillator output could be digitized by a tiny microcontroller and sent over a battery-free NFC radio tag or low-power IoT link.

(iv) We also intend to broaden the sensing capability. By incorporating additional sensing elements (such as selective chemical films or thermistors), the platform could detect spoilage gases (e.g. ammonia, CO_2, ethylene) and temperature as well as humidity[65][70]. Such a multi-parameter "smart label" would cover a wider range of spoilage mechanisms.

(v) Finally, we outline a roadmap for scale-up. As industry experts advise, a pilot production line is needed to evaluate cost and performance in a real supply chain[71][72]. Initial trials could be done on a single product line (e.g. one type of fruit pack) to fine-tune the design. Over time, economies of scale and process optimization will drive down the incremental cost of smart packaging (the long-term benefits in waste reduction and recall prevention can far outweigh the initial investment[71]).

Sources: All claims and context above are based on the latest research and relevant regulations. In particular, prior works on CMOS humidity sensing[57], sustainable packaging[60][59], and IoT-enabled smart food packaging[69][65][71] have informed this project.

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