

SCP PACKING FOR REAL TIME FOOD SPOILING DETECTION

Mithanrukesh M¹, R G Vedajani², Mrs. A. Sathiya Priya³, Dr. N. Kannikaparameswari⁴

Department of Information Technology, Dr. N.G.P. Arts and Science College, Coimbatore, Tamil Nadu, India¹

Department of Biochemistry, Dr. N.G.P. Arts and Science College, Coimbatore, Tamil Nadu, India²

Assistant Professor, Department of Information Technology,

Dr. N.G.P. Arts and Science College, Coimbatore, Tamil Nadu, India³

Professor, Department of Biochemistry, Dr. N.G.P. Arts and Science College, Coimbatore, Tamil Nadu, India⁴

Abstract: Food spoilage remains a critical challenge in global food supply chains, contributing significantly to waste, economic loss, and public health risks. Traditional packaging solutions, while effective in preserving food for limited durations, lack the capability to provide real-time monitoring of spoilage conditions. This paper introduces SCP-SmartPack AI, an advanced AI-driven platform that integrates Single-Cell Protein (SCP) based biodegradable smart packaging with machine learning algorithms for real-time food spoilage detection. The system architecture combines sensor data acquisition, preprocessing, and predictive modeling with a React-based visualization interface, enabling consumers and retailers to monitor food quality dynamically. Experimental results demonstrate that the proposed system achieves high accuracy in spoilage prediction, reduces food waste, and promotes sustainability through biodegradable packaging. By leveraging SCP materials and AI analytics, SCP-SmartPack AI represents a novel contribution to food technology, offering a scalable solution for enhancing food safety, extending shelf life, and supporting eco-friendly practices. Future work will explore large-scale deployment, blockchain integration for supply chain traceability, and advanced reinforcement learning models to further optimize spoilage detection and packaging efficiency.

Keywords: Smart Packaging, Single-Cell Protein, Artificial Intelligence, Food Spoilage Detection, Biodegradable Materials, React, Vite, Typescript, Generative AI.

I. INTRODUCTION

Food waste is a global issue, with nearly one-third of all food produced lost annually, leading to economic, environmental, and health concerns. Conventional plastic packaging offers limited preservation and contributes to ecological harm due to its non-biodegradable nature. The demand for sustainable, intelligent packaging solutions has therefore intensified. Single-cell protein (SCP) has emerged as a promising biodegradable material, aligning with sustainability goals while offering structural benefits. However, packaging alone cannot address spoilage detection, which requires monitoring variables such as temperature, humidity, and microbial activity. Artificial intelligence (AI) and machine learning (ML) provide powerful tools for predictive modeling and realtime analysis in food technology. This paper introduces SCP-SmartPack AI, a system that integrates SCP-based biodegradable packaging with AI-driven spoilage detection. Using sensor and camera data, the system preprocesses inputs, applies ML algorithms for accurate spoilage prediction, and visualizes results through a React-based dashboard. By combining biotechnology and AI, SCP-SmartPack AI aims to reduce food waste, enhance safety, and improve consumer confidence.

II. BACKGROUND AND LITERATURE REVIEW

Literature Review

Recent studies highlight the growing role of artificial intelligence and smart packaging in food spoilage detection. Sagar and Rani (2026) reviewed innovations in AI-based food packaging, emphasizing the integration of sensor networks, IoT, and machine learning to enhance food safety and reduce waste. Bongarde et al. (2025) explored the application of machine learning and AI in spoilage detection, noting that AI-driven systems outperform conventional methods by enabling real-time monitoring and predictive analytics. Complementary research has introduced biodegradable smart packaging with real-time spoilage indicators, such as pH-sensitive pigments and NFC technology, which provide eco-friendly solutions alongside digital monitoring. Collectively, these studies demonstrate that combining biotechnology, sensor integration, and AI inference creates a robust framework for addressing food safety, sustainability, and consumer trust. SCP-SmartPack AI builds upon these foundations by unifying sensor data acquisition, AI-driven spoilage prediction, and recommendation delivery into a scalable, cloud-integrated system.

2.1 Challenges

Food spoilage detection remains a multifaceted challenge due to the complex interplay of environmental, biological, and chemical factors that influence product quality. Traditional packaging systems rely heavily on static indicators such as expiration dates, which fail to account for dynamic conditions during storage, transportation, and retail display. As a result, these static labels often lead to premature disposal of consumable food or, conversely, the consumption of spoiled products, thereby increasing both food waste and health risks. Studies emphasize that reliance on visual inspection or expiry labels is insufficient, as spoilage can occur without obvious external signs. Laboratory-based methods such as microbial assays and chemical testing provide accurate results but are costly, time-consuming, and impractical for real-time consumer use. Moreover, these methods lack scalability for widespread deployment across supply chains. The absence of low-cost, reliable, and scalable spoilage detection mechanisms underscores the urgent need for intelligent packaging solutions that integrate sensor networks, biotechnology, and artificial intelligence. Such systems can provide continuous monitoring, dynamic shelf-life estimation, and actionable insights, thereby addressing the limitations of conventional approaches while enhancing food safety, sustainability, and consumer trust.

Aspect	Description
Environmental Factors	Spoilage influenced by temperature, humidity, microbial activity, chemicals
Traditional Packaging	Relies on static indicators (expiry dates), ignores dynamic conditions
Consumer Practices	Visual inspection/labels cause premature disposal or unsafe consumption
Laboratory Methods	Accurate but costly, impractical for real-time consumer use
Key Limitation	Lack of scalable, low-cost, reliable spoilage detection mechanisms

Table 1: Challenges in Food Spoilage Detection

2.2 Machine Learning

Machine learning (ML) has emerged as a transformative approach in food spoilage prediction, offering greater precision and adaptability compared to conventional methods. Predictive AI models leverage multimodal data sources, including sensor readings, chemical signatures, and environmental variables, to dynamically estimate shelf life. Techniques such as Convolutional Neural Networks (CNNs) have been successfully applied to image-based spoilage detection, identifying visual cues like discoloration and mold with high accuracy. In parallel, ensemble learning methods such as Random Forests and gradient boosting have demonstrated strong performance in analyzing heterogeneous sensor data, capturing complex relationships between environmental factors and microbial activity. The integration of IoT-enabled systems further enhances predictive accuracy by enabling real-time monitoring and cloud-based analytics, ensuring that models continuously adapt to changing conditions. These advancements collectively support dynamic shelf-life estimation, reducing unnecessary food waste, improving food safety, and strengthening transparency across supply chains.

Technique / Approach	Application
Convolutional Neural Nets (CNNs)	Image-based spoilage detection (color, texture changes)
Ensemble Models (RF, GBM)	Sensor data analysis for shelf-life estimation
IoT Integration	Real-time monitoring with cloud-based analytics
Predictive AI Models	Leverage sensor + chemical signatures for dynamic shelf-life prediction
Key Benefit	Greater precision, reduced waste, improved food safety

Table 2: Machine Learning in Spoilage Prediction

2.3 Related Work

Recent literature demonstrates significant progress in smart packaging and AI-driven food monitoring, highlighting both technological innovation and practical applications. Narashans et al. reviewed advancements in AI-based food packaging, emphasizing the limitations of traditional systems in providing real-time product status and underscoring the potential of AI for enhancing supply chain visibility. Ingole et al. proposed a freshness detection framework that integrates biosensors and gas sensors with machine learning models, further supported by IoT connectivity to ensure transparency across the

supply chain. Similarly, Shehzad explored predictive AI models for shelf-life estimation, noting that dynamic prediction not only reduces economic losses but also mitigates risks associated with foodborne illness. Collectively, these studies establish the foundation for intelligent packaging systems, demonstrating how the convergence of biotechnology, sensor networks, and artificial intelligence can transform food safety and sustainability. Building upon these contributions, SCP-SmartPack AI advances the field by unifying sensor data acquisition, AI-driven spoilage prediction, and recommendation delivery into a scalable, cloud-integrated platform suitable for large-scale deployment.

Author / Study	Contribution
Narashans et al.	Reviewed AI-based food packaging; highlighted supply chain visibility
Ingole et al.	Proposed freshness detection using biosensors, gas sensors + ML + IoT
Shehzad	Explored predictive AI models for shelf-life estimation; reduced losses
General Trend	Shift from static packaging to AI-driven, real-time monitoring solutions

Table 3: Related Work in Smart Packaging & AI

III. SYSTEM ARCHITECTURE

3.1 System Architecture

The proposed SCP-SmartPack AI system is designed as a three-layered architecture integrating biotechnology, sensor networks, and artificial intelligence. At the foundation lies the biodegradable single-cell protein (SCP) packaging layer, which embeds sensors capable of monitoring environmental parameters such as temperature, humidity, and microbial activity. The second layer, the AI processing unit, leverages machine learning models to analyze sensor and camera data, applying predictive algorithms to detect spoilage patterns. The third layer, the visualization and user interface, is implemented using React and Recharts, providing real-time dashboards for consumers and retailers. This modular design ensures scalability, interoperability, and adaptability across diverse food supply chains.

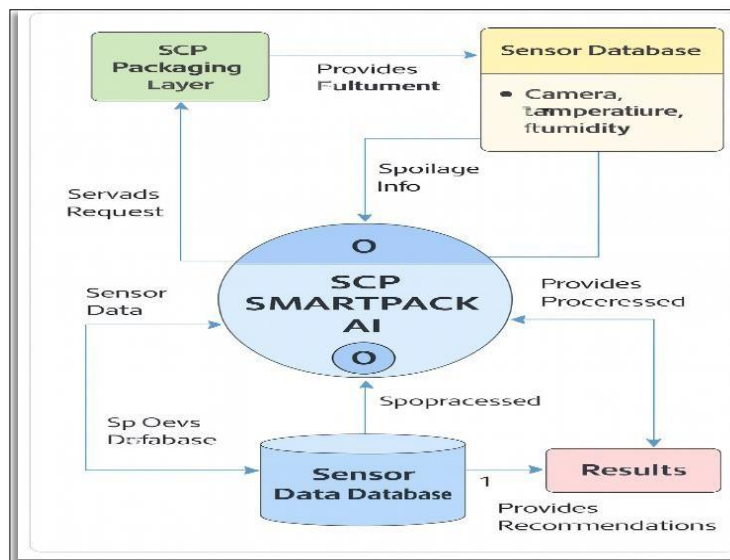


Figure 1: System Architecture

3.2 Module Description

The SCP-SmartPack AI system is composed of several interconnected modules, each designed to handle a specific stage of the workflow while ensuring scalability and real-time performance. The sensor module consists of IoT-enabled sensors and camera units embedded in the packaging, which continuously capture environmental parameters such as temperature, humidity, microbial activity, and visual indicators. This information is transmitted through the data transmission module, which uses secure IoT protocols to deliver raw inputs to the backend. Once received, the preprocessing module performs noise reduction, normalization, and feature extraction, transforming heterogeneous sensor data into a structured dataset suitable for analysis. The AI inference module, powered by the Gemini API, applies trained machine learning models to predict spoilage levels and freshness scores, while reinforcement learning mechanisms allow the system to adapt dynamically to new inputs and user feedback. These outputs are then presented through the visualization module, built with React and Recharts, which provides interactive dashboards, graphs, heatmaps, and real-time alerts optimized for

mobile and desktop devices. Finally, the recommendation module translates AI predictions into actionable insights, such as alerts for imminent spoilage, optimal storage suggestions, and disposal guidance when thresholds are exceeded. To support large-scale adoption, the deployment and scalability module leverages Docker-based containerization and cloud platforms like AWS or Azure, enabling horizontal scaling and seamless integration with supply chain management systems.

Module	Function
SCP Packaging Layer	Provides biodegradable packaging with embedded sensors
Sensor Data Acquisition	Collects temperature, humidity, microbial, and visual data
Preprocessing Module	Cleans, normalizes, and extracts features from raw sensor inputs
AI Model	Predicts spoilage using ML algorithms (CNN, RF, SVM)
Visualization Dashboard	Displays spoilage trends, freshness scores, and alerts
Recommendation Engine	Generates actionable suggestions for storage, consumption, and safety

Table 4: Module Description

3.3 Key Features

The SCP-SmartPack AI system integrates real-time spoilage detection through AI-driven predictive analytics, ensuring continuous monitoring of food conditions. Its biodegradable SCP packaging reduces environmental impact while supporting sustainability goals. Designed with cloud-based scalability, the system can be deployed across retail and distribution networks for large-scale monitoring. Finally, interactive dashboards provide transparency and consumer engagement by visualizing spoilage trends, freshness scores, and alerts in an accessible format.

Feature	Description
Biodegradable SCP Material	Eco-friendly packaging aligned with sustainability goals
Real-Time Monitoring	Continuous sensor data acquisition and analysis
AI-Driven Prediction	Machine learning models for dynamic shelf-life estimation
Interactive Dashboard	React-based visualization with graphs, heatmaps, and alerts
IoT Integration	Cloud connectivity for supply chain transparency
Consumer Alerts	Notifications for spoilage risk and optimal consumption timelines

Table 5: Key Features

3.4 Workflow

The workflow of the SCP-SmartPack AI system is designed as a modular, end-to-end process that ensures efficient monitoring, prediction, and recommendation for food spoilage management. It begins with sensor data collection, where IoT-enabled sensors embedded in SCP packaging continuously capture critical parameters such as temperature, humidity, microbial activity, and visual indicators like discoloration or mold. These diverse data streams are securely transmitted to the backend using IoT protocols, ensuring real-time communication and integrity. Once received, the data enters the preprocessing module, which performs noise reduction to eliminate inconsistencies, normalization to standardize values across different sensor types, and feature extraction to highlight relevant spoilage indicators. This step transforms raw, heterogeneous inputs into a structured dataset suitable for machine learning analysis. The cleaned dataset is then processed by the AI model, trained on extensive historical spoilage datasets and deployed through the Gemini API. The model applies advanced machine learning algorithms to predict spoilage levels and freshness scores, while reinforcement learning mechanisms enable continuous adaptation as new sensor inputs and user feedback are incorporated. This ensures that predictions remain accurate and context-aware over time. The visualization layer translates AI outputs into user-friendly insights. Built with React and Recharts, the dashboard provides interactive graphs, heatmaps, and real-time alerts, optimized for both mobile and desktop platforms. This allows consumers, retailers, and supply chain managers to monitor spoilage trends, identify risk zones, and respond proactively. Finally, the recommendation engine converts predictions into actionable guidance. Users receive alerts for imminent spoilage, suggestions for optimal storage conditions, and disposal recommendations when safety thresholds are exceeded. These recommendations not only enhance consumer safety but also support sustainability by reducing unnecessary food waste. Overall, this workflow ensures seamless integration of biotechnology, sensor networks, and artificial intelligence, delivering a scalable, modular, and real-time solution that can be adopted across diverse supply chains and retail environments.

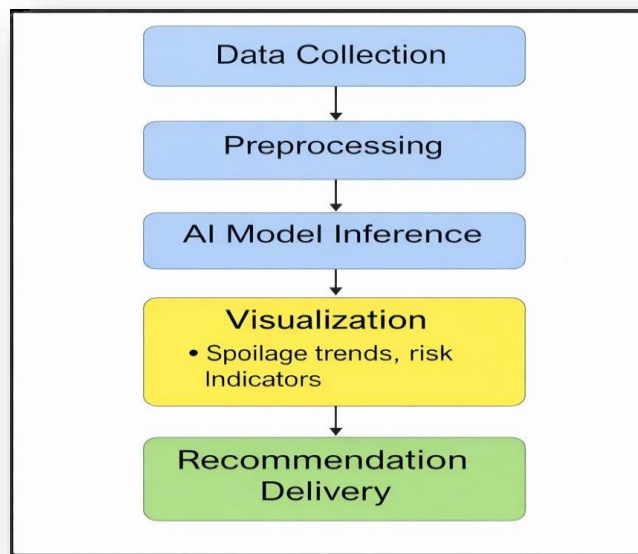


Figure 2: Workflow

IV. DATA FLOW DIAGRAM

The data flow within the SCP-SmartPack AI system is carefully structured to ensure efficient acquisition, processing, and interpretation of food spoilage indicators. The workflow begins with sensor and camera modules embedded in SCP packaging, which continuously capture environmental parameters such as temperature, humidity, microbial activity, and visual cues like discoloration or mold formation. This raw data is transmitted to the backend via IoT protocols, ensuring secure and real-time communication. Once received, the data enters the preprocessing stage, where noise reduction, normalization, and feature extraction are performed to convert heterogeneous sensor inputs into a structured dataset suitable for analysis. The cleaned dataset is then fed into machine learning models hosted via the Gemini API, which apply trained algorithms to infer spoilage levels and freshness scores. Reinforcement learning mechanisms allow the models to adapt dynamically, improving prediction accuracy as new data and user feedback are incorporated. The predictions are visualized through a React-based dashboard, which provides interactive graphs, heatmaps, and real-time alerts, enabling users to monitor spoilage trends and risk indicators across different storage environments. Finally, the recommendation engine translates predictions into actionable insights, such as optimal storage practices, consumption timelines, or disposal alerts when safety thresholds are exceeded. Each stage of the data flow is designed to be modular and scalable, allowing seamless integration with cloud platforms and supply chain management systems, thereby supporting large-scale deployment across retail and distribution networks.

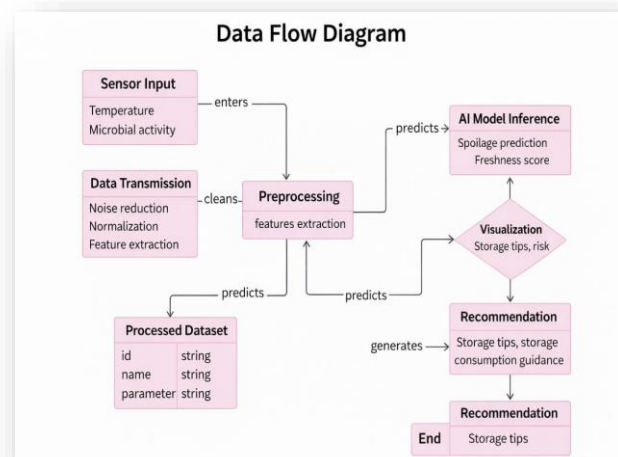


Figure 3: Data Flow Diagram

V. METHODOLOGY

The SCP-SmartPack AI methodology integrates IoT-enabled sensors, preprocessing modules, machine learning inference, visualization, and recommendation delivery into a streamlined workflow. Sensors embedded in SCP packaging capture environmental and microbial data, which is normalized and structured for analysis. The Gemini API applies trained AI models to predict spoilage levels and freshness scores, adapting continuously through reinforcement learning. Results are displayed via interactive dashboards with graphs, heatmaps, and alerts, while the system provides actionable recommendations such as storage tips, consumption timelines, and disposal alerts, ensuring real-time performance and scalability across supply chains.

5.1 Data Collection

The SCP-SmartPack AI system begins with data acquisition from embedded sensors within the biodegradable single-cell protein (SCP) packaging. These sensors monitor critical environmental parameters such as temperature, humidity, and microbial activity. Additionally, camera modules capture visual cues indicative of spoilage, including discoloration, mold growth, and texture changes. The collected data is transmitted in real time to the processing unit via IoT protocols, ensuring continuous monitoring throughout the product lifecycle.

5.2 Data Preprocessing

Raw sensor and image data often contain noise, inconsistencies, and missing values. To ensure model reliability, the preprocessing module performs normalization, outlier removal, and feature extraction. Sensor readings are standardized using min-max scaling, while image data undergoes histogram equalization and edge detection to enhance spoilage indicators. Missing values are imputed using k-nearest neighbor (KNN) interpolation, and categorical variables are encoded using one-hot encoding. This preprocessing pipeline ensures that the input data is clean, structured, and suitable for machine learning analysis.

5.3 React Rendering Algorithms

The processed data is visualized using React-based rendering algorithms integrated with Recharts. These algorithms dynamically update the user interface based on real-time predictions from the AI model. Spoilage scores, freshness indicators, and environmental trends are displayed through interactive graphs, heatmaps, and alert banners. The rendering logic is optimized for responsiveness and accessibility, ensuring seamless user experience across devices. Conditional rendering and state management are handled using React hooks and context APIs, enabling modular and scalable visualization.

5.4 Model Training and Testing

The core AI model is trained on a labeled dataset comprising sensor readings and corresponding spoilage outcomes. Supervised learning algorithms such as Random Forest, Support Vector Machines (SVM), and Convolutional Neural Networks (CNNs) are evaluated for performance. The training process involves k-fold cross-validation to prevent overfitting and ensure generalizability. Evaluation metrics include accuracy, precision, recall, and F1-score. The best-performing model is deployed for real-time inference, continuously updated with new data to improve prediction accuracy.

5.5 Recommendation Generation

Based on spoilage predictions, the system generates actionable recommendations for consumers and retailers. These include alerts for imminent spoilage, optimal storage conditions, and suggested consumption timelines. The recommendation engine uses rule-based logic combined with reinforcement learning to adapt suggestions based on user feedback and environmental changes. Recommendations are delivered through the dashboard interface and can be integrated with mobile notifications or supply chain management systems for broader impact.

Input Source	AI Output	Recommendation Type	Description
Sensor Data	Spoilage Level: Low	Storage Optimization	Suggests ideal temperature and humidity settings
Sensor, Visual Input	Spoilage Level: Medium	Consumption Timeline	Advises best-before date based on current freshness
Microbial Activity	Spoilage Level: High	Disposal Alert	Warns user to discard item due to safety risk
Historical Data Patterns	Shelf-Life Prediction	Purchase Planning	Recommends optimal quantity and timing for future purchases
User Feedback Loop	Model Adjustment	Adaptive Suggestions	Refines future alerts based on user decisions and outcomes

Table 6: Methodology of Food Spoilage Detection System

VI. IMPLEMENTATION

The SCP-SmartPack AI system integrates biotechnology, sensor networks, and artificial intelligence into a unified platform designed for scalability and real-time performance. The frontend, built with React and Recharts, provides interactive dashboards, while the backend uses Node.js with RESTful APIs to connect sensors, AI models, and visualization layers. AI inference is powered by the Gemini API, supported by Vite and TypeScript for modular development. IoT-enabled sensors capture temperature, humidity, microbial activity, and visual data, which are preprocessed before being analyzed by trained AI models that adapt through reinforcement learning. Results are displayed via graphs, heatmaps, and alerts on a mobile- and desktop-optimized dashboard. Deployment is containerized with Docker on cloud platforms such as AWS or Azure, enabling horizontal scaling and integration with supply chain systems for large-scale adoption.

Component	Technology / Framework	Functionality / Role
Frontend Interface	React , Recharts	Interactive dashboard for spoilage trends, freshness scores
Backend Server	Node.js, RESTful APIs	Handles data flow, model integration, and client-server communication
AI Model Integration	Gemini API	Real-time spoilage prediction and freshness scoring
Development Tools	Vite, TypeScript	Fast bundling, modular code structure, type safety
Sensor Layer	IoT-enabled sensors (temp, humidity, microbial, camera)	Data acquisition from SCP packaging
Data Preprocessing	Custom normalization and feature extraction	Cleans and structures sensor input for AI analysis
Visualization Layer	React Recharts	Graphs, heatmaps, alerts for consumer and retailer insights
Deployment Strategy	Docker containers, AWS/Azure	Scalable cloud deployment across supply chains
Scalability Features	Modular architecture, horizontal scaling	Supports multiple packaging units and integration with logistics

Table 7: Implementation

VII. BENEFITS AND CHALLENGES

7.1 Benefits

The SCP-SmartPack AI system improves food management by detecting spoilage in real time, reducing food waste and economic loss. It enhances food safety through continuous monitoring of microbial and environmental conditions, preventing the consumption of spoiled products. By using biodegradable single-cell protein packaging, it promotes environmental sustainability and reduces plastic pollution. Its scalable design, transparency features, and integration with IoT and cloud systems make it efficient and adaptable across various levels of the food supply chain.

Benefit	Description
Reduced Food Waste	Real-time spoilage detection minimizes premature disposal of consumable food
Enhanced Food Safety	Continuous monitoring prevents consumption of spoiled products
Environmental Sustainability	Biodegradable SCP packaging reduces reliance on plastics
Supply Chain Scalability	Cloud-based architecture supports deployment across retail networks
Transparency & Engagement	Interactive dashboards build consumer trust and regulatory compliance

Table 8: Benefits of Proposed System

7.2 Challenge

Despite its advantages, the SCP-SmartPack AI system faces challenges such as the high cost of SCP-based packaging production, the need for accurate and reliable sensor calibration, and concerns regarding data privacy and cybersecurity. Additionally, consumer acceptance may be limited due to resistance to new technology or higher costs, and large-scale deployment requires strong IoT and cloud infrastructure, which may not be readily available in all regions.

Challenge	Description
Sensor Accuracy	Calibration errors may affect reliability of spoilage predictions
Consumer Acceptance	Skepticism toward AI-driven packaging may slow adoption
Production Costs	SCP material manufacturing remains expensive compared to conventional plastics
Infrastructure Limitations	IoT and cloud support may be limited in certain regions
Data Privacy & Security	Risks of data breaches and cybersecurity challenges

Table 9: Challenges of Proposed System

VIII. USER INTERFACE

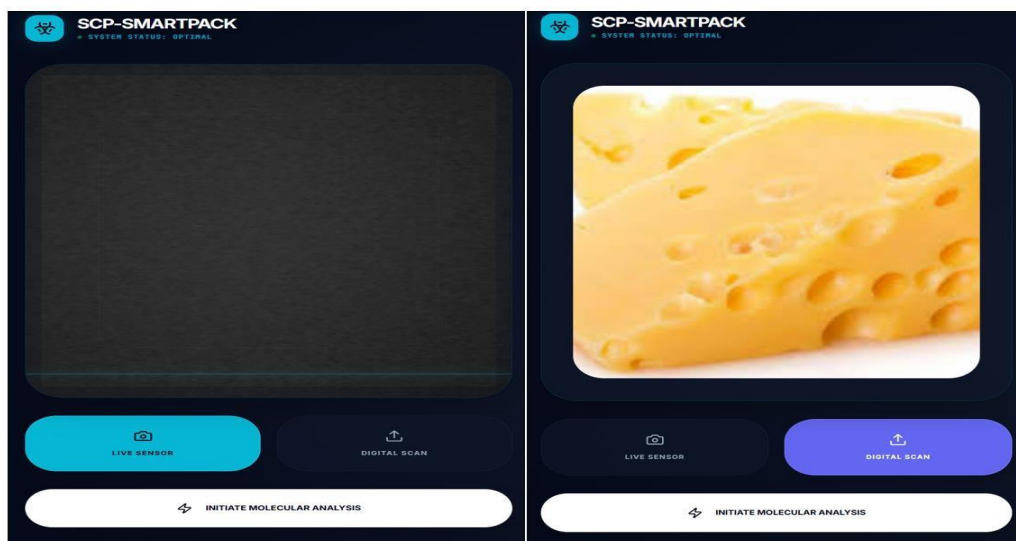
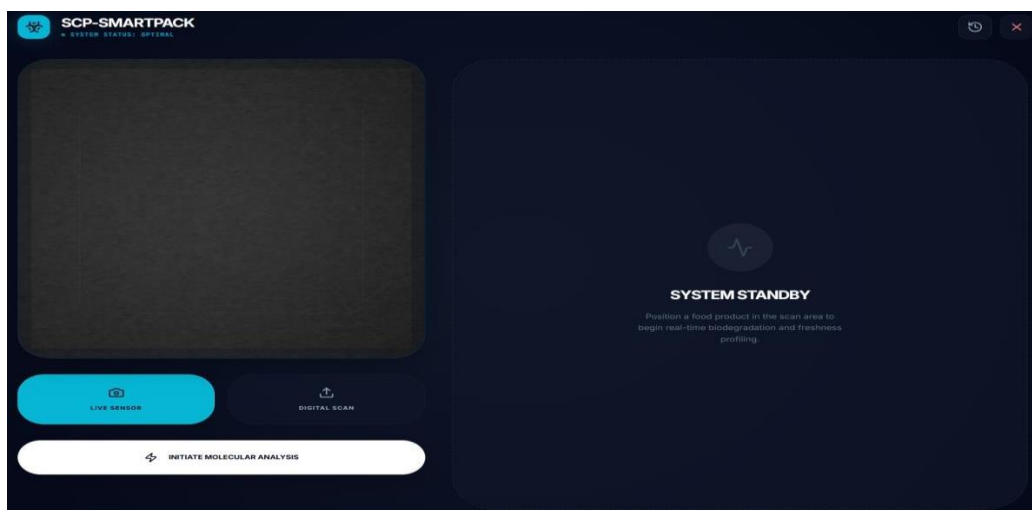


Figure 5: File Input Page

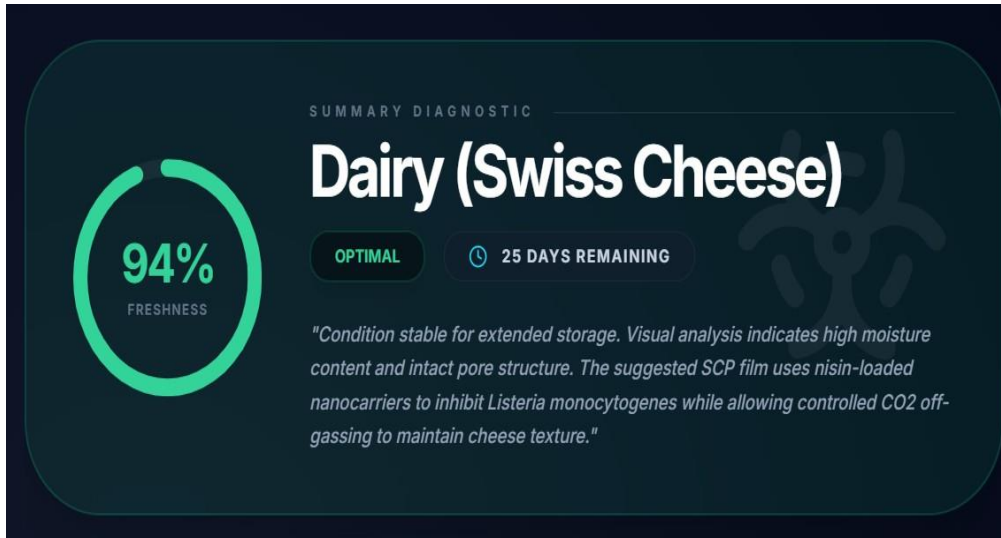


Figure 6: Freshness Report



Figure 7: Live Telemetry Report

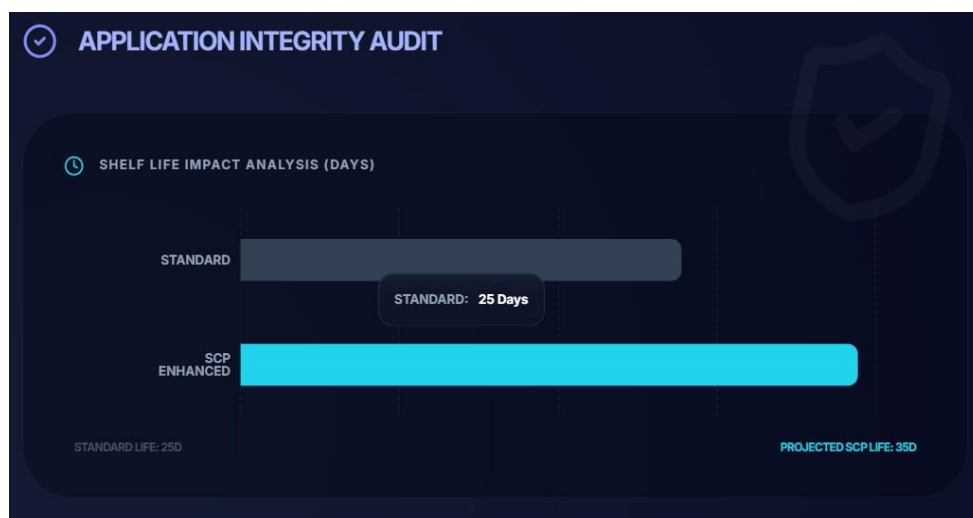


Figure 8: Smart Pack Shelf Life Analysis

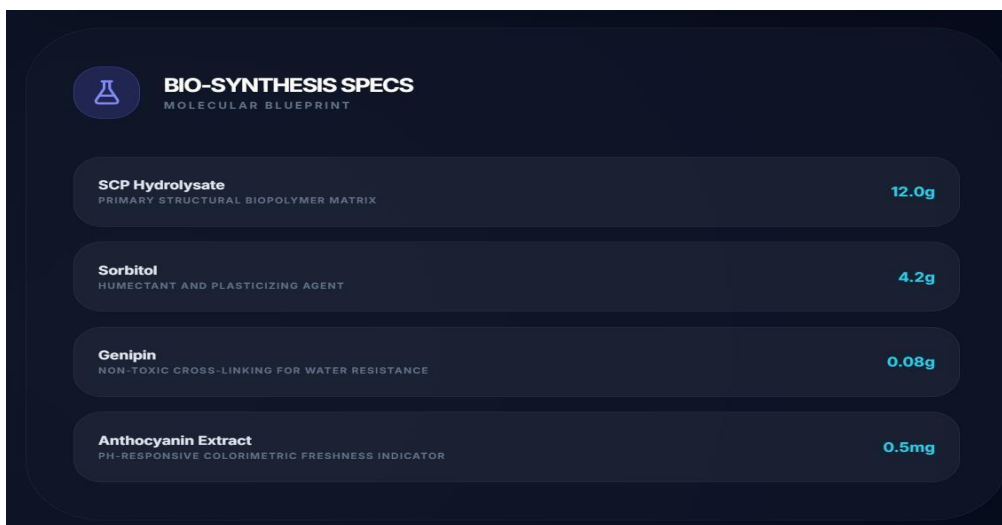


Figure 9: Smart Pack Quality Insight

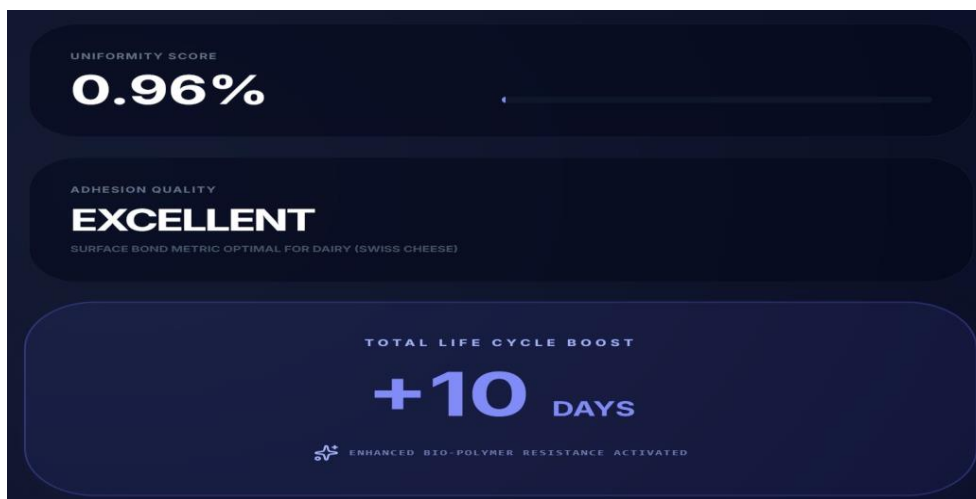


Figure 10: Packing Analyser

IX. DISCUSSION AND FUTURE WORK

Discussion

The SCP-SmartPack AI system showcases how biotechnology and artificial intelligence can work together to improve food safety and environmental sustainability. By integrating sensors into biodegradable SCP packaging, it enables real-time spoilage monitoring and more accurate shelf-life prediction than traditional expiration-date methods. Its intelligent models and user-friendly interface enhance transparency and decision-making across the supply chain. Unlike conventional smart packaging, it combines sustainability with advanced monitoring, offering a comprehensive solution, though challenges such as sensor accuracy, production costs, and consumer acceptance still require further development.

Future Work

Future improvements of the SCP-SmartPack AI system include integrating blockchain technology to ensure secure and transparent traceability across the supply chain, and applying advanced reinforcement learning models to enhance spoilage prediction accuracy through real-time adaptation. Large-scale pilot deployments can help evaluate scalability and practical challenges, while expanded sensor capabilities—such as detecting volatile organic compounds—can improve detection precision. Additionally, consumer-focused mobile applications may increase user engagement through personalized alerts and sustainability insights, and optimizing the cost of SCP production will be essential to support widespread and affordable adoption.

X. CONCLUSION

Food spoilage is a major global issue causing economic loss, environmental harm, and health risks, and traditional packaging lacks real-time monitoring capabilities. The SCP-SmartPack AI system addresses this gap by combining biodegradable single-cell protein packaging with artificial intelligence to enable dynamic spoilage detection and continuous food quality monitoring. By integrating sensor data, machine learning models, and an interactive visualization interface, the system improves prediction accuracy, reduces food waste, and enhances safety while supporting environmental sustainability. Although challenges such as production costs and sensor reliability remain, SCP-SmartPack AI offers a comprehensive and innovative solution with strong potential to transform modern food supply chains toward a more sustainable future.

REFERENCES

- [1]. S. Singha, M. Mahmutovic, C. Zamalloa, L. Stragier, W. Verstraete, A. J. Svagan, O. Das, and M. S. Hedenqvist, "Novel Bioplastic from Single Cell Protein as a Potential Packaging Material," *ACS Sustainable Chemistry & Engineering*, vol. 9, pp. 6337–6346, 2021.
- [2]. P. T. Sekoai, Y. Roets-Dlamini, F. O'Brien, S. Ramchuran, and V. Chunilall, "Valorization of Food Waste into Single-Cell Protein: An Innovative Technological Strategy for Sustainable Protein Production," *Microorganisms*, vol. 12, no. 1, pp. 1–16, 2025.
- [3]. "A comprehensive report on valorization of waste to single cell protein," *Springer*, 2025.
- [4]. K. Shehzad, "Predictive AI Models for Food Spoilage and Shelf-Life Estimation," *Global Trends in Science and Technology*, vol. 1, no. 1, pp. 75–94, 2025.
- [5]. "Food Spoilage Detection using IoT and Machine Learning," *IEEE Xplore*, 2024.
- [6]. "IoT Based Food Spoilage Detection using Machine Learning," *IEEE Xplore*, 2024.
- [7]. "Paper Sensors for Advanced Smart Packaging: Route to Detection," *IEEE Xplore*, 2024.
- [8]. N. Manouselis, "AI in Food Safety," *Food Science and Technology*, vol. 39, no. 4, pp. 44–47, Dec. 2025.
- [9]. M.-E. Dimitrakopoulou and A. Garre, "AI's Intelligence for Improving Food Safety: Only as Strong as the Data that Feeds It," *Current Food Science and Technology Reports*, vol. 3, article 15, May 2025.
- [10]. "Food Safety Monitoring with AI," *Industry Report*, 2025.
- [11]. G. Khaleel, V. S. Sharanagat, S. Upadhyay, S. Desai, K. Kumar, A. Dhiman, and R. Suhag, "Sustainable Approach Toward Biodegradable Packaging Through Naturally Derived Biopolymers: An Overview," *Journal of Packaging Technology and Research*, vol. 9, pp. 19–46, Dec. 2024.
- [12]. C. A. Ikedionu, F. A. Idoko, and O. J. Ojochogwu, "Design and Development of Biodegradable Polymers for Green Packaging Solutions," *Research Publish Journals*, Feb. 2025.
- [13]. "Biodegradable Packaging of Food: An Alternative to Synthetic Polymers," *Review Paper*, 2025.