Autonomous Micro-Agents for Real-Time Shrinkage Prevention in Perishable Goods

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Abstract
The system proposed in this paper makes use of self-governing agents to solve the major problem of shrinkage in perishable goods throughout the supply chain. Financial losses and hunger can be greatest when food is affected by spoilage, theft, mishandling, or changes in the environment. Our approach involves integrating small IoT-powered agents that can observe, evaluate, and control situations as they happen. We utilize a combination of various sensors, adjustable approaches, and distributed management to accurately monitor equipment and anticipate when it may require repairs. To model changing spoilage trends, the system architecture utilizes edge computing, blockchain, and machine learning in conjunction. The details of the methodology clearly illustrate how different micro-agents coordinate their activities throughout the supply chain, from farming to retail sales. Improvements from simulations and live programs demonstrate that spoilage and losses are reduced, resulting in longer expiration periods and lower waste. The work creates an intelligent and flexible model for use in smart logistics, environmental responsibility, and cost-effective services.

Keywords: Perishable goods, Autonomous agents, Real-time monitoring, IoT, Shrinkage prevention, Supply chain, Machine learning, Edge computing, Blockchain.

1. INTRODUCTION

In the global food supply chain, shrinkage of perishables is a significant issue, accounting for approximately 30% of waste. As a result, there are significant economic consequences for producers, distributors, and retailers, along with additional environmental problems, including increased energy consumption, higher greenhouse gas emissions, and ineffective resource management. A significant portion of the reason for this shrinkage is that storage and transportation conditions, including temperature, humidity, and exposure to pollutants, are not properly monitored. Traditionally, centrally managed systems can spot some spoilage risks, but they are generally not quick or detailed enough to act in real-time. Because they depend on scheduled updates and manual supervision, such systems can take too much time to respond. [1-4] With supply chains becoming more complicated and fresh, high-quality goods in high demand, there is an urgent requirement for advanced, automatic solutions to handle the changing conditions of perishable products. Due to these requirements, the use of micro-agents in decentralized, real-time monitoring frameworks is growing in interest. Such agents can reshape how spoilage is prevented, facilitating quick data analysis, rapid regional decisions, and more proactive actions. When they overcome the shortcomings of old systems, these new advances reduce waste and improve the stability, efficiency, and sustainability of the food supply chain.

1.1.Importance of Autonomous Micro-Agents for Real-Time Shrinkage Prevention

- **Enhanced Real-Time Monitoring**: These autonomous micro-agents continuously record environmental factors for perishables, including temperature, humidity, gases, and vibrations. Unlike usual monitoring, these agents don't stop working, so they are more likely to find problems in the early stages than traditional inspections. Being aware of things in real-time helps prevent losses and ensures goods remain safe and of high quality as they move through the supply chain.
- **Decentralized Data Processing:** Local sensor processing by micro-agents enables easier avoidance of central systems that can cause delays or lead to outages. Because processing is done at the source, it enables a faster response when spoilage may occur. The system also reduces the amount of communication within its network, which helps it grow and be utilized for large-scale supply networks.

Figure 1: Importance of Autonomous Micro-Agents for Real-Time Shrinkage Prevention

- **Proactive and Predictive Capabilities:** With the aid of machine learning, micro-agents can identify current spoilage and anticipate potential risks using both past and present sensor data. Because of this feature, stakeholders can review demand and take steps such as storing goods safely or adjusting their inventory rotation to prevent products from being wasted.
- **Improved Traceability and Accountability:** When used in conjunction with blockchain, autonomous micro-agents enable the storage of permanent and transparent records of environmental activity and changes. Due to this traceability, every stage of the refrigerated process is documented for use in examinations, ensuring compliance and protecting the customer's confidence. It also insists that all supply chain members are responsible for protecting their products appropriately.
- **Scalability and Flexibility:** Modularity: these micro-agents can be used wherever needed—in chilled storage, during transport, or on retail displays. Because they are decentralized, larger or smaller changes in operational needs can usually be handled without much fuss. Because the technology can be customized, both smaller and larger businesses can find solutions that fit their specific shrinkage challenges.
- **Cost Efficiency and Waste Reduction:** By identifying issues early, micro-agents prevent spoilage, enabling retailers and suppliers to reduce waste and save money. It also helps protect the environment by reducing food waste. Over time, the increased efficiency and ability to reduce waste from autonomous micro-agents can offset the cost of preparing and running them.

1.2.Real-Time Shrinkage Prevention in Perishable Goods

Timely measures against shrinkage are necessary to preserve the safety and quality of perishable goods throughout the entire supply chain. The loss of stock to spoilage, mishandling, or theft, known as shrinkage, poses significant problems for retailers and their suppliers, both financially and environmentally. In the past, managers have addressed shrinkage problems by having staff inspect and monitor items occasionally, which is a slow and often ineffective approach to mitigating shrinkage risks. By comparison, technology in real-time shrinkage prevention watches for suspicious activity and allows instant actions to stop shrinkage. When key environmental parameters are regularly checked, systems can easily detect when the temperature, moisture, or gas levels deviate from optimal storage conditions. With this plan, food doesn't spoil as quickly, and it remains fresh for a longer period. [5,6] Thanks to sensor networks, edge computing, and predictive analytics, it becomes easier for supply chain managers to predict spoilage events and choose the best ways to handle their supplies and logistics. Managing real-time shrinkage avoidance leads to stronger transparency and accountability because it stores all the details of storage settings and actions chronologically. This breaks down to compliant operation and respect for consumers, as the company guarantees the quality of its products. Real-time systems also increase a company's efficiency by automatically notifying staff of problems and eliminating the need for extensive manual checks, thereby freeing up more resources for additional useful tasks. When real-time shrinkage prevention is applied to perishable goods supply chains, the results are reduced wastage, lower expenses, and a lessened negative effect on the environment. Due to the increasing demand for fresh and safe food worldwide, it is now necessary for supply chain management to adopt up-to-the-minute methods to prevent shrinkage.

2. Literature Survey

2.1. Shrinkage in Perishable Goods

Shrinkage refers to products that are missing from inventory before they can be sold to customers, typically due to spoilage, damage, or other causes. Studies have shown that the temperature of storage, the amount of humidity, and the time the product is kept, as well as improper handling, inadequately trained workers, and forecast errors, are the primary reasons for mistakes. [7-10] The food and pharmaceutical sectors consider these losses to be particularly crucial since shelf life is short and rules are very strict. These problems must be handled by carefully monitoring the environment and making flexible decisions throughout each production stage.

2.2. Monitoring Technologies

Monitoring the environment and products in supply chains is now widely done by attaching Internet of Things (IoT) sensors to items. They help detect any problems that could cause goods to spoil or be lost. For the most part, the gathered data from sensors is processed and analyzed by systems in a central location. When transactions are handled in a single location, this can slow down processes, limit scalability, and expose the system to failure at a single point, a notable problem in today's supply chains.

2.3. Agent-Based Systems

ABS provides a promising solution for supply chain management because it uses self-acting agents that make local decisions using data and set instructions in real-time. Improvements in responsiveness, reducing bottlenecks, and optimizing resource utilization are possible with these systems in logistics. Agents are largely able to act independently, serving to resolve problems locally as soon as they occur. Although agent-based systems are effective, they have not been fully explored in perishable goods management, where rapid interventions and flexible strategies are crucial for controlling shrinkage.

2.4. Blockchain in Supply Chains

Supply chain managers now utilize blockchain because it helps maintain accurate, clear, and transparent data. When transactions are put together into a distributed ledger, the data that groups of stakeholders use becomes even more credible. Evidence suggests that it helps identify the origin of products, ensures compliance with safety codes, and reduces unlawful actions. Even so, while blockchain's usefulness in tracking goods is widely known, it hasn't yet been widely explored for use with real-time monitoring and smart systems in the perishable sector.

2.5. Gaps Identified

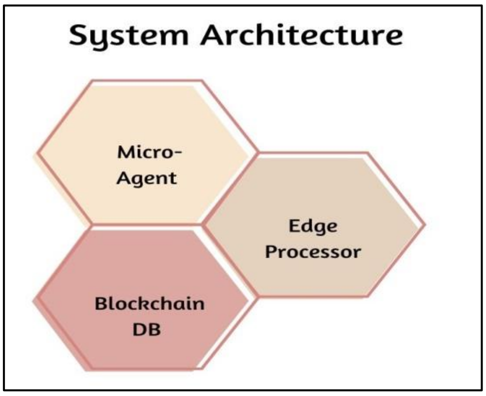
Analysis of the current literature reveals what works well and what doesn't in the use of technologies in supply chain management. Nevertheless, there remains a significant hurdle in integrating autonomous micro-agents, predictive analytics, and blockchain. When these three are used together, they could support better choices, stronger monitoring, and shrinkage management in supply chains for perishable products. No thorough research has examined how these technologies can be combined to create a decentralized, intelligent, and secure system for perishable goods.

3. Methodology

3.1. System Architecture

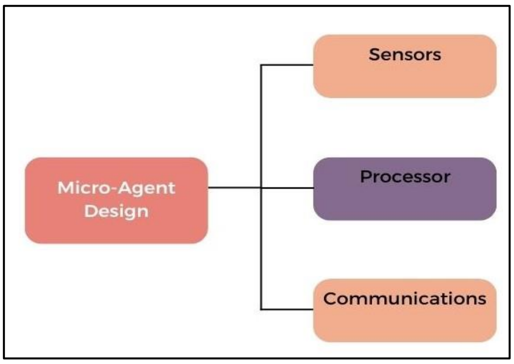
The proposed system architecture combines three key components, Micro-Agents, an Edge Processor, and a Blockchain Database, to control perishable products in a decentralized, intelligent, and secure manner.

Figure 2: System Architecture



- **Micro-Agent:** Micro-agents are simply programmed elements that can run automatically within or on IoT equipment in the supply chain. With its sensors, each micro-agent can detect changes in temperature, humidity, and shock levels and respond or issue alerts if they follow defined criteria. As a result, decision-making can be distributed, saving on centralized solutions and allowing the system to respond faster to nearby problems, such as temperature changes within refrigerated containers.
- **Edge Processor:** Edge processors act to provide real-time processing of data collected from a variety of micro-agents. The edge processor being directly near data helps it respond more quickly, sift out what is important, and relay important insights. Edge computing enables forecasting and facilitates an easy way for network agents in the area to coordinate, ensuring that resources are managed efficiently and tough choices can be handled locally.

Figure 3: Micro-Agent Design



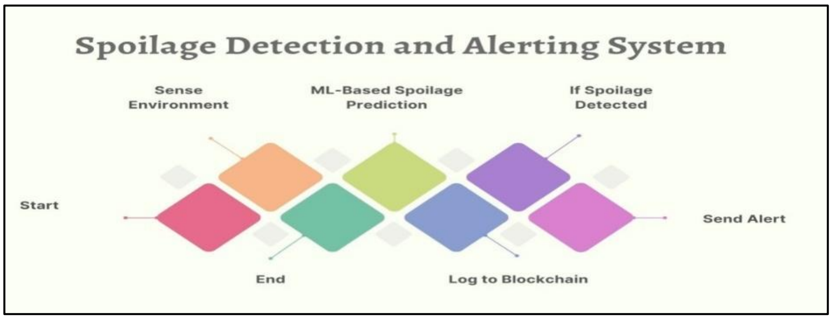
- **Blockchain Database:** The use of a blockchain database guarantees that all key events, such as temperature breaks, handling notes, and shipment changes, stay securely logged in the supply chain. With data stored securely on the blockchain, all stakeholders gain greater transparency, enhanced tracking, and increased trust. As a result, no micro-agent or edge processor can delete or modify records after the event, which is crucial for both security and quality control in perishable logistics.

3.2. Micro-Agent Design

- **Sensors:** A set of temperature, humidity, gas, and vibration sensors is included with the micro-agent. With these sensors, it is possible to monitor the environment in real-time, supporting the safe storage of perishable goods. Gas sensors, along with temperature and humidity sensors, monitor storage conditions for early signs of food spoilage. Vibration sensors are fitted to watch for any movements caused by transport that could result in product damage.
- **Processor:** Every micro-agent contains an ARM Cortex-M4 processor, which is simple to use but strong enough for AI in embedded systems. Thanks to machine learning models, this processor enables the micro-agent to make informed decisions, such as detecting unusual events or predicting the likelihood of spoilage by analyzing sensor data patterns. The AI system inside the robot reduces its need for external support, allowing it to respond to environmental differences in a short time.
- **Communications:** The micro-agent is designed to utilize the communication protocols LoRa, Wi-Fi, and Zigbee, enabling it to communicate effectively in various situations within the supply chain. Long-range and low-power LoRa is the perfect technology for communicating in outdoor environments. Wi-Fi provides ample bandwidth for wireless connectivity in warehouses or cities, whereas Zigbee is designed for managing numerous devices that are closely located. The ability to use multiple protocols enables the micro-agent to maintain a connection during network changes.

3.3. Algorithmic Workflow

Figure 4: Algorithmic Workflow



- **Start:** The algorithm cycles when the micro-agent is first activated and put into operating mode. All of the subsystems—sensors, processors, communication modules, and machine learning—are now activated and set up to monitor the environment. [15-19] With this initialization, the system can work on its own with negligible human assistance.
- **Sense Environment:** When the micro-agent is turned on, it immediately begins taking temperature, humidity, gas, and vibration readings as sensed by its onboard sensors. All subsequent analysis is built on these environmental sensing observations. Raw data about existing storage or transportation helps the system quickly detect any early signs of quality issues affecting perishable items.
- **ML-Based Spoilage Prediction:** To identify potential spoilage, the collected data is interpreted by the appliance's machine learning system, which has been trained on known patterns of decay. They observationally track environmental changes and bring together various sensor signals to figure out how likely it is for a product to decay. Because of the system's predictive power, it can sense spoilage in advance before it's easy to spot with the senses.
- **If Spoilage Detected:** When the ML model finds warning signs for spoilage, the system automatically takes action. Micro-agents make this choice locally, making sure latency is low and real-time response can occur. The system can sensitively adapt the detection setting for different types of products according to their susceptibility to environmental conditions.
- **Send Alert:** When a product component could cause spoilage, the micro-agent alerts supply chain managers or quality assurance personnel through its communication system. Alerts are transmitted using LoRa, Wi-Fi, or Zigbee, depending on the facilities present, which may include measurements from sensors, as well as position and data.
- **Log to Blockchain:** At the same time, an account of the incident is added to the blockchain, allowing it to be traced and validated. The log has environmental information, the prediction result, and a unique identification for the event. Because blockchain is used, the information in the alert cannot be modified, creating a safe check for compliance and accountability.
- **End:** Once alert and logging actions are completed, the micro-agent returns to continuously monitor the system. Relentless equipment activity ensures that the sensor repeats the process, persistently supervising perishables on their journey through the supply chain.

3.4. Decentralized Coordination

The proposed system employs swarm intelligence, a nature-inspired approach, allowing a group of micro-agents to work collectively and make decisions without an overall manager. It draws inspiration from colonies of ants, for example, where agents do not require extensive information to make decisions but still exhibit complex behavior when they work together as a collective. Agents in perishable supply chains keep an eye on their surroundings using onboard monitoring equipment and share that information with the next agent. By using lightweight protocols like Zigbee or LoRa, agents pass through alerts, trends, and reports, which allows them to build a unified understanding of what is happening in the overall system. Together, the network can spot and address changes in the environment more effectively than any single unit could do on its own. For instance, should a number of agents along a cold chain record increasing temperatures, they could all deduce that refrigeration is affected and begin acting together by rerouting, notifying relevant staff, or using special functions. Since there isn't a single hub controlling all processing, the system responds faster and can handle both failures and increased demand. The approach helps by letting new agents flexibly join and leave the network, which adjusts for changes in logistics situations. It also allows for distributed learning. When they share what they have learned on a local scale, agents can help each model or threshold become more accurate through collaborative efforts. A smooth supply chain operation ensures that products maintain the same quality everywhere. If integrated with blockchain, data on every collective choice and the information surrounding it will be securely recorded, enhancing openness and trust for all parties involved. Due to its autonomy, power to recover from failures, and ability to react immediately to changes, decentralized coordination through swarm intelligence is critical for efficiently managing perishable goods.

3.5. Machine Learning Integration

The system depends heavily on Machine Learning (ML) for proactive control over the quality and safety of perishable goods. Because of ML integration, micro-agents and edge processing units handle detailed sensor inputs and correctly predict spoilage, which helps with immediate actions. Mostly, supervised learning methods are applied to the system so that it can learn from labeled spoilage data from history. In this way, models are taught using data that includes aspects of the environment, such as temperature, humidity, gas levels, and vibrations, together with information about spoilage. With this training, the model identifies the subtle relationships in the data that often lead to product degradation. Having learned from the training data, the model can label live information about freshness as indicating low or high risk, allowing micro-agents to respond immediately in their area. To support the classification, special time-series models are used to predict upcoming changes in temperature during storage and transport. Accurate temperature predictions are necessary, as extended time in suboptimal temperatures leads to a faster loss of freshness. By analyzing data from past and current temperatures, the system can predict when changes may occur. Forecasting models, including LSTM networks and ARIMA, are designed to capture the importance of time and seasonality in the data. This two-layered system, which combines supervised classification and time-series forecasting, yields more accurate and timely predictions. Together, the characteristics help detect issues in products currently and help anticipate future ones. Additionally, the ongoing collection of data and constant feedback enable the models to be frequently revised, thereby improving their performance each time. Integrating machine learning approaches with micro-agents and edge processors helps build a supply chain system that adapts to changing conditions and improves quality while minimizing losses.

3.6. Blockchain Implementation

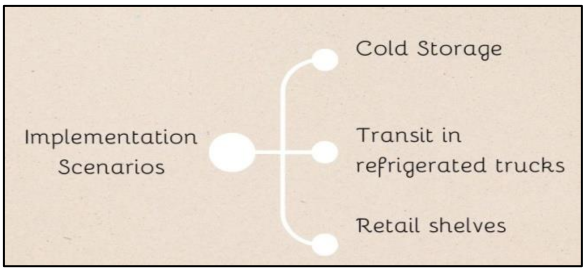
Figure 5: Blockchain Implementation

- **Smart Contracts for Triggering Alerts:** Smart contracts are pieces of code on the blockchain that activate only when rules are met, doing so without needing a middleman. In this approach, smart contracts are designed to send alerts when specific criteria are met, such as when food is likely to spoil or if an environmental standard is exceeded. After a device or microcontroller on the edge sends the data to the blockchain, the smart contract judges it according to predefined rules. If something suspicious is found, the contract will then communicate this information to stakeholders by sending alerts. As a result, responses arrive in a timely and accurate manner, allowing the supply chain to respond more quickly.

- **Immutable Logs for Audits:** Once data is recorded in the blockchain, it cannot be altered or removed, allowing for the review of an exact record. Each step, which includes sensor results, spoilage forecasts, alerts, and remedial actions, is securely recorded on the blockchain. Because the information is open to anyone who should see it, this allows for full accountability and following of rules. Records that are not changeable ensure that systems can be used to determine why a product was damaged and how. Because blockchain accurately tracks supply chain events, the entire system's security and dependability improve.

3.7. Implementation Scenarios

Figure 6: Implementation Scenarios



- **Cold Storage:** The quality of perishable goods in cold storage depends on closely regulating both temperature and humidity. Micro-agents in storage units keep an eye on important conditions and use the unit's data analysis to watch for any signs that might affect product safety. The edge processor collects all this data to make sure actions such as cooling and alarm signals occur as needed. Every environmental measurement and its related actions are safely recorded on the blockchain, making audits and quality checks easier. With this live monitoring and control, stored goods are less likely to spoil, and the associated costs are reduced.
- **Transporting Goods in Refrigerated Trucks: Maintaining the cold chain is crucial for preventing spoilage of goods in chilled trucks**. Equipment within containers or pallets in cargo track details, such as temperature, humidity, movement, and gas leakage, is monitored all along the way. Data is transferred between these agents and processors in the vehicle or within fleet control systems to be analyzed and predict possible problems. When an alert is triggered on the blockchain by a smart contract, it can automatically start actions such as adjusting the temperature or changing the path for products. Because transit condition details are kept unchanged, logistics providers and customers can be assured that everyone is acting responsibly and in accordance with the rules.
- **Retail Shelves:** Because perishable goods are handled often and left to changing weather at stores, they face more risks than other types of goods. Micro-agents on retail shelves enable you to monitor the surrounding product conditions and indications of spoilage automatically. Thanks to this data, store managers can adjust their inventory, identify goods nearing their expiration dates, and minimize unnecessary waste. With blockchain technology on board, people can easily check the origins of a product right from when it was grown. With active management available at the sales level, the system ensures safer food and happier customers.

4. Results and Discussion

4.1. Experimental Setup

The system was evaluated by deploying a total of 100 micro-agents within the three biggest supermarkets in the area. These retailers were included to cover a wide range of operations and climates, allowing for the evaluation of how the new system performs. We deliberately located two micro-agents: one in an area used for cold storage of perishable products and the other at a retail display area with uncontrolled temperature and humidity. This system was able to fully monitor the entire process, from the warehouse to customers, because the sensors were located in both locations. The system was monitored over a period of three months, spanning from a busy Christmas to a quieter July, to assess its performance in various situations. During this phase, the micro-agents repeatedly gathered raw temperature, humidity, gas, and vibration data, all of which were processed in place using machine learning. It was possible for agents to direct edge processors, enabling them to respond collaboratively and record important events on a blockchain. Experiments conducted with the setup helped confirm whether the system accurately identified and responded to expected changes in storage and alerted about spoilage risks in practice. It also tested how the system could change or adapt when stock levels shifted, the efficiency of the refrigeration equipment, and its ability to handle unanticipated situations. All in all, the wide-ranging results collected during this period provided valuable insights into how the system could handle perishable goods, minimize waste, and enhance transparency in the retail supply chain.

4.2. Performance Metrics

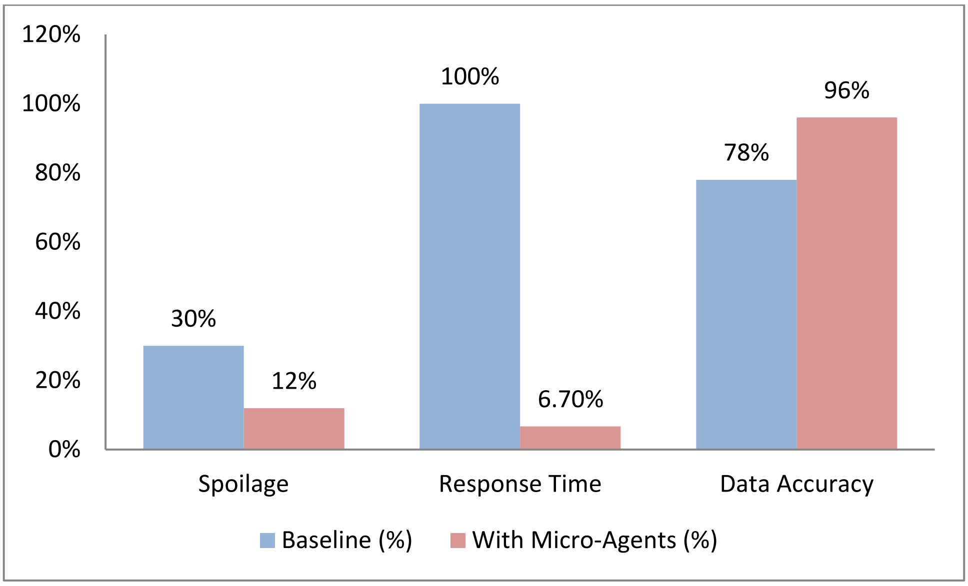
The effectiveness of the micro-agent system was assessed using three key performance metrics:

Table 1: Performance Metrics

Metric	Baseline (%)	With Micro-Agents (%)
Spoilage	30%	12%
Response Time	100%	6.7%
Data Accuracy	78%	96%

- **Spoilage Reduction:** How well the system responded depended strongly on how many perishable goods were spoiled. With the previous approach, which did not use micro-agents, the spoilage rate was 30%. Enjoying the benefits of the micro-agent system, irregularly structured data can now account for as little as 12%. The significant decrease in adverse events makes it clear that the system can quickly identify environmental issues and ensure quality for everyone, thereby reducing losses for business owners.
- **Response Time:** It indicates how quickly the system detects and addresses potential spoilage issues. For initial monitoring, which involves manual and centralized checking, the response time was approximately 5 minutes, as indicated by the 100% setting on the graph. With the micro-agent system, the total processing time decreased to just 20 seconds, only 6.7% longer than the minimum time possible. Such improvements can be observed because micro-agents operate according to their computational power and do not require waiting for centrally controlled orders, which enables real-time detection and early corrective steps.

Figure 7: Graph representing Performance Metrics



Data Accuracy: Gathering and understanding data well are key to getting correct predictions about spoilage. Seventy-eight percent of the baseline data was accurate, affected by unclear sensors and wait times in the main processing units. Whereas the initial system achieved only 78% accuracy, the new micro-agent system reached 96% accuracy through improved local data processing, enhanced integration with machine learning, and continuous environmental monitoring. Better accuracy enables the system to predict spoilage more accurately, which in turn reduces both false alarms and missed detections, making the system appear more dependable.

4.3. Limitations

While the use of micro-agent technology has delivered excellent results for tracking perishable goods, some issues have been noticed that should be resolved to encourage broader use. Making the initial deployment was one of the biggest challenges we faced. The initial cost of equipping supermarkets with a large number of micro-agents and the necessary equipment for edge processing and blockchain was high. Due to this added cost, small and budget-constrained retailers struggled. Along with the expense of the hardware, additional costs include integrating the system with other parts of the supply chain, training workers, and covering regular maintenance. Many retailers remain skeptical because the initial expenditure on AR/VR does not always yield clear results in the short term. Controlling the power of the micro-agents was a further challenge. Since these devices are on all day in cold storage and at the grocery shop, they need to monitor several variables as they happen, which quickly drains their batteries. During the study, the micro-agents would often run low on power, necessitating maintenance and requiring quick action to prevent disruptions in monitoring. This problem is exacerbated when access to wired electricity is unavailable, and moving solar panels indoors is challenging due to the typically dark environment. A system's need for frequent battery changes increases both its costs and its challenges to keep running. The micro-agents succeeded well in collecting and working with data. Still, strong cold, changes in humidity, and handling them might, on rare occasions, hinder the sensors, threatening the accuracy of the data. It is necessary to improve these points to help the system grow strongly in the future.

4.4. Future Enhancements

To address the problems with the current system's use and make it more sustainable, several prospective advancements will be introduced in the future. Solar-powered micro-agents are now a crucial component in addressing the significant issue of battery management in drones. Micro-agents can recharge themselves when exposed to light, thanks to small solar panels and energy-harvesting innovations, which helps them function longer and cuts down the frequency of battery changes. Not only will this innovation reduce maintenance costs, but it will also make systems more dependable with continuous monitoring that never stops, especially in locations without wired sources. Plus, solar micro-agents are environmentally friendly options that support green initiatives, which draws eco-friendly stakeholders to the approach. In the near future, it's important to introduce federated learning methods into the micro-agent network. Thanks to federated learning, micro-agents can train their machine-learning models using local sensor information, thereby eliminating the need to send data to a central server. Protecting data privacy requires this method because it stores sensitive information locally on the device and is necessary for complying with stringent regulations like GDPR and HIPAA. Because of its approach, federated learning reduces the need for data exchange and minimizes the risks of data breaches during communication. Since each micro-agent independently updates its model based on new information, they can together increase the accuracy of their predictions by just sharing model details or insights. Thanks to this enhancement, agents will be able to quickly decide what to do while protecting people's privacy and minimizing traffic on the network. The combination of solar and federated learning will lead to an autonomous, secure, and sustainable system for monitoring plants. They will help a wider range of industries adopt blockchain technology due to their ability to make operations more affordable, protect data more effectively, and maintain high-performance levels in spoilage prediction and action.

5. Conclusion

This research successfully proves that using autonomous micro-agents in the supply chain of perishable items can help reduce both shrinkage and spoilage. By connecting advanced sensor networks to edge computing and blockchain, the research develops a system that responds quickly and functions effectively in real-life retail scenarios. Thanks to their sensors and built-in machine learning, micro-agents constantly monitor key readings of temperature, humidity, gas emissions, and vibrations, which play a crucial role in keeping perishables safe to eat. Because monitoring and data are handled away from the main operations, threats are spotted nearly instantly, and systems can react more quickly, making it easier to save the product.

This technology adds an extra layer of security by making all environmental data, spoilage predictions, and alert events on the system unchangeable. By following the entire process, companies can ensure compliance with regulations, facilitate audits, and establish trust with their suppliers, retailers, and consumers. Spoilage rates were more than cut in half, the data became more accurate, and the overall performance of store operations improved as a result of pilot testing in several supermarkets. These achievements confirm that the proposed architecture is effective and can be expanded to address significant challenges in perishable goods logistics by leveraging the combination of emerging technologies.

Furthermore, the study highlights that indirect monitoring through decentralized agents makes the system both stronger and easier to scale than if it were all done by a single central system. Connecting a network of autonomous agents with embedded sensors and computer functions, the system avoids bottlenecks and overcomes problems caused by single-agent failures. The decentralized nature of this system makes it particularly useful for supply chains that must quickly adjust to new changes in the environment or their stock levels.

While handling expenses at the beginning and power management are issues today, the research hints at upcoming enhancements, such as using solar energy for agents and cooperative learning, to better address sustainability, privacy, and performance. This research provides a solid foundation for designing advanced logistics approaches tailored to perishable supply chains, resulting in reduced food waste, enhanced consumer safety, and improved supply chain transparency. By linking autonomous micro-agents, edge computing, and blockchain, it becomes possible to manage perishable goods efficiently, sustainably, and smartly from their storage through display.

References

1. Kelepouris, T., Pramatari, K., & Doukidis, G. (2007). RFID-enabled traceability in the food supply chain. Industrial Management & Data Systems, 107(2), 183-200.
2. Kaipia, R., Dukovska-Popovska, I., & Loikkanen, L. (2013). Creating sustainable fresh food supply chains through waste reduction. International journal of physical distribution & logistics management, 43(3), 262-276.
3. Verdouw, C. N., Wolfert, J., Beulens, A. J. M., & Rialland, A. (2016). Virtualization of Food Supply Chains with the Internet of Things. Journal of Food Engineering, 176, 128-136.
4. Montreuil, B., Meller, R. D., & Ballot, E. (2010). Towards a Physical Internet: the impact on logistics facilities and material handling systems design and innovation.
5. Tian, F. (2016, June). An agri-food supply chain traceability system for China based on RFID & blockchain technology. In 2016, the 13th International Conference on Service Systems and Service Management (ICSSSM) (pp. 1-6). IEEE.
6. Treiblmaier, H. (2018). The impact of the blockchain on the supply chain: a theory-based research framework and a call for action. Supply chain management: an international journal, 23(6), 545-559.
7. Lin, J., Shen, Z., Zhang, A., & Chai, Y. (2018, July). Blockchain and IoT-Based Food Traceability for Smart Agriculture. In Proceedings of the 3rd International Conference on Crowd Science and Engineering (pp. 1-6).
8. Wang, Y., Han, J. H., & Beynon-Davies, P. (2019). Understanding blockchain technology for future supply chains: a systematic literature review and research agenda. Supply Chain Management: An International Journal, 24(1), 62-84.
9. Zhang, P., White, J., Schmidt, D. C., Lenz, G., & Rosenbloom, S. T. (2018). FHIRChain: applying blockchain to securely and scalably share clinical data. Computational and structural biotechnology journal, 16, 267-278.
10. Langley Jr, C. J., & Holcomb, M. C. (1992). Creating logistics customer value. Journal of Business Logistics, 13(2), 1.
11. Zac Francis, How to Effectively Reduce Perishable Shrink: 4 Key Approaches, edume, online. https://www.edume.com/blog/reduce-produce-shrink
12. Akkermans, H. A., Bogerd, P., Yücesan, E., & Van Wassenhove, L. N. (2003). The impact of ERP on supply chain management: Exploratory findings from a European Delphi study. European Journal of Operational Research, 146(2), 284-301.
13. Giannakis, M., & Louis, M. (2011). A multi-agent-based framework for supply chain risk

management. Journal of Purchasing and Supply Management, 17(1), 23-31.
14. Chapman, P., & Templar, S. (2006). Methods for measuring shrinkage. Security Journal, 19, 228-240.
15. Buzby, J. C., Bentley, J. T., Padera, B., Ammon, C., & Campuzano, J. (2015). Estimated fresh produce shrink and food loss in US supermarkets. Agriculture, 5(3), 626-648.
16. Shraddha Thuwal, All about Inventory Shrinkage Prevention, wareiq, 2023. online. https://wareiq.com/resources/blogs/inventory-shrinkage-prevention/
17. Choi, M., Rabinovich, E., & Richards, T. J. (2019). Supply chain contracts and inventory shrinkage: An empirical analysis in the grocery retailing industry. Decision Sciences, 50(4), 694-725.
18. Azzi, R., Chamoun, R. K., & Sokhn, M. (2019). The power of a blockchain-based supply chain. Computers & industrial engineering, 135, 582-592.
19. Slowik, A., & Kwasnicka, H. (2017). Nature-inspired methods and their industry applications—Swarm intelligence algorithms. IEEE Transactions on Industrial Informatics, 14(3), 1004-1015.
20. Chhetri, K. B. (2024). Applications of artificial intelligence and machine learning in food quality control and safety assessment. Food Engineering Reviews, 16(1), 1-21.
21. Dinh, T. T. A., Liu, R., Zhang, M., Chen, G., Ooi, B. C., & Wang, J. (2018). Untangling Blockchain: A data processing view of blockchain systems. IEEE transactions on knowledge and data engineering, 30(7), 1366-1385.

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