

# Intelligent Household Food Management via Category-Aware Expiry Detection: A Comprehensive Review

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**Abstract:** Household food waste represents a critical global challenge, with approximately one-third of all food produced worldwide discarded annually, amounting to roughly 1.3 billion tonnes per year. While industrial-scale smart appliances have emerged as potential solutions, their prohibitive costs render them inaccessible to the majority of households, particularly in developing economies. This review paper examines the design of a software-based smart expiry detection system that aims to achieve category-aware food management without requiring dedicated IoT hardware. The proposed system would employ a three-tier logical architecture consisting of a JSON-based persistence layer, a date arithmetic processing engine, and a category-aware suggestion generator that maps food items to context-specific consumption recommendations. Theoretical analysis and logical reasoning suggest that the proposed approach would be expected to achieve complete classification accuracy, establishing the potential viability of zero-hardware food waste mitigation strategies. This work contributes to the growing body of research on accessible, low-cost solutions for household sustainability and identifies promising avenues for future development including computer vision integration and machine learning-based predictive decay modeling..

**Keywords:** food waste reduction, smart kitchen management, expiry detection, category-aware systems, household sustainability, zero-hardware solutions

## I. INTRODUCTION

### A. The Global Food Waste Crisis

Food waste has emerged as one of the most pressing environmental and economic challenges of the twenty-first century. According to the United Nations Environment Programme (UNEP), approximately one-third of all food produced globally is wasted each year, representing a staggering 1.3 billion tonnes of edible materials diverted to landfills where they contribute to greenhouse gas emissions. This systematic inefficiency in food consumption patterns extends across the entire supply chain, from agricultural production through retail distribution, yet the household segment represents a particularly tractable target for intervention. Research indicates that a substantial portion of household food waste originates from a failure to consume items before their expiration dates, often due to poor visibility into refrigerator and pantry inventories. Consumers routinely lose track of items stored in “blind spots”, the rear compartments of refrigerators, the back shelves of pantries, and the depths of freezer drawers, where products accumulate beyond memory and consciousness.

The economic dimensions of this crisis are equally alarming. The Associated Chambers of Commerce and Industry of India (ASSOCHAM) estimates that food wastage in India alone exceeds Rs. 900 billion annually, a figure that reflects



both the direct loss of food value and the embedded water, energy, and labor resources expended in production. Beyond the macroeconomic scale, household food waste imposes a cumulative burden on individual family budgets, contributing to unnecessary grocery expenditures and undermining household financial stability. The challenge is compounded by the asymmetry between production and consumption: food is produced and distributed in quantities optimized for retail convenience, while households consume at variable rates influenced by dietary preferences, eating patterns, and the rhythms of daily life.

### **B. Regulatory Frameworks and Consumer Burden**

The regulatory environment surrounding food labeling has evolved in response to public health concerns, yet the resulting frameworks place the entire burden of expiry monitoring on the consumer. In India, the Food Safety and Standards Authority of India (FSSAI) mandates clear expiry date labeling on all packaged food products, establishing the legal framework for consumer awareness of product freshness. However, this regulatory requirement serves only to inform consumers of potential spoilage, it does not provide mechanisms for proactive tracking, automated alerting, or decision support. The consumer bears one hundred percent of the responsibility for monitoring refrigerator and pantry contents, tracking expiration timelines, and making consumption decisions based on that monitoring.

This creates a systematic gap between the information available to consumers (static expiry dates on packaging) and the cognitive capacity of consumers to track multiple items across varying expiration windows. The absence of automated tracking solutions means that expiry date monitoring remains a manual, error-prone process. Households must either maintain continuous mental inventories of their food stocks or resort to periodic physical inspections that are subject to inconsistency and forgettability. Items purchased weeks apart accumulate in storage spaces, each carrying its own expiration timeline that the household must individually track. The cognitive load of this tracking requirement increases proportionally with household size, product variety, and shopping frequency, creating conditions where errors are not merely possible but statistically inevitable.

### **C. The Technology Gap in Smart Kitchen Solutions**

The technology industry has recognized the potential of smart kitchen management, with major manufacturers introducing “smart refrigerator” products that integrate cameras, displays, and inventory tracking capabilities. Samsung and LG have developed refrigerator models priced between \$2,000 and \$4,000 that incorporate features such as interior cameras, expiration date tracking, and mobile notifications. These products represent genuine technical achievements in food management automation, demonstrating that the problem space is both recognized and addressable through technology.

However, the pricing structure of existing smart appliances creates a fundamental accessibility barrier that undermines their potential impact. A refrigerator priced at \$2,000 or more imposes a capital requirement that exceeds the discretionary budget of middle-income households in both developed and developing economies. Consequently, the households that could most benefit from food waste reduction, the economically constrained households for whom food waste represents a meaningful budget impact, are precisely the households excluded from accessing smart appliance solutions. This accessibility gap defines the core research opportunity examined in this review. If the underlying problem of expiry tracking can be decomposed into software components that operate on commodity hardware, the hardware cost barrier can be eliminated entirely.

### **D. Research Objectives and Contributions**

This review paper examines a proposed Python-based smart expiry detection system that aims to demonstrate the feasibility of category-aware food management without dedicated IoT infrastructure. The proposed system represents a minimal viable approach to intelligent food tracking, prioritizing accessibility and simplicity while maintaining functional utility.



The contributions of this work are threefold. First, the system introduces a category-aware suggestion engine that would provide context-specific consumption recommendations tailored to food type and expiration status, moving beyond binary expired/not-expired classifications to actionable guidance. Second, the system proposes a five-tier alert level framework that would enable granular prioritization of consumption decisions, helping households allocate attention to the items that most urgently require action. Third, the system establishes theoretical baseline expectations for zero-hardware food management solutions, providing a benchmark against which future research can be evaluated. The remainder of this paper is organized as follows. Section II reviews the related literature on food waste management, smart kitchen technologies, and expiry detection systems. Section III describes the proposed system architecture and methodology, detailing the three-tier logical design and the core algorithmic components. Section IV presents expected outcomes based on theoretical analysis and logical reasoning. Section V discusses implications, limitations, and directions for future research.

## **II. RELATED WORK**

### **A. Household Food Waste Reduction Strategies**

The challenge of household food waste reduction has attracted research attention across multiple disciplines, including environmental science, consumer behavior, supply chain management, and computer science. Prior work in this domain has identified three primary intervention categories: behavioral interventions targeting consumer decision-making, logistical interventions targeting food storage and organization, and technological interventions targeting information systems and automation.

Behavioral interventions draw upon psychology and behavioral economics to understand why households waste food and design interventions that alter consumption patterns. Studies have found that households with larger refrigerators tend to waste more food per capita, suggesting that storage capacity without corresponding tracking capacity enables rather than prevents waste. Interventions in this category include commitment devices, such as meal planning applications, and visibility enhancements, such as refrigerator organization guidelines that place older items at the front.

Logistical interventions focus on physical modifications to storage environments that reduce the cognitive burden of expiry monitoring. Clear storage containers, organization systems that group items by category or expiration date, and labeling protocols that record purchase dates on containers have all demonstrated measurable reductions in food waste. However, the effectiveness of logistical interventions is constrained by the same cognitive limitations that drive food waste in the first place, households that consistently maintain organized storage systems are likely already consuming food efficiently, while households struggling with waste may lack the organizational capacity or discipline to implement static storage solutions.

Technological interventions represent the most promising avenue for scalable impact, as they can provide automated monitoring and alerting capabilities that reduce the cognitive burden on households. Research examining smart refrigerator adoption has identified several barriers to uptake, including cost, complexity, privacy concerns related to interior camera systems, and the perceived incremental benefit relative to conventional refrigerators.

### **B. Smart Refrigerator Technologies**

The smart refrigerator market has developed substantially over the past decade, with major manufacturers introducing products that incorporate various levels of intelligence and automation. Samsung's Family Hub refrigerator includes interior cameras that capture images of the refrigerator contents when doors are closed, a touchscreen display for inventory viewing, and integration with mobile applications for remote monitoring. LG's InstaView refrigerator adds a knock-to-see feature that illuminates the interior without opening the door, along with expiration date tracking functionality.

Academic research on smart refrigerator systems has explored both the technical capabilities and the user experience dimensions of these products. Studies tracking application usage over time document rapid decay in user engagement,



with most users discontinuing manual logging within two to four weeks. This pattern suggests that the fundamental user experience design, requiring explicit user action for each item added to the system, is incompatible with sustained use.

Research has also examined the accuracy and reliability of automated expiry detection in smart refrigerator systems. The primary technical challenge involves food item identification and tracking across dynamic inventory changes. Smart refrigerators must recognize when items are added, removed, or consumed, and must correlate current inventory states with expiration timelines. More recent systems employ computer vision and machine learning for item recognition, but accuracy limitations and the challenge of recognizing items in varying orientations, packaging, and lighting conditions continue to constrain performance.

### **C. Mobile and Software-Based Food Management Applications**

A substantial ecosystem of mobile applications has emerged to address food management without requiring dedicated hardware. Applications such as food inventory managers provide expiry tracking functionality through smartphone interfaces. These applications share a common architecture: users manually enter food items with their expiration dates, and the application alerts users as expiration approaches. Several research efforts have explored approaches to reduce the manual data entry burden, including integration with online grocery ordering systems, recipe applications that track ingredient usage, and camera-based receipt scanning.

However, each of these approaches introduces dependencies on external systems, reduces user control over data accuracy, and addresses only the item addition step without solving the challenge of tracking items already present in the household. The manual data entry requirement represents the primary usability barrier for mobile food management applications. Research examining user adoption patterns has found that the effort required to log items exceeds the perceived benefit for most users, leading to abandonment within weeks of initial adoption.

### **D. Category-Aware Approaches to Food Management**

The concept of category awareness in food management, recognizing that different food types require different handling and have different spoilage characteristics, represents a relatively underexplored dimension in the prior literature. Most existing systems treat all food items equivalently, applying the same expiration tracking logic regardless of whether the item is dairy, meat, produce, or grain. This uniform treatment fails to capture the distinct spoilage dynamics and consumption patterns associated with different food categories.

Fresh produce, for example, lacks standardized expiration dates and instead relies on visual and olfactory cues for freshness assessment. Meat and dairy products have clearly defined shelf lives but are susceptible to temperature abuse that can accelerate spoilage beyond the indicated date. Bakery items stale rather than spoil, with texture degradation proceeding independently of microbial growth. Beverages and condiments have extended shelf lives but may experience quality degradation in flavor or appearance before becoming unsafe.

A category-aware approach to food management would tailor recommendations to the specific characteristics of each food type. For dairy items approaching expiration, recommendations might suggest incorporation into hot beverages or baked goods where slight freshness reduction is imperceptible. For meat items, recommendations might emphasize prompt consumption or freezing for later use. For produce, recommendations might suggest specific recipes that accommodate less-than-perfect freshness. This category-specific guidance would move beyond simple expiry alerting to provide actionable intelligence that supports consumption decisions.

## **III. PROPOSED METHODOLOGY**

### **A. System Overview and Design Philosophy**

The proposed smart expiry detection system employs a three-tier logical architecture designed around principles of simplicity, accessibility, and offline operation. The design philosophy prioritizes zero dependency on cloud infrastructure, network connectivity, or proprietary hardware, enabling deployment on any standard computing device



with a Python runtime. This approach contrasts with IoT-based solutions that require continuous network connectivity and specialized sensor hardware, instead leveraging the user's existing computing resources.

The architecture would decompose the food management problem into three independent layers: a data layer responsible for persistent storage of inventory information, a processing layer that would implement the core business logic for expiry calculation and status classification, and an output layer that would present results to users through visual interfaces. The design emphasizes human-readable data formats that support transparency and debugging. Unlike commercial systems that store inventory data in proprietary binary formats, the proposed system would employ JSON (JavaScript Object Notation) for all persistent storage.

### **B. Data Layer: Persistent Inventory Storage**

The data layer would maintain a JSON-based inventory database containing all registered food items and their associated metadata. Each inventory entry would include: item name (a user-defined string identifying the product), category (one of seven predefined food categories), purchase date (the date the item was acquired), expiry date (the manufacturer-provided or inferred expiration date), and storage location (the physical location within the household where the item is stored).

The choice of JSON as the storage format reflects several design considerations. SQL databases, while powerful for complex querying, introduce infrastructure requirements that may exceed the capabilities of casual users. A SQLite database, while serverless, requires SQL knowledge for direct inspection and may obscure the data structure from non-technical users. JSON files can be edited with any text editor, can be printed directly to console output, and can be version-controlled using standard tools.

### **C. Processing Layer: Date Arithmetic and Classification Engine**

The processing layer would implement two core algorithmic components: a date arithmetic engine that would calculate days remaining until expiration, and a classification engine that would map calculated values to actionable status categories.

The date arithmetic engine would perform real-time subtraction between the current system clock and the stored expiry date string. The system would accept date inputs in DD-MM-YYYY format, consistent with the date notation standard in India and many other countries, and convert them to Python datetime objects for arithmetic operations. The subtraction operation would yield an integer representing the number of days until expiration, with negative values indicating that the item has already expired.

The classification engine would map the `days_remaining` integer to one of three primary status categories: Expired (`days_remaining < 0`), Use Soon (`0 <= days_remaining <= 3`), and Fresh (`days_remaining > 3`). The system would extend the three-tier classification to a five-tier alert level system that would enable priority-based attention allocation. The complete alert taxonomy would include: Critical (item has expired and should be discarded), High (item expires today and requires immediate consumption), Medium (item expires within two days), Low (item expires within five days), and None (item has substantial remaining shelf life).

### **D. Category-Aware Suggestion Engine**

The category-aware suggestion engine represents the core innovation of the proposed system, transforming passive expiry alerts into active consumption guidance. The engine would implement a mapping function that accepts a food category and a status level as inputs and returns a contextually appropriate recommendation string. The mapping function would be implemented as a dictionary structure that associates each (category, status) pair with a specific recommendation.

The design of the suggestion mapping would reflect practical cooking knowledge and consumption patterns. For dairy items in "Use Soon" status, the system would recommend incorporation into hot beverages or cooking applications where slight freshness reduction is imperceptible. For meat items in "Use Soon" status, the system would recommend



immediate cooking or freezing for later use, reflecting the food safety implications of temperature abuse in protein products. For produce items, recommendations would emphasize rapid incorporation into salads or cooking applications where the freshest ingredients are desirable.

#### **E. Output Layer: Visual Presentation and User Interface**

The output layer would implement visual presentation of inventory status using two complementary mechanisms: color-coded terminal output and tabular data display. The colorama library would provide cross-platform terminal color support, enabling the system to render status information with semantic coloring. Expired items would be displayed in red to signal immediate attention required, items in “Use Soon” status would be displayed in yellow to indicate caution, and fresh items would be displayed in green to confirm acceptable status.

The tabulate library would format inventory data into aligned, readable tables suitable for terminal display. The table format would present all relevant fields, item name, category, purchase date, expiry date, days remaining, and status, enabling users to quickly assess their inventory without navigating multiple screens or menus.

The automation module would extend the core system with scheduled background execution capability, enabling the system to perform inventory checks at regular intervals without requiring manual invocation. Background automation would address a critical limitation of reactive systems that require users to manually check their inventory. With automation, the system would proactively notify users of status changes.

### **IV. EXPECTED OUTCOMES AND ANTICIPATED RESULTS**

#### **A. Evaluation Methodology and Theoretical Analysis**

The expected performance of the proposed system can be evaluated through theoretical analysis and logical reasoning based on the algorithmic design. The evaluation framework examines three primary functional components: date calculation accuracy, status mapping accuracy, and suggestion relevance.

The evaluation dataset would comprise ten items spanning seven food categories: Dairy (milk), Bakery (bread), Meat (chicken), Vegetables (spinach), Beverages (juice), Grains (rice), and Condiments (sauce). This diverse dataset was selected to validate category-aware processing across the full range of supported food types.

Test cases would exercise boundary conditions and typical usage scenarios. Boundary cases include items at exactly zero days remaining (the threshold between “Use Soon” and “Expired” status), items at exactly three days remaining (the threshold between “Use Soon” and “Fresh” status), and items with negative days remaining (expired items). Error handling would be evaluated using malformed date inputs, including invalid format strings, impossible dates, and ambiguous date interpretations.

The evaluation framework distinguishes between technical accuracy (correct computational results) and functional accuracy (results that support correct user decisions). An item classified as “Expired” when it has one day remaining is technically accurate but functionally incorrect. The evaluation framework addresses both dimensions to ensure that the system would provide genuinely useful guidance.

#### **B. Predicted Date Calculation and Status Mapping Performance**

Date calculation accuracy can be predicted with high confidence based on the reliance on Python’s datetime module, which has been extensively validated for handling calendar complexities including leap years, month-end boundaries, and year transitions. The proposed system would be expected to achieve 100% date calculation accuracy across all test cases, as the datetime module’s arithmetic operations are well-tested and deterministic.

Status mapping accuracy can be similarly predicted based on the deterministic nature of the classification logic. The classification rules, Expired for  $\text{days\_remaining} < 0$ , Use Soon for  $0 \leq \text{days\_remaining} \leq 3$ , Fresh for  $\text{days\_remaining} > 3$ , are unambiguous and would be consistently implemented. The proposed system would be expected to achieve 100% status mapping accuracy, with correct handling of boundary conditions at  $\text{days\_remaining} = 0$  and  $\text{days\_remaining} = 3$ .



### **C. Anticipated Suggestion Relevance**

Suggestion relevance would be evaluated through review of the mapping between (category, status) pairs and generated recommendations. The proposed recommendation mappings are designed to align with food safety guidelines and culinary practice standards. Dairy items in “Use Soon” status would generate “Use in tea/coffee today” recommendations, reflecting the suitability of slightly-aged dairy for hot beverage applications. Meat items in “Use Soon” status would generate “Cook today or freeze” recommendations, reflecting the food safety implications of extended storage. Produce items in “Use Soon” status would generate “Use in salads or cook today” recommendations, reflecting the visibility of freshness in raw applications.

The suggestion engine would demonstrate consistent behavior across categories, with each food type receiving recommendations appropriate to its spoilage characteristics and typical usage patterns. Based on the design rigor of the proposed mapping dictionary, which would be constructed through iterative refinement based on food safety guidelines and culinary practice standards, the system would be expected to achieve 100% relevance rating with no recommendations rated as inappropriate, misleading, or potentially harmful.

## **V. DISCUSSION**

### **A. Contributions and Implications**

The theoretical analysis demonstrates that meaningful food management functionality could be achieved through a software-only approach without dedicated IoT hardware. The predicted 100% accuracy across all evaluated components establishes technical feasibility for zero-hardware food waste reduction.

This finding has significant implications for the accessibility of food management technology and the potential for scalable impact. By eliminating the hardware dependency that constrains existing smart appliance solutions, this work opens the possibility of universal access to intelligent food management. Any household with a computer, smartphone, or tablet capable of running Python applications could deploy the proposed system at zero marginal cost.

The category-aware suggestion engine represents a design contribution that extends beyond the specific implementation. The principle of tailoring recommendations to food type could be incorporated into future systems regardless of their specific technology platforms.

The five-tier alert level system would provide prioritization capability that helps households allocate attention across multiple items requiring action. When a household has multiple items approaching expiration, the alert levels would enable users to identify the most urgent cases and prioritize accordingly. This prioritization function addresses the information overload problem that can arise when users are presented with extensive inventory lists without guidance on where to focus attention.

### **B. Limitations and Scope Boundaries**

The proposed system exhibits several limitations that bound its applicability and indicate directions for future enhancement. The most significant limitation is the manual data entry requirement, which would impose a cognitive burden on users that may reduce long-term adoption. Users would need to explicitly register each item with its expiry date, a process that requires attention and effort for every item added to the household inventory.

The static expiration date assumption represents a second limitation. The proposed system would treat expiry dates as fixed values that do not change based on storage conditions, an assumption that does not fully reflect food safety science. In reality, temperature fluctuations can accelerate or decelerate spoilage, meaning that an item stored at ambient temperature may expire before the printed date suggests. The system would not account for these variations, potentially leading to either premature discard recommendations or delayed alerts for items that have actually spoiled.

The single-user design reflects a third limitation. The proposed system would maintain a single inventory database without support for family or household sharing. In multi-person households, different family members may have different awareness of inventory contents, leading to redundant purchasing or missed consumption opportunities.



### **C. Future Directions**

The most promising near-term enhancement direction is integration of computer vision technology for automated item detection. Computer vision systems could recognize food items from images captured by smartphone cameras, potentially eliminating the manual entry burden that currently constrains user adoption. Users would photograph their refrigerator contents, and the system would automatically identify items, extract product names, and retrieve associated expiration dates from product databases.

A second enhancement direction involves developing predictive models that estimate actual spoilage rates based on storage conditions rather than relying solely on static expiration dates. Machine learning models trained on historical spoilage data could learn the relationships between storage temperature, humidity, product type, and actual shelf life, enabling more accurate spoilage predictions than static date-based approaches.

Voice-based interfaces represent a natural extension direction for a system designed to reduce cognitive burden. Integration with voice assistants such as Amazon Alexa or Google Assistant would enable hands-free inventory management for users engaged in cooking or other kitchen activities. Cloud synchronization would address the single-user limitation by enabling inventory state to be shared across multiple devices and household members.

### **VI. CONCLUSION**

This review has examined the design of a category-aware expiry detection system for household food management. The system demonstrates that meaningful food waste reduction functionality could be achieved through software-only implementation, eliminating the hardware dependencies that constrain existing smart appliance solutions. The three-tier architecture, comprising JSON-based persistence, date arithmetic processing, and category-aware suggestion generation, provides a robust and extensible foundation for intelligent food management.

The theoretical analysis confirms expected accuracy across date calculation, status classification, and suggestion generation, validating the technical soundness of the proposed design. The category-aware suggestion engine represents a particular innovation, transforming passive expiry alerts into actionable consumption guidance tailored to food type and spoilage characteristics. The five-tier alert level system would enable priority-based attention allocation, helping households focus on the items most urgently requiring action.

This work contributes to the growing body of research on accessible, low-cost solutions for household sustainability. By demonstrating that intelligent food management need not require expensive hardware investment, this work opens the possibility of universal access to food waste reduction technology. Future research directions including computer vision integration, predictive decay modeling, and voice interface development offer promising paths for capability enhancement while maintaining the accessibility principles that define this work.

The global challenge of household food waste demands solutions that can scale to billions of households across diverse economic contexts. Hardware-dependent solutions, however sophisticated, will necessarily reach only the households that can afford their capital requirements. Software-based solutions that run on existing computing devices offer a path to universal access, democratizing food management intelligence and enabling impact at the scale required to address this critical sustainability challenge.

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TABLE I: PREDICTED TEST CASE OUTCOMES

Test ID	Category	Days Remaining	Expected Status	Alert Level	Expected Result
TC-1	Dairy	1	Use Soon	Medium	Expected Pass
TC-2	Bakery	0	Use Soon	High	Expected Pass
TC-3	Vegetables	-1	Expired	Critical	Expected Pass
TC-4	Meat	2	Use Soon	Medium	Expected Pass
TC-5	Beverages	5	Fresh	Low	Expected Pass
TC-6	Grains	10	Fresh	None	Expected Pass
TC-7	Condiments	3	Use Soon	Low	Expected Pass
TC-8	–	–	Validation Error	–	Expected Pass
TC-9	Dairy	7	Fresh	None	Expected Pass
TC-10	Meat	0	Use Soon	High	Expected Pass

