The Role of the Internet of Things (IoT) in the Global Food Industry and Strategic Frameworks for Food Waste Mitigation in India

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Abstract

The global food system faces a critical inconsistency – while agricultural production is sufficient to feed the world's population, inefficiency in supply chains leads to massive food insecurity. Current estimates suggest that one-third of all food produced is lost or wasted annually. This report investigates how the Internet of Things (IoT) serve as a technological solution to this crisis by creating transparent, data-driven supply chains. While the first part of the report looks at a global context for IoT applications, the core analysis focuses on India. Despite being a leading global food producer, India suffers from post-harvest losses estimated at INR 1.53 lakh crore annually. This research identifies structural barriers such as land fragmentation and energy deficit, and proposes a strategic framework based on prudent innovations and digital public integration via the AgriStack. Furthermore, the report substantiates these strategies through case studies of Indian enterprises, demonstrating how shared infrastructure models like Cold-Chain-as-a-Service (CCaaS) and “SmartFarm” platforms are successfully mitigating losses in agriculture sectors.

Key Words: Internet of Things (IoT), Food Supply Chain, Cold Chain Management, Food Waste Mitigation, Precision Agriculture, Post-Harvest Loss, Cold-Chain-as-a-Service (CCaaS), Digital Twin, AgTech, AgriStack, Indian Agriculture, Sustainable Development.

1. Introduction: Global Food Waste and the Smart Tech Solution

While agricultural production of the global food system is sufficient to feed the world's projected population of 9.7 billion by 2050, it faces a critical inefficiency in supply chains that leads to massive food insecurity. The Food and Agriculture Organization (FAO, 2021) estimates that approximately one-third of all food produced for human consumption i.e., nearly 1.3 billion tonnes, is lost or wasted annually. This wastage represents a dual crisis – a humanitarian failure in a world where hunger persists, and an environmental disaster, as rotting food waste releases methane (CH_4), a greenhouse gas 25 times more potent than carbon dioxide (US EPA, 2023). To address these fundamental issues, the global economy is progressively shifting toward the Internet of Things (IoT) as an essential solution.

1.1 Defining Internet of Things (IoT)

The Internet of Things (IoT) is not a single technology but a theoretical framework where physical objects are embedded with sensors, processing power, and software, allowing them to connect and exchange data with other devices over the internet (Al-Fuqaha et al., 2015). In essence, IoT bridges the gap between the physical and digital worlds by transforming passive objects in various sectors, such as heart monitors, streetlights, or shipping containers, into active participants in a network. These devices can report their status, environment, and location in real-time without human intervention. This capability is foundational to "Industry 4.0," where IoT enables predictive maintenance; for instance, in Germany’s automotive sector, companies like BMW and Siemens use sensors to detect minute vibrations or heat changes that signal impending equipment failure, allowing for repairs during scheduled downtime (Kang et al., 2016; Lasi et al., 2014).

The utility of IoT extends across diverse sectors by enforcing efficiency through real-time monitoring. In healthcare, it enables remote patient tracking (Islam et al., 2015), while in urban planning, it optimizes traffic flow and power grids

(Zanella et al., 2014). This same architecture is now being pivoted toward the food industry to ensure safety and reduce waste. By digitizing operations, stakeholders can monitor the temperature, humidity, and location of perishables in the food supply chain, shifting from reactive management to a proactive, data-driven system (Kamble et al., 2020).

1.2. The Pivot to the Food Industry in India

This transition is particularly urgent for India. Based on the NABARD Consultancy Services (NABCONS) (2022) report, despite being a leading global producer of milk, fruits, and vegetables, India suffers from post-harvest losses estimated at INR 1.53 lakh crore annually. Unlike developed nations where waste occurs at the retail and consumer levels, India’s loss occurs early in the supply chain due to poor infrastructure. This report identifies how India can leverage the industrial success of IoT and mitigate these losses and secure its food. By using smart technology to keep constant digital records of food, India has a chance to leap forward in IoT usage and not rely on old and expensive systems.

2. Technological Frameworks and Global Applications

To understand the impact of IoT, it is important to look beyond the hardware and understand the architecture that enables decision-making. The IoT ecosystem operates through a layered structure: the Perception Layer (sensors that gather data), the Network Layer (connectivity tools like RFID and LoRaWAN), and the Application Layer (cloud computing and analytics) (Gubbi et al., 2013).

Globally, this architecture is applied across three critical stages in the Food Value Chain (FVC).

2.1. Precision Agriculture (Pre-Harvest):

Avoidance of food wastage begins before harvest of crops. Precision agriculture uses environmental sensors to monitor soil moisture and crop health. For instance, Variable Rate Technology (VRT) allows tractors to apply water and fertilizer only where specifically needed, ensuring uniform crop growth and reducing the number of vegetables rejected for being the wrong size (Abade, Vidigal and Ferreira, 2022). Furthermore, Artificial Intelligence (AI) models can analyse weather data to predict pest attacks, allowing farmers to intervene early and prevent mass crop failure (Akter and Wamba, 2019).

In the United States, John Deere utilizes IoT-integrated "See & Spray" technology. Using computer vision and machine learning, tractors identify specific weeds among crops, applying herbicide only to the weeds. This precision reduces chemical waste by up to 77%, ensuring healthier crop yields and reducing chemical runoff into groundwater (John Deere, 2023).

2.2. Intelligent Logistics (The Shift to FEFO):

One of the most significant innovations in global food logistics is the shift from "First-In, First-Out" (FIFO) to "First-Expired, First-Out" (FEFO). In traditional warehousing, the oldest stock is shipped first. However, IoT sensors can now track the thermal history of a specific food container. If a newer batch of fruit was exposed to higher temperatures during transit, sensors will detect a rise in ethylene gas which is a signal of ripening (Kamble, Gunasekaran and Gawankar, 2020). The system will then direct workers to ship that "at-risk" batch immediately, regardless of when it arrived, thereby preventing spoilage (Pang et al., 2015).

The Danish shipping giant Maersk utilizes its "Remote Container Management" (RCM) system across its fleet of over 380,000 refrigerated containers (Reefers). The system provides real-time visibility into temperature and humidity. When any prescribed temperature deviation occurs, the system alerts technicians immediately, preventing the spoilage of millions of dollars’ worth of perishables during long-haul sea transits (Maersk, 2022).

2.3. Retail and Dynamic Pricing:

At the retail stage, IoT-enabled electronic shelf labels communicate with inventory systems. If a product is close to its expiration date, the system can automatically lower the price on the digital display. This dynamic pricing strategy encourages consumers to purchase the item, clearing stock that would otherwise end up as waste in a landfill (Zhang, Liu and Liu, 2022).

In Norway, the supermarket chain MENY implemented a "Waste-Advisory" system using IoT scales and digital labels. By tracking the exact shelf-life of products in real-time and applying automated discounts, the chain reported a 25% reduction in meat waste within the first year of implementation (Matvett, 2019).

3. Critical Analysis of the Indian Landscape

India presents a unique challenge where high agricultural output meets structural inefficiency. In addition, significant regional climate variations around the year with temperatures crossing forty degrees Celsius in summer in central and Northern India must also be considered to inspect supply chain logistics. To analyse the challenges in the logistics infrastructure, some key issues are identified.

3.1. The Structural Disconnect:

The primary barrier is the fragmentation of land. Approximately 86% of Indian farmers are smallholders owning less than two hectares (Ministry of Agriculture & Farmers Welfare, 2015). Operating on marginal profits, these farmers lack the upfront capital to invest in high-end sensors, as operating on such a limited scale makes individualized technology adoption financially unviable. Furthermore, the traditional "Mandi" marketing system involves multiple middlemen consisting of aggregators, commission agents, and wholesalers. Every time the produce physically changes hands across this complex network, data about the produce quality is lost, and the cold chain (temperature control) is essentially broken (Joshi, Banwet and Shankar, 2009). This continuous disruption creates severe blind spots in supply chain visibility, directly preventing the end-to-end traceability that IoT systems require.

3.2. The Infrastructure Deficit:

India's cold storage capacity is heavily distorted. While the country has an impressive 32 million tonnes of cold storage space, nearly 75% of this infrastructure is designed exclusively for potatoes. Because different foods require very specific temperature and humidity levels to stay fresh, these single-purpose potato facilities cannot simply be used for other crops. As a result, there is a critical shortage of "multi-commodity" cold storage facilities with adjustable climate zones required for high-value, sensitive items like fruits, vegetables, and dairy (The Associated Chambers of Commerce and Industry of India ASSOCHAM, 2024).

Furthermore, the problem extends beyond the storage buildings to how the food is moved. A successful logistics network requires constant temperature control, but in India, perishables are frequently transported in open, non-refrigerated trucks. Exposing sensitive crops to unmanaged thermal conditions over long distances breaks the cold chain entirely, leading to rapid rotting and degradation before the produce even reaches the market (Jha et al., 2015).

3.3. Connectivity and Power:

The foundation of any digital system is a reliable supply of electricity and a strong internet connection. However, the reality of rural India presents a major hurdle for these technologies. Power outages are a frequent occurrence, meaning that smart devices can easily lose power or fail to recharge. Additionally, high-speed internet networks are often weak, patchy, or completely unavailable in remote farming regions.

The problem is that standard IoT devices are typically designed for modern urban environments, built on the assumption that they will have a 24/7, uninterrupted connection to cloud servers. When placed in rural agricultural settings, these conventional devices struggle. Because they rely on a constant internet connection to function, a simple network drop or power cut will cause them to fail, preventing them from recording or transmitting the vital data needed to monitor and save the crops (Narwane, Gunasekaran and Gardas, 2022).

4. Strategic Frameworks for Adoption in India

Given the economic and infrastructural constraints, simply copying Western models will not work. India requires a bold strategy based on prudent Innovation and shared services across stakeholders.

4.1. Frugal Innovation and Retrofitting:

Upgrading every transport vehicle in India to a modern refrigerated truck is too expensive and impractical. A more realistic and affordable approach is "retrofitting" – adapting the regular trucks that are already on the road. Instead of trying to cool an entire vehicle, suppliers can use "Smart Boxes."

These are heavily insulated containers lined with special Phase Change Materials (PCM), which function like advanced, long-lasting ice packs. They can keep produce chilled at specific temperatures for several days without needing to be plugged into any electrical power source. Because these boxes maintain their own internal climate, they can be safely loaded onto standard, non-refrigerated open trucks. This dramatically lowers the financial barrier, allowing smaller logistics companies and farmers to transport sensitive food safely without buying a specialized fleet (CLASP, 2023).

Furthermore, the technology used to track these boxes does not have to be complicated. A basic, everyday smartphone can serve as the system's communication hub (an IoT gateway). It can connect to the temperature sensors inside the smart boxes via Bluetooth to gather data locally. If the truck is driving through a remote agricultural area with no internet connection, the phone simply stores the temperature readings. As soon as the truck enters a town with a mobile signal, the phone automatically uploads the saved data to the cloud. This clever use of existing, everyday devices entirely removes the need to buy expensive, specialized tracking equipment (Radjou and Prabhu, 2015).

4.2. Digital Public Infrastructure (The AgriStack):

The Indian government is currently building something called the "AgriStack," which is essentially a massive, nationwide digital foundation for the agriculture sector. It is a centralized hub where all agricultural information comes together. By combining private, on-the-ground information from trucking and logistics companies with public information – like real-time weather forecasts, soil conditions, and daily market prices – the government can build a "Digital Twin."

A Digital Twin is a live, highly detailed virtual model or replica of the entire country's physical food supply chain operating on a computer screen. Having this massive virtual map allows policymakers and businesses to see the big picture and practice "macro-balancing." This means they can look at the country as a whole and shift resources to where they are needed most before problems occur.

For example, if the system's live data shows that there is a massive surplus of onions sitting in Mumbai, while at the same time detecting a severe shortage of onions in Bangalore, it can flag this imbalance immediately. Instead of letting the onion surplus rot in Mumbai, which often forces farmers to dump their unsold crops and crashes local prices, the system can help coordinate the logistics to transport that extra food to Bangalore. This smart, data-driven balancing act ensures that consumers get the food they need, keeps market prices stable for the farmers, and prevents massive amounts of food waste (MicroSave Consulting, 2025).

4.3. Cold-Chain-as-a-Service (CCaaS):

To solve the agricultural "Capital Trap" – a frustrating cycle where smallholder farmers lose their harvests simply because they do not have the massive upfront funds needed to buy their own cooling equipment, the industry must change how it operates. Instead of expecting individual farmers to purchase expensive infrastructure, the system needs to move toward shared service models.

This is where "Cold-Chain-as-a-Service" (CCaaS) comes into play. Under this model, farmers do not need to build or buy their own specialized storage spaces. Instead, they can simply rent a small, dedicated section of a shared, high-tech cold room on a flexible, pay-per-use basis. It works like a pay-as-you-go mobile phone plan where the farmer only pays for the exact amount of space they use for the specific number of days they need to keep their crops cold.

IoT technology is the crucial ingredient that makes this shared system work fairly and securely. Smart sensors inside the facility track exactly whose produce is stored where and for how long. This automated tracking ensures that the billing is completely transparent and perfectly accurate, so farmers are never overcharged. Additionally, these sensors connect to the internet, allowing farmers to use a smartphone to remotely monitor the temperature and safety of their specific crates from miles away, giving them peace of mind (Climate Policy Initiative, 2021).

5. <u>Case Studies: Evidence from the Indian Field</u>

To move beyond theoretical frameworks, it is essential to examine real-world applications where IoT has successfully mitigated waste and improved economic outcomes for Indian stakeholders. The following case studies cover three critical sectors – Dairy, Horticulture, and Precision Agriculture.

5.1. Case Study 1: Digitizing Milk (Stellapps Technologies)

India produces more milk than any other country, but a massive amount of it spoils because it isn't chilled quickly enough and the collection system is highly disorganized from multiple small-scale farmers. Furthermore, milk quality is often measured subjectively, which leads to arguments and unfair payments. To fix this, a Bangalore-based start-up named Stellapps Technologies created a smart system called "SmartMoo." At village collection centres, they use smart sensors to instantly and accurately measure milk quality, like its fat content, so farmers know exactly what their milk is worth. At the same time, another connected system called ConTrak constantly watches the temperature of the bulk milk coolers. If the milk ever gets warmer than a safe 4°C, the system automatically sends a warning to managers so they can fix the issue before the milk goes bad (Stellapps, 2020).

Because of this constant digital monitoring, the overall quality of the milk improved by 29%. Farmers ended up making about 20% more money because they were paid fairly for good quality milk and lost much less to spoilage. On top of that, the companies collecting the milk used the live data to plan the most efficient driving routes for their trucks, which cut their fuel costs significantly (Vivriti Capital, 2022).

5.2. Case Study 2: Frugal Cold Chain for Smallholders (Ecozen Solutions)

Small farmers in states like Andhra Pradesh often must sell their crops immediately for very low prices because they lack the resources for storage to keep the crops fresh. Normal cold storage buildings don't work well for them as rural power grids are highly unreliable. To help, Ecozen Solutions built "Ecofrost," a portable cold room powered entirely by solar energy. Instead of relying on regular, expensive batteries, it uses special thermal plates that can keep the room cold for up to 30 hours without any power. Farmers can use a mobile app to check the temperature inside their cold room from anywhere. The app additionally looks at live market prices and compares them to how long the crops will stay fresh, telling the farmer the exact best day to sell for the highest profit (Ecozen Solutions, 2022).

Working with a local farmers' group, this technology allowed farmers to safely store high-value and delicate items, like flowers and beans for up to three weeks. This stopped them from throwing away unsold food and boosted their overall income by 2.5 times. For example, bean farmers could safely hold onto their harvest when market prices were low and wait to sell until the price doubled from INR 30 to INR 60 per kg, for example. Most of all, farmers didn't have to buy expensive cold rooms; they simply rented space using the "Cold-Chain-as-a-Service" model, making the technology highly affordable (Ashden, 2018).

5.3. Case Study 3: Precision Agriculture at Scale (Cropin Technology Solutions & PepsiCo)

Large food companies often struggle to predict exactly how much food their network of thousands of small farms managed under them will produce, making logistics very difficult. To make farming more predictable, CropIn created a platform called "SmartFarm." This system takes high-resolution pictures from satellites and combines them with weather data from smart sensors on the ground to create a highly detailed virtual map – a "digital twin" of every single farm. This system acts like an early warning radar, sending alerts to farmers if insects are about to attack or if the crops are getting too dry, long before any physical damage is visible to the human eye.

When PepsiCo India used this system with their potato suppliers, farmers were able to water their crops at the perfect time and prevent diseases from destroying their harvest before it even started. As a result of this constant monitoring, the smart system was able to predict exactly how many potatoes would grow with 92% accuracy. Because the logistics managers knew exactly how much food was coming weeks in advance, they could organize their transport trucks perfectly. This eliminated the usual transport delays that cause food to rot at the farm, ensuring a smooth flow from the farm to the factory (Cropin, 2025).

6. Conclusion

Securing India's food supply chain requires shifting focus from retail-level waste to mitigating early-stage, post-harvest losses. As demonstrated by localized applications in dairy digitization and solar-powered cold storage, IoT integration offers a viable pathway out of traditional, energy-intensive infrastructure. However, scaling these solutions requires moving away from individualized tech adoption toward shared, data-driven logistics networks.

Success depends on a collaborative approach from various fronts. The government must provide the digital backbone via the AgriStack, the private sector must innovate with low-cost "smart" hardware, and financial institutions must support service-based models like CCaaS.

By shifting the national focus from simply trying to grow more crops to protecting the food that is already harvested, India can finally stop its staggering INR 1.53 lakh crore annual financial loss. Ultimately, this collaboration will build a modern food system that is sustainable, highly profitable for local farmers, and secure for the nation's future.

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