RE-INVENTING THE FOOD SUPPLY CHAIN WITH IOT: A DATA-DRIVEN SOLUTION TO REDUCE FOOD LOSS

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ABSTRACT

The global food supply chain needs to evolve to meet a 50 percent increase in food demand by 2050. While food production grows every year, according to a report by the Food and Agriculture Organization (FAO), around 25 percent of roots and tubers, 20 percent of fruits and vegetables, 8 percent of grains and pulses, and 13 percent of animal products are lost before distribution. The majority of such losses are attributed to inadequate monitoring and poor handling during storage and transport. Moreover, the handling of produce in the supply chain also impacts its nutritional content and shelf life. Such losses, when coupled with the rising frequency of epidemics and climate events, further exacerbate the problem of food security for the global population. In addressing the problem of food loss in the supply chain, the biggest hurdle is the lack of traceability and information. On one hand, precision farming helps improve food production efficiency. On the other hand, useful insights post-harvest are not measured due to cost limitations. The ones that are measured often end up in silos or are lost. To overcome these challenges, we propose a framework that leverages low-power IoT sensing networks, smart edges, and data-driven optimization to re-invent the supply chain. In this work, we derive from lessons learned while working with various agricultural supply chain partners and share insights based on some technology solutions that we have explored. We take a bottom-up approach in analyzing the major challenges faced by today's food supply chain. Starting with individual food pallets, we propose ways to develop an agile and low-cost data pipeline that can sense and track the food as it moves through the global supply chain. Further, we propose a dedicated optimization framework that can leverage cloud analytics to boost sustainability and efficiency in the global food chain to meet the growing demand.

INTRODUCTION

Feeding a world population of 10 billion by 2050 is a grand challenge for humanity. The United Nations (UN) 2021 sustainable development report noted that the world is currently not on track to achieve the goal of zero hunger by 2030. The COVID-19 pandemic has only exacerbated this problem. In the face of decreasing land availability and viability, water scarcity, nutrition deficiency, and climate change, the need is for effective innovation to improve the efficiency of existing agri-food systems and prepare them to meet this goal.

While there are gears in motion that are working toward boosting sustainable food production to meet local and global demands, this is merely the first step in the right direction. Food availability of the future depends not only on growing more food, but also on reducing the loss of food. Today, we generate more food than is needed to feed the current population. However, according to a recent UN 2019 State of Food and Agriculture (SOFA) report, 40 percent of all food grown today is simply wasted [1]. Food loss is known primarily to affect the ability to meet demand, but it also has other implications due to additional stress on the environment and the resources that are used to produce, harvest, and transport the food. Such loss is hence unprofitable and unsustainable, especially in the face of growing resource constraints, and makes it impossible to meet the increasing food demand. Therefore, the big challenge that remains to be tackled is the problem of food loss.

Reducing food loss demands a critical examination of the food supply chain that interlinks communities and continents. The SOFA report identifies critical loss points across the supply chain, where such loss has the highest impact on food security and economy. Specifically, these are the post-harvest stages of packaging, storage, and transportation.

In both low- and high-income countries, losses occur mainly due to inadequate infrastructure or technical breakdowns in the supply chain that result in poor management of parameters such as temperature and humidity during storage and transportation. Furthermore, due to the lack of any meaningful traceability within the food chain, critical information pertaining to shelf life and nutrition are also lost.

The Internet of Things (IoT) is a recent technological paradigm that has started a new revolution in the area of food production. The use of terrestrial sensing networks in combination with remote sensing technology has enabled more efficient and sustainable management of the food production process. We see vast literature on how precision farm sensors that pick up details like soil moisture, soil nutrients, and temperature provide data to help determine the optimal amounts of irrigation, fertilization, and so on [2]. Working with remote sensing, using drones and satellites, we can now provide precise weather updates, large-scale soil and plant health data, and useful harvest estimates to farmers, as demonstrated in [3]. Newer farming practices are also being developed that can transform agriculture from a major carbon generator to a significant means of carbon capture [4]. The remote and terrestrial sensing modalities play a key role in assessing the benefits of such agricultural practices at varied granularity. While IoT has proven its effectiveness on the farm, boosting the efficiency and sustainability of traditional farming methods, its potential remains largely untapped in the next steps of transporting the produce to end consumers.

As the post-harvest stages contribute to substantial food loss and emissions, there is a clear need for low-cost, scalable, and reliable infrastructure that can adapt to the existing systems while improving their efficiency.

In this article, we provide an analysis of the problems contributing to food loss at the various stages of food supply chains. We take a bottom-up approach, starting with sensing at the pallet level, and define a paradigm that can accommodate existing systems while solving the key problems, as shown in Fig. 1. Our contributions are as follows:

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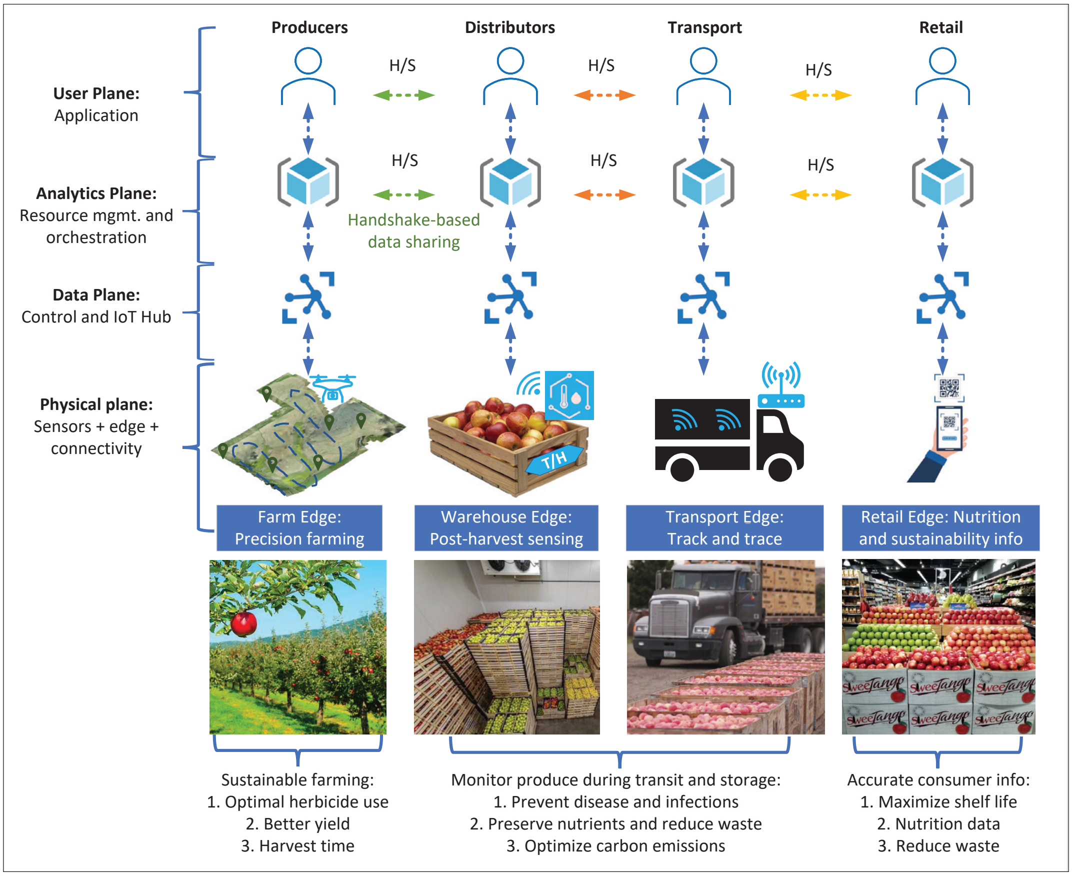

FIGURE 1. A data-driven food supply chain highlighting the physical, data, analytics, and user planes The physical plane emphasis lies in connected IoT networks, along with context-aware connectivity, that can sense and track at the edge. This plane is optimized to reduce loss locally. The data and analytics planes function at a local and global level based on supply chain entity handshakes. This stage performs optimization to meet global goals, like carbon reduction and route planning, based on data derived across the supply chain. The user plane optimizes for parameters like shelf life and nutrition, based on demands by competing and collaborating entities. This is also the user facing end of the platform. From data capturing smart edges in the farm to the end consumer, the aim here is to retain valuable information in a trusted and secure framework that adds value to the supply chain while minimizing loss and costs.

- A comprehensive analysis that establishes the need for low-cost, real-time sensing that monitors the produce during storage and transport, to identify and isolate *critical loss points*. We also outline the infrastructure requirements and the current challenges in realizing such a network.
- Scope and definition of edge systems and connectivity requirements that enable near-real-time communication. This helps identify problems, raise timely alerts, and accommodate quick interventions to help improve food safety, preserve nutrition, and prevent food loss.
- Establishing the need for a unifying analytics platform that utilizes shared data from farm and supply chain IoT networks to optimize factors such as carbon footprint, shelf life, price, and demand. Such platforms enable real-time interaction in a market with collaborators and competitors alike, while ensuring trust and security of information.

TRACEABILITY FOR TRUST IN AGRI-FOOD SUPPLY CHAIN

Traceability is important for establishing two key features in the supply chain: validating *sustainability* and ensuring *safety and accountability*. The FDA defines traceability as the ability to follow the movement of a product and its ingredients through all steps in the supply chain, both backward and forward. However, current FDA protocols only mandate that each entity in the supply chain maintain traceability records that go one step forward and backward. Additionally, a large part of the supply chain is excused from maintaining such records. Such limited record keeping coupled with aggregation at various stages results in massive hemorrhaging of end-to-end traceability information. This makes issuing recalls and implementing safety measures a humongous challenge.

CASE STUDY: WALMART AND ITS MANGOES

Mangoes are grown in warmer climates and shipped worldwide using cold storage. During transportation and storage, they can suffer decay, heat injuries, and surface defects due to improper environmental conditions [5]. They are also susceptible to listeria and salmonella contamination.

In order to ensure quality, Walmart analyzes and monitors items throughout its supply chain. Starting at harvest, to processing, distribution, and storage, key parameters are logged to determine quality and marketability at each stage [5]. Recently, Walmart partnered with IBM to develop a blockchain-powered system to track the produce and tested it on sliced mangoes. This enables them to collect and track data to benchmark performance beyond the capability of traditional systems. However, this blockchain still relies on human recorded data, which can be unreliable and prone to manual error. Implementing such a data trail becomes more complex and prone to error

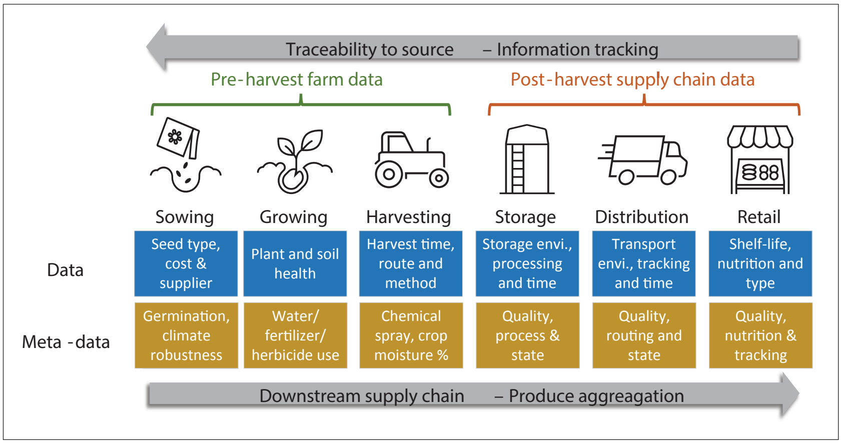

FIGURE 2. A standard agricultural supply chain. In the downstream, information to be stored increases as produce is aggregated at various stages. Traceability of the produce from the end product back to the source is the ultimate goal, which can, for instance, help prevent spread of food-borne illnesses and rapidly deploy interventions to prevent loss.

as the supply chain starts to incorporate external entities. To ensure trust in traceability systems, autonomous and secure data aggregation nodes, such as the smart edges described in the following sections, must be an integral component.

Enabling Traceability

To establish end-to-end traceability, there are a couple of challenges that need to be addressed. Primarily, the food supply chain is a global pipeline that transcends multiple countries and their guidelines. The first barrier to entry is that not all countries can readily implement infrastructure to support seamless monitoring and traceability. Further, food supply chains constitute various entities, such as farmers, processors, transporters, distributors, and retailers. With little transparency into their interactions, limited data is shared across these entities. Insights into the sustainability of such operations are also thereby limited. For example, calculating the carbon footprint of any operation involves not only the energy spent on farming but also storage, transport, and so on. Thus, it is challenging to compute such metrics without the infrastructure and incentive to share the information.

To improve transparency and traceability across supply chains, we propose a data aggregation model as shown in Fig. 2. In this data model, we propose collection of key parameters at each stage with their respective meta-data to create a stream of information that can be mined to extract actionable information for each entity. For example, the pre-harvest data such as water use, fertilizer use, planting, and harvesting method can be used to calculate the carbon footprint and quality of the crop. Such metrics are then supplemented by downstream information during transport, storage, and retail stages to build a holistic view of the environmental impact of such operations. A smart edge coupled with a dedicated analytics system can guarantee that such records are autonomous and free from human error, thereby guaranteeing trust. Below, we discuss the edge solutions, connectivity requirements, and optimization approaches that can enable such a system for a global supply chain.

Data-Driven Food Supply Chain: IoT and the Smart edge

The Need for Granular Sensing and Tracking

Precision technology has greatly benefited modern farms by improving monitoring granularity, thereby enabling efficient resource utilization to boost productivity. Leveraging low-cost, commodity IoT hardware, we have so far developed and deployed effective smart edge devices to support precision agricultural applications. These include sensing to monitor crop/soil health and optimize fertilizer or water usage [6]. The next steps lie in extending such a precision monitoring and information trail to post-harvest stages of the food supply chain. Our proposed framework for such integration is shown in Fig. 1. Today, all information about farming practices is lost or aggregated post-harvest. A great example of this is the use of herbicides and fertilizers. With increased awareness of high-dose chemical harm, only plants targeted by precision sensing are sprayed. Despite being a strong indicator of produce quality and safety, information pertaining to such treatment is entirely lost. Hence, there is a strong need to aggregate such information at the farm edge and retain it through the subsequent stages of the global supply chain.

Extensive studies also show that post-harvest transport and storage conditions directly impact the nutritional value and quality of the produce. Maintaining a controlled environment helps retain freshness and prolong the life of the produce. For instance, temperature controls the respiration in produce, which impacts their moisture content and directly relates to nutrition loss. Thus, all stages of the supply chain, from pre-harvesting on-farm activities to transport and storage environments, have critical data points that directly impact the quality and life of the produce. However, retaining such data is no trivial task as agricultural supply chains extend across the globe with aggregation happening in massive volumes at each stage. The low profit margins also make entities reluctant to any change that requires large infrastructure investments.

Tracking essential information along the supply chain is a problem that demands a low-overhead solution that can be deployed at scale. The IoT paradigm that utilizes low-cost, low-maintenance hardware for precision applications provides a fitting solution to this problem.

Case Study: Smart Edge for Produce

Critical loss in produce is primarily attributed to diseases and damage during and post-harvest. A study carried out as early as 1977 noted the significant loss of vitamins in leafy vegetables when stored at improper temperature ranges [7]. A more recent study highlights the importance of properly monitored storage and transport facilities to prevent infestation by disease-causing microbes that lead to accelerated spoilage [8]. Multiple such studies over the past two decades have indicated the need for monitoring and maintaining a suitable food environment in post-harvest stages to minimize loss. However, we have only started exploring options to implement such monitoring solutions.

As an example, perishable fruits like apples are large-scale harvests that rely heavily on cold storage for year-round availability and global trade. In the case of the apple industry, IoT solutions monitor on-farm practices to optimize production and provide a measure of quality. Once harvested, we need a technology solution that first propagates this information to subsequent stages. Further, the technology needs to function in the cold storage and transportation environments over months to track and manage the post-harvest quality and prevent loss. Continuous and autonomous pallet-level tracking can help alleviate loss by connecting granular quality information, followed by identification and management of critical loss points. However, due to the low profit margins and the global nature of the industry, instances of such implementation are limited to specific entities in the supply chain. To pro-

Solution name	Type	Sensing	Sensing Cost/Effort	Real-Time Data
SpotSee	Calorimetry sensor	Temperature and humidity	Low/Moderate	No. Manual phone application
iFoodDS	Barcode tracker	Manual inspection	low/Moderate	No. Transit inspections
Zest Labs	Barcode and sensing	Temperature and manual timestamp	Low/Moderate	No. Transit scans
Varcode	Dynamic barcode sensing	Temperature and time	Low/Moderate	No. Transit phone scan
Farmsoft	Wireless RFID	Only ID and local tracking	Low/Low	Yes. Limited RFID tracking
Telesense	Wireless bulk sensing	Temperature, moisture, CO_2	High/Low	Yes. Cellular connected

TABLE 1. Commercial low-cost sensing and tracking solutions in the agricultural supply chain.

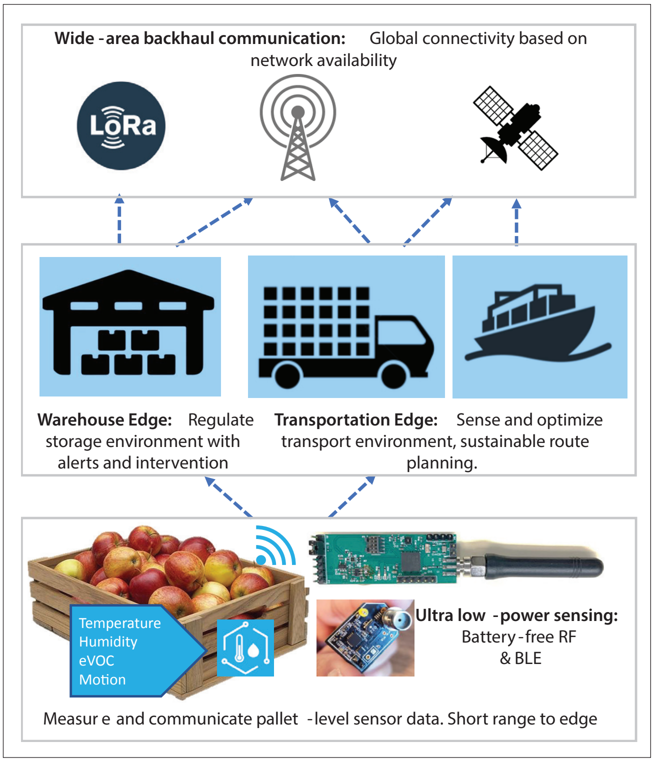

FIGURE 3. We divide the end-to-end IoT network employed in the food supply chain into two levels. The first level creates a local IoT network connecting end devices such as sensors to the edge devices. The smart edge at this level hosts a low-cost short-range IoT network with a variety of sensors that monitor the pallet environment, such as temperature, humidity, trace gas levels, and motion. The edge can either act as a gateway to directly connect these IoT sensors to the cloud, or alternatively, implement simple local interventions for autonomous management. In the second level, the edge devices connect with the base stations that extend the connectivity to the global Internet. Long-range connectivity solutions like LoRa or DtS-IoT provide backhaul connection to the cloud for large-scale optimization. The connectivity option at this level is subject to constraints posed by the different stages in the supply chain like storage or global transport.

mote widespread acceptance across the supply chain, there is a need for technology that is low-cost with reduced need for manual intervention.

IoT-Powered Smart Edge

Monitoring and tracking produce, as it moves through the supply chain, is a challenging task that demands food-specific sensing, local and global tracking capabilities, and computational support for error detection and correction. Commercially, few such low-cost edge solutions exist, and they are summarized in Table 1. These solutions help to coarsely track produce and to note any detrimental conditions that arise during transportation or storage. It is also established that meta-data from such measurements, when propagated along the supply chain, provide avenues to learn practices that best extend shelf life and prevent loss. However, these existing solutions either have limited capabilities, need manual intervention for reading and inference of data, or are expensive. Consequently, such technology does not scale easily.

As a first step to address the impediments to scaling, we envision using low-cost sensors, like battery-free tags, to sense and communicate at the pallet level as illustrated in Fig. 3. Such battery-free devices use mere microwatts of power to sense and communicate [9]. Hence, they can be sustained on harvested energy without the need for batteries. These tags not only reduce the cost of sensing, but the absence of batteries means they can work reliably in a wide range of temperatures. This includes cold storage facilities where traditional battery-operated IoT sensors tend to fail. Notably, these simple sensors can be made using food-safe materials allowing for safer integration in the food supply chain and helping reduce the amount of e-waste associated with IoT sensors. A network of such battery-less sensors enables real-time monitoring at the pallet-level as produce moves through the supply chain. Such real-time monitoring also helps eliminate redundant manual work of extensive visual inspections and sparse measurement of parameters such as produce temperature upon arrival. The sensors can also be augmented to detect trace amounts of gases, such as ethylene and CO_2, which accelerate ripening and alter taste and texture of produce rendering them unfit for commercial buyers. For use in the food supply chain, identifying food-safe materials, energy sources for powering sensors in the storage and transport environment, and developing food-specific sensing modalities are interesting challenges to be addressed.

At a higher level, the benefits of IoT combined with a compute edge enables agile real-time decision making. The edge complements simple sensing by boosting functionality from mere data collection to actual information processing that generates actionable insights. Timely alerts from such systems are key to isolating the critical loss points and mitigating post-harvest food loss. Being low-cost and requiring less manual intervention (which is a major source of error and cost), such autonomous IoT networks can be deployed easily within trucks and warehouses to work reliably in most parts of the world.

Connectivity for Traceability

Even within the United States, only 25 percent of the land mass is connected with reliable cellular services (primarily heavily populated areas). The coverage drastically degrades over rural areas and water bodies such as oceans. Hence, providing reliable connectivity that can work across the globe is a major hurdle in the path of achieving an efficient supply chain. Having central entities like the UN involved in planning the future of food is a step in the right direction, as this effort needs global guidelines. However, the first step starts locally.

CASE STUDY: LOCAL AND GLOBAL CONNECTIVITY

Over the recent decades of the IoT boom, most early efforts aimed at low-power and low-data-rate networks for connected sensing. Solutions like RFID, Bluetooth, Zigbee, Z-Wave, and NFC have emanated from these efforts. The next drive of innovation has focused on extending the range of IoT communication to address demands for long-range connectivity. This drive, together with the higher-bandwidth next-G efforts, has brought about low-power long-range IoT connectivity solutions, such as LoRaWAN, NB-IoT, SigFox, and TV white spaces (TVWS) IoT [6, 10]. Although these solutions are capable of extending the connectivity for miles from a base station, remote areas still lack a reliable backhaul. With this core motivation, the IoT industry is currently going through the next revolution — direct-to-satellite IoT (DtS-IoT) [11]. Here, an IoT device anywhere on Earth can directly communicate with a low Earth orbit (LEO) satellite and communicate over thousands of miles. The IoT connectivity technologies from each of the three evolution tiers are meant to serve divergent application scenarios. The food supply chain, with its unique global reach, encompasses all such divergent application contexts, as shown in Fig. 3. For example, the producers and transporters prefer low-power and long-range connectivity solutions (LoRaWAN, TVWS IoT, DtS-IoT, etc.)) given the large farm size and transit points. In contrast, short- or mid-range and ultra-low-power solutions (Bluetooth, Zigbee, RFID, etc.) are widely used within warehouses and trucks.

Food supply chains span continents, traveling across the globe through various modes of transport. Establishing reliable communication for efficient traceability and monitoring during such transit poses an interesting challenge.

To accommodate this diversity, the data plane and physical plane of the system must be designed to work in conjunction to realize such a dynamic ecosystem. Here, the challenges are twofold: first, enabling support for divergent IoT connectivity technologies, and second, dynamically configuring them based on the data-sharing handshake between different entities. To support this, the smart edge in Fig. 3 operates as a gateway for a network of sensor nodes and can be deployed in various types of physical devices ranging from single-board computers to a local PC. Individual modules here are built to support mainstream IoT connectivity protocols that while installed in the edge container can support over-the-air updates.

SPANNING CONNECTIVITY ACROSS THE SUPPLY CHAIN

The following challenge lies in extending the local networks for global applications and enabling dynamic connectivity selection. As discussed above, the footprint of a food supply chain stretches globally from remote farms and across the oceans. The available and preferable connectivity options for the edge device communicating information to the global network (i.e., the Internet) vary in these geographical regions. For example, in the ocean and remote transit areas, DtS-IoT is the sole option to date. On the other hand, cellular-based NB-IoT and LoRaWAN gateways are preferable in urban areas considering the cost, power consumption, and quality of communication links. While the benefits of next-G connectivity solutions are limited solely to heavily populated urban areas, newer innovations are beginning to connect other parts of the world. Hence, the selection of the preferable connectivity option cannot remain static across entities in the supply chain. Figure 3 provides an example of how the preferred connectivity option for the transport edge changes along the route traveled by produce. To address this challenge, one proposed smart edge strategy is to leverage a connectivity heatmap that indicates the optimal connectivity option depending on the geo-location of the edge device. Such a heatmap is partially generated by the data plane based on global knowledge; for example, weather prediction, historical data on connectivity options, availability of infrastructure, cost, and power models. It is then shared with the smart edge and regularly updated. The edge completes the heatmap utilizing real-time data including signal quality, network performance, battery status, and so on. As illustrated in Fig. 3, we divide the end-to-end IoT network employed in the food supply chain into two levels. The first level creates a local IoT network connecting end devices to the edge. It can utilize the connectivity technologies from the first two tiers, like battery-free RF or BLE, to accumulate data at the edge. In the second level, the edge devices serve as base stations that extend the connectivity to the global Internet. Here, IoT connectivity solutions from the second and third tiers operate. Such a reconfigurable framework enables flexibility to independently leverage technology improvements across the pipeline.

CLOSING THE LOOP: REAL-TIME OPTIMIZATION TO BOOST PRODUCTIVITY AND EFFICIENCY

EFFECTIVE INFORMATION EXCHANGE FOR AGILE SUPPLY CHAINS

Today's consumers are empowered with more information than ever before. However, a recent international data corporation report notes that still, over 80 percent of the data in the supply chain is retained in silos or lost. Segregating information into independently operated silos leads to partially informed decision making, which results in significant losses and inefficiencies in the supply chain [12]. Furthermore, the impact of these inefficiencies compounds exponentially in the presence of extreme events such as the CoVID pandemic and the Suez Canal blockage. Increasing transparency in supply chains to promote information flow can grant agility to recover from such outlier trigger events, faster and dynamically. Increased visibility also allows for precise analysis and better decision making to individuals and organizations, making them less susceptible to disruptions.

Realizing this vision of greater transparency and agility in the supply chain needs IoT-based smart edge systems and connectivity, but they are only one part of the solution. While IoT networks generate data with granularity in the physical plane, it is equally imperative to draw meaningful insights and act on this data to benefit the larger supply chain. Therefore, the other important part is to assess and interpret the collected data while acting in dynamic environments with significant stochastic behaviors. This can be achieved through an extensive analytics plane that accounts for the demands of multiple supply chain entities. We propose using a multi-agent optimization framework in the analytics plane to optimize the cost-time-sustainability profile for the supply chain environment of competitors and collaborators.

Various optimization techniques have been in use over the past decades, but they do not accurately distinguish between external stochastic effects and internal pairwise interactions within the supply chain. The recent advances in reinforcement learning and deep learning enable a more informed strategy optimization approach [13]. These tools accommodate environmental uncertainty while allowing for inter-player coordination and competition. However, supply chains present two unique challenges to multi-agent reinforcement learning. First, rein-

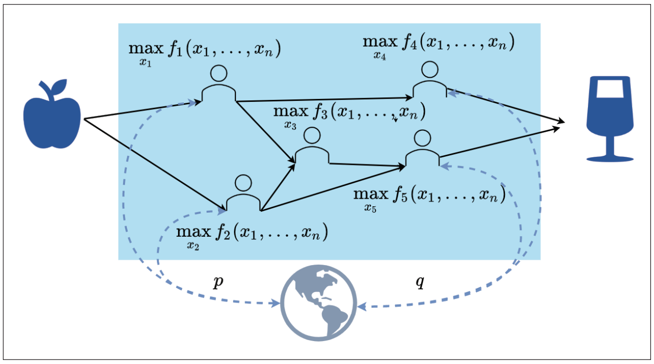

FIGURE 4. Competing partners are connected within a supply chain while allowing organizations to focus on maximizing their individual objective. A third-party cloud solution enables this collaboration in a trusted environment while individual organizations retain privacy on trade secrets.

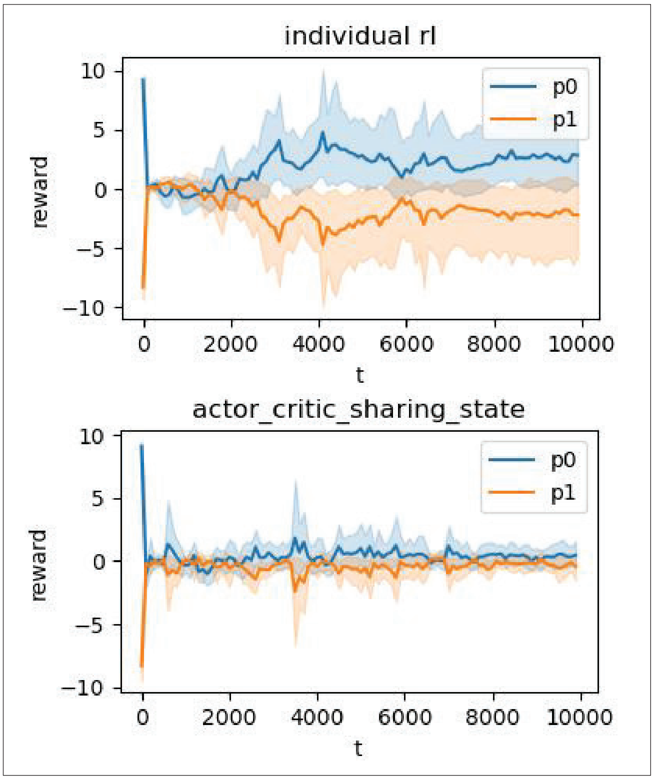

FIGURE 5. Actor-critic training analysis on a two-player supplier-retailer supply chain. Player rewards are the total revenue of players subtracting operational expenditure including holding cost. The top plot shows player rewards when training with player-specific forecasts. The bottom plot shows player rewards when players share local demand forecasts with each other.

forcement learning targets optimal control settings where the global state information is public. However, information within the supply chain is segregated into hierarchical networks. Second, sustainability objectives are markedly distinct from typical robotic performance benchmarks. Thus, enforcing sustainability metrics while preserving players' capacity for coordination and competition requires a greater understanding of competitive multi-agent learning dynamics.

CASE STUDY: FORECAST-INFORMED STRAWBERRY SUPPLY CHAIN

Deemed a superfood, fresh strawberries will experience over 26 percent global market growth over the next five years [14]. The global strawberry supply chain is dominated by a small oligarchy of retailers and is fiercely competitive, resulting in high information segmentation within the chain.

The global fresh strawberry supply chain is sensitive to supply and demand disruptions, and the sensitivity is further exacerbated by the lack of communication among retailers. By providing a cloud-based third-party information exchange platform that is designed to optimize each player's revenue, each entity can securely share information for mutual benefit. By sharing necessary information across all levels of the chain, suppliers can ensure less food wastage by more accurately meeting retail demands, and retailers can better calculate shelf life and anticipate supply shortages or surpluses to set retail prices accordingly. Furthermore, the platform provides a wealth of information and forecasts that could protect its participants from the cascading effects of chain disruptions such as the one caused by the Suez Canal blockage.

ENABLING A MULTI-AGENT OPTIMIZATION FRAMEWORK

Multi-agent optimization frameworks are ideal for mixed collaborative-competitive systems with hierarchical information flow. Within the supply chain analytics, they build on state-of-the-art AI technology to address the following critical needs within the supply chainL

- **Forecast-driven decision making:** This involves leveraging data made available through IoT sensors and edge to generate data-driven forecasts for the optimization algorithm.
- **Game-theoretical competitive equilibrium:** Using game-theory-derived models can ensure fairness for the participating organizations, in which each organization's decisions are dedicated to improving their own objectives.
- **Cloud-based third-party information exchange platform:** This enables supply chain entities to share information securely within a third-party platform and jointly optimize shared objectives such as reducing food loss, certifying the sustainability of food transportation, and decreasing carbon emissions. Figure 4 shows the interaction pattern of each organization with the third-party cloud solution as the enabler.

Due to the supply chain's inherent information structure, an information exchange platform is essential for adapting multi-agent learning paradigms, such as centralized learning decentralized execution. Such a framework can support actor-critic reinforcement learning methods, and enable players to securely publicize data-driven forecasts and jointly explore competitive equilibria. As shown in Fig. 5, empirical results for training actor-critic methods on a two-player, supplier-retailer supply chain suggest that sharing forecasts decreases the reward gaps between players and reduces training variance. In this simulation, the unit price of raw material is constant, the consumer demand is a stochastic function that varies linearly with player one's price, and both players have a lead time of three time steps between ordering and receiving products.

Such a platform may also facilitate a greater understanding of how individual local forecasts affect the robustness of the overall supply chain. Empirically, simulated evidence of such systems supports the usage of local forecasts to improve a supply chain's global efficiency. Specifically, in business models such as vendor-managed inventory (VMI), both retailers and suppliers benefit when retailers directly pass on demand forecasts to the suppliers [15].

DISCUSSION AND CONCLUSION

The agri-food industry today faces unsustainable loss with an imminent need to boost efficiency in order to meet the future food and nutrition demands. Extensive work is being undertaken to leverage technology such as IoT to establish an efficient and sustainable food production process. However, the potential of IoT and smart systems remains largely untapped in the post-harvest supply chain stages. These stages have been identified by the UN as critical loss points that contribute to significant food loss.

The next steps, for industry and research alike, lie in first, innovating efficient, low-cost, and scalable methods to monitor and track in the global food supply chain, and second, enabling effective decision making through information sharing and increased transparency. The proposed smart, connected edge framework — which leverages the IoT paradigm — will fundamentally change what we know about our food. It can help estimate accurate produce shelf life and nutrition, reduce loss, and minimize the spread of food-borne illnesses. A reliable data tracking and connectivity framework, coupled with reinforcement-learning-based optimization, embed trust, transparency, and safety in the supply chain. The proposed framework identifies key planes — physical, data, communication, and analytics — that can be dynamically configured to accommodate the needs of specific operations while ensuring the key requirements of trust and transparency. Such a framework adds value by reducing costs and losses while promoting information sharing. More importantly, it helps governing bodies such as the UN and FDA to monitor and incentivize practices that can help sustainably meet future food goals.

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