Reducing food losses by improving the efficiency of the banana supply chain in the Antioquia corridor in Colombia

Sethuramanujam A.[1], Fernandez Cedi, L.N. [2]
***Advised by Dr. Mejia Argueta, C*[3]*. Dr. Antonini, C.* [4]*, Dr. Jose Larco*[4]**

1: Praxis Business School, India
2: Groupe Ecole supérieure d'Agriculture d'Angers, France
3: CTL, MIT, United States of America
4: UTEC, Peru

1. Introduction

In 2011, the Food and Agricultural Organization of the United Nations (FAO) estimated that one-third of the food produced in the world for human consumption was lost or wasted (FAO, 2021d). Ten years later, a World Wildlife Fund (WWF) study calculated the percentage of food destined for consumption wasted along the entire chain. It reached 1.2 billion tons of food lost on farms and 931 million tons wasted at the retail, food service, and household levels, which accounts for around 40% (WWF-UK, 2021). All this wasted food could feed more than double the number of undernourished people worldwide, estimated to be between 720 and 811 million in 2020 (see figure 1) (FAO, 2021e; World Food Programme, 2020).

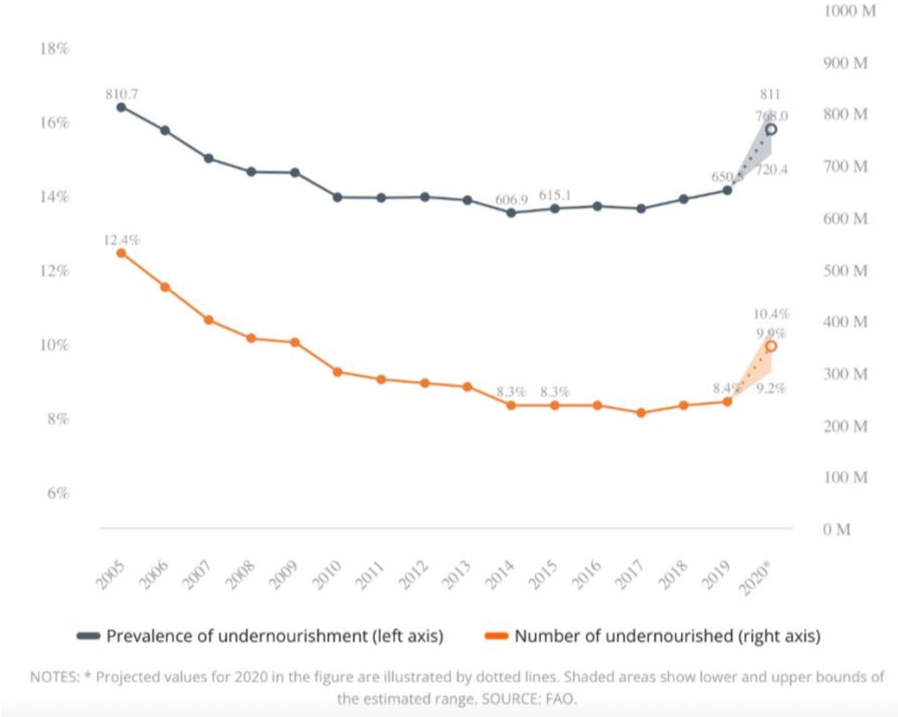


Figure 1. Prevalence of undernourishment and the number of undernourished in the world (FAO, 2021e)

Food loss and waste estimates have not improved. According to the World Resources Institute (WRI), they result in annual economic losses of $940 billion and a significant environmental impact (World Resources Institute, 2021). However, there is greater awareness and interest in reducing the food loss and waste problem among policy makers and all actors in the supply chain, from producers and processors to distributors, retailers, and consumers worldwide. This global awareness of the problem became evident in the 2030 Agenda for Sustainable Development Goals (SDG) when target 12.3 was defined to halve food waste per capita by 2030 at the levels of retail and final consumers, as well as to reduce food losses at the production and supply chain levels (FAO, 2021d).

According to the World Food Programme (2020), there is a difference in where the greatest losses occur in developing and industrialized countries (World Food Programme, 2020). In the first ones, 40% of losses are generated during post-harvest and processing, while in the latter more than 40% of losses occur during retail and consumer levels. In Colombia, an upper-middle-income country, 9.76 million tons of food (one-third of the produced) are lost or wasted annually (Broad Leib et al., 2021; World Bank, 2021). Although many farmers are poor in Colombia, 40% of their harvest is lost (1.93 million tons), which is equivalent to 19.8% of all food lost at post-harvest and storage levels; and 3.5% is lost in the transformation processes (FAO, 2021c; Rangel, 2016).

The WWF-UK study (2021) estimated that fruits and vegetables are the second largest group in losses, with 26% of the world's total production wasted, just after fish and seafood. Mattsson et al. (2018) studied three large retail stores in Sweden to identify " hot spot" products that contribute to most fruit and vegetable waste. They identified the top 20 items for 80% of the waste. Banana was among the top 10 most wasted products, with apple, grape, lettuce, pear, sweet pepper, and tomato**.** In Colombia, 62% of losses correspond to fruit and vegetable chains (FAO, 2021c). Banana is a major food product for the Colombian economy. Bananas are the most exported fresh fruit in the world and the third most important export crop in Colombia (Beekman et al., 2019). Colombia is the fifth largest banana exporter in the world (FAO, 2021b).

FAO has put in place two separate indices in target 12.3: the Food Loss Index (FLI) and the Food Waste Index (FWI) to have a better understanding and quantification of the food loss problem and also to measure the changes and evaluate the impact of policies and investments on the efficiency of the supply chain. The first index refers to losses from post-harvest or production up to (but not including) the retail level, while the second refers to food waste at the retail and consumer levels (FAO, 2021a).

Initial estimations of the FLI calculated in 2016 showed that 14% of food was lost on average worldwide from the time it was harvested until it arrived at the retailers, without including them. In Latin America and the Caribbean, the percentage was calculated at that time as 11.6% (FAO, 2021a). Recent estimates indicate, however, that global food losses from primary production, including everything left in the field and along the supply chain, could be as high as 20-25% (WWF-UK, 2021).

Some of the reasons why produce items are lost at the early stages of the supply chain include: products not meeting the quality expectations demanded by retailers and consumers, problems during transport, inadequate on-farm storage conditions, food prices relative to production costs, and difficult access to markets (Cattaneo et al., 2021; Liu, 2014; Rangel, 2016; Rolle et al., 2006; World Food Programme, 2020). Colombian farmers have faced many transportation problems. For example, there are delays, incorrect types of vehicles, inadequate control of vehicle temperature, poor road maintenance, and poor hygiene conditions. Those lead to the contamination and spoilage of the products (Mejía et al., 2021; Martínez et al., 2014). Furthermore, in Colombia, the fresh food supply chain, as in many emerging markets, has many fragmented and dispersed farmers supplying fresh produce to urban areas. Colombian farmers rely greatly on intermediaries to sell their produce, which, in addition to increasing prices for the final consumer, creates handling problems and leads to food losses (Mejia & Garcia-Diaz, 2018).

One strategy used to reduce intermediation and help small and medium farmers access larger markets is the development of regional food hubs (Mejía et al., 2021). Barham et al. (2012) defined a regional food hub as a "business or organization that actively manages the aggregation, distribution, and marketing of source-identified food products primarily from local and regional producers to strengthen their ability to satisfy wholesale, retail, and institutional demand." These authors also suggested that food hubs could reduce waste, for example, by maintaining products of consistent quality and by doing on-site composting and recycling. In addition, reducing the number of intermediaries could also shorten the amount of time fresh produce would be on the move and under constantly changing transport and storage conditions such as temperature and humidity. The latest is some of the most influential factors in the growth of micro-organisms that cause spoilage and damage in the produce (Hammond et al., 2015).

Regional food hubs were already built in Bogotá, D.C., the capital of Colombia, to connect farmers to shop owners through an information system. However, issues like poor internet connectivity and logistics caused the strategy to fail (Mejia & Garcia-Diaz, 2018). But regional food hubs have worked well in developed countries like Canada, the United States, and Italy, where food hubs were built to create a sustainable food ecosystem (Blay-Palmer et al., 2013; Koch & Hamm, 2015; Morganti & Gonzalez-Feliu, 2015). For a regional food hub to work and be key to reducing losses, basic technology and an efficient logistics system need to be synchronized.

Considering the above, the outcome of this project is to carry out a case study on the banana supply chain in the Antioquia corridor in Colombia. We want to understand the main causes of losses in the different stages of the banana supply chain and explore solutions to reduce the loss based on the problems identified.

Specifically, the methodology to address the aforementioned goal aims to: a) map the flows of banana in Colombia from farmers in Antioquia to key customers in Medellín and to provide a first order understanding on how these products are being transported, stored, transformed and consumed along the supply chain; b) perform a diagnosis of the banana supply chain in the aforementioned corridor and understand the gaps in the the different stages of the supply chain that are causing food loss; c) propose an actionable framework to reduce food loss by defining the right time and temperature conditions in transportation vehicles and storage sites; d) structure a high-performance, social inclusive, long-term sustainable, agile, flexible shock resistant and efficient supply chain for a Colombian transportation company that currently only transports construction material; d) propose a transportation business model by defining the right time and temperature conditions for the banana to be transported.

2. Literature Review

We organize this section with an overview of the literature and the challenges for the three main stages in food supply chains: 1) production, 2) post-harvest and transportation, and 3) retail and consumption, placing special emphasis on the issues that may eventually result in losses. These elements will be important to develop a methodology to tackle food loss, specifically at the Post-Harvest and transport stage. Although we focus on the post-harvest and transport stages in our research, how bananas are produced and handled at the farm might dictate how the banana should be handled during the remaining stages and supply chain processes.

2.1 Banana features and its supply chain characterization

Bananas are crucial in strengthening food security and reducing poverty levels in emerging economies (Akinyemi et al., 2017). They are a good energy source, provide several health benefits due to their high content of nutrients that help the cardiovascular and digestive systems, and might even reduce the risk of cancer (Harvard school of public health, 2018; Medical news today, 2020). Nevertheless, because of their physicochemical features (e.g., sugar content), they are vulnerable to fungal and bacterial attacks, and they are one of the “hot-spot” items contributing to most of the food waste (Blomme et al., 2017; Kuyu & Tola, 2018; Mattsson et al., 2018). For this reason, according to Akinyemi et al. (2017), they must be consumed within three weeks from harvest and require rapid distribution and marketing. However, special attention should be paid to storage and transportation conditions to avoid losses. For example, the optimal storage temperature and relative humidity for bananas are 13 - 14 degree Celsius and of 85% to 90%, respectively (Venkatachalam et al., 2018).

Multiple scholars and organizations worldwide have studied banana value chains and the factors constraining banana production and post-harvest handling. The factors affecting banana quality, physical features, and freshness are well documented. Banana supply chains can be thought to have three stages: 1) the production stage, 2) the post-harvest and transport stage, and 3) the retail stage. The factors affecting banana quality, texture, and freshness are well documented. At every stage, there are unique issues faced by the banana supply chain actors. To name a few, production stage issues could include diseases, poor agricultural practices, lack of technology access, and difficulty accessing markets. The issues during the post-harvest transport stage could include damage during transportation, improper packaging, and inadequate temperature management. Finally, issues during the retail stage could include deterioration and storage constraints (Lebersorger & Schneider, 2014).

2.2 Production Stage

Worldwide, product losses are more pronounced in the production stage, with 500 million tons lost every year. It corresponds to 32% of loss and waste along the value chain. Fruits and vegetables account for almost half of the total losses occurring during production, the other half being distributed among roots and tubers, cereals, milk, eggs, meat, oilseeds, and pulses, as shown in figure 2 (Gustavsson, 2011; Hegnsholt et al., 2018).

Pests and diseases greatly impact yields, productivity, and the lifetime of bananas. The most common diseases affecting bananas are caused mainly by two types of fungi (*Mycosphaerella fijiensis and Fusarium oxusporum*) and by several types of bacteria that cause significant yield losses in banana crops. Particularly in Colombia, diseases such as Moko and Pseudostem Wet Rot, caused mainly by bacteria of the *Ralstonia solanacearum* type, have generated losses of up to 100% in some areas (Blomme et al., 2017; Selvaraj et al., 2019).

The OECD-FAO Agricultural Outlook 2020-2029 report states that Banana Fusarium Wilt disease continues to threaten banana production worldwide. The new strain of the disease Tropical Race 4 (TR4) can affect a broader range of bananas; an eradication method for this new strain is not yet available (OECD & FAO, 2020). Colombia reported its first infection case of this strain in August 2019 (FAO, 2021b).

Of course, weather conditions also affect crop yield and production. Climate change, in particular, has shown negative effects on banana production, and worst-case scenarios are foreseen, especially in Colombia and Costa Rica. The rising temperatures and changes in rainfall are some factors that will cause problems in the regions of Antioquia, La Guajira, and Magdalena in Colombia. (Noleppa et al., 2020).

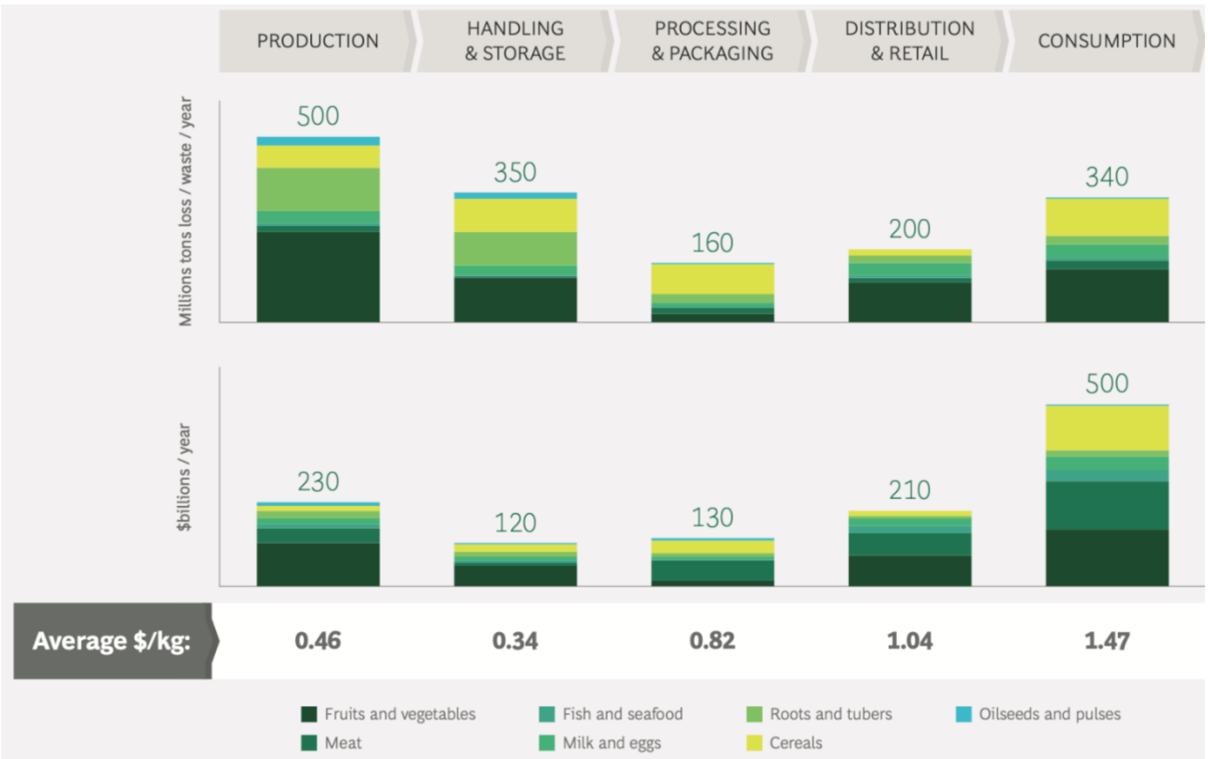


Figure 2. Food Loss and Waste Occur Across the Value Chain (Food and Agriculture Organization of the United Nations, Global Food Losses and Food Waste, 2011; FAOSTAT Database; BCG FLOW model as cited in Hegnsholt et al., 2018)

Due to uncertainties in weather conditions and the occurrence of pests or diseases, many larger producers tend to produce larger quantities than demand requires. If the result is a surplus, the overproduction may be wasted because selling it for processing or as animal feed is not as profitable as selling it to retailers (Gustavsson, 2011).

Lack of skilled labor, lack of technology, and difficulties in accessing markets are other relevant factors leading to food losses at the production stage. Farmers who are not well trained in harvesting techniques or suffer from poverty may harvest too early, sometimes to make money more quickly. These practices can result in losses caused by products not meeting the quality requested by retailers and the nutritional requirements needed for the products to be consumed (Gustavsson, 2011). Many producers in developing countries cannot afford the high costs necessary to finance workers (especially high-skilled ones) or production and harvesting equipment, often being forced to watch their crops rot in the field (WFP, 2020).

It is also important to study the effect of certifications on banana plantation efficiency and yield a better understanding of the source of banana loss and waste. Beekman et al. (2019) studied the Rainforest

Alliance (RA) certified and non-certified banana plantations in Magdalena, Colombia, to observe the differences in cultivation practices between the two groups. While they conclude that the certified plantations tend to have a higher banana yield than non-certified plantations, they acknowledge the potential selection bias in the study and call for further research to validate their results.

Ostertag et al. (2014) revealed that Fairtrade certification of bananas produced in the Magdalena department and the Urabá region in Colombia led to an increased standard of living for smallholders, lower banana production costs, improved market access, etc. However, the authors do not directly address certifications' impact on banana losses (Ostertag et al., 2014). So far, the research focus has been on the impact of certifications on banana yield, worker conditions, farm management, and production costs, among other aspects. However, whether the certified plantations differ from the non-certified plantations in terms of the impact that banana handling and other logistics operations would have at the plantation level on the eventual banana loss has not been studied yet.

2.3 Post-Harvest transport Stage

Guo et al. (2020) define four stages for banana post-harvest operations. Banana picking, the first operation in post-harvesting, refers to detaching banana bunches from the banana stem. Then, the next stage after the production stage is post-harvest transport. In-center transportation refers to the modes by which the picked bananas are transported from the orchards to the collection centers located near the orchards. Outbound transportation refers to the movement of bananas from collection centers near the orchards to commercial processing workshops. Banana de-handing is a commercial processing operation between banana picking, transportation, cleaning, and packaging post-harvesting.

Human handling of bananas in the banana post-harvest stage leads to loss due to incorrect handling practices. Thus, innovating automation and intelligence in banana post-harvest operations are important (Guo et al., 2020). Some plantations have picking machines able to identify the maturity level of the bananas, for which machine learning algorithms such as support vector machines and AdaBoost algorithms can be used (Guo et al., 2020).

The application of convolutional neural networks for banana maturity detection and optical sensing system for banana ripening detection have been discussed by various authors (Li et al., 1997; Rajkumar et al., 2012, 2015; Ramadhan et al., 2020). Also, banana picking system design is widely studied worldwide (Guo et al., 2020; Huang et al., 2021; Wang et al., 2013). The scholarly research on banana-picking systems has focused on designing and developing autonomous equipment. There is a gap in the existing knowledge regarding using these machines in developing countries like Antioquia in Colombia. Challenges associated with procurement and usage and the resulting reduction in banana loss attributed to this equipment have not been analyzed entirely.

Once bananas are harvested, certain chemicals are applied to extend the bananas' lifetime and promote the fruit ripening process. Bananas are classified as climacteric fruits. Climacteric fruits were initially described as those increasing their respiration dramatically and, therefore, the production of CO2 during ripening (Biale, 1964, as cited in Paul et al., 2012). They continue to ripen even after being removed from the plant (Goldy, 2019). This fact happens because, during the ripening process, they produce high levels of ethylene, which can trigger the initiation of ripening (Maduwanthi & Marapana, 2019; Paul et al., 2012).

The ripening process of bananas after harvesting is very important, not only because of the characteristics associated with product quality, such as taste, sugar and acid content, aroma, texture, and appearance, depending on ripening, but also because over-ripening can lead to losses (Maduwanthi and Marapana, 2019). For this reason, it is very important to control the ethylene content during the storage and transportation stages. In a study conducted in Nigeria, the authors found that 56.3% of the overripe bananas were discarded, 34.2% were sold at lower prices, 8.5% were given away as gifts, and 1% was used for family consumption (Akinyemi et al., 2017).

Formulations such as post-harvest banana dip technology can help delay the yellow coloration process in bananas, maintain banana firmness, minimize the losses, and extend the shelf life of bananas (Baez-Sañudo et al., 2009; Venkatachalam et al., 2018). However, the existing chemicals and available technologies for fruit preservation are not utilized due to practical difficulties, high cost, and non-availability (Venkatachalam et al., 2018). In the Colombian banana supply chain, the availability and affordability of such chemicals are not well known.

Banana market structure, production season, and transportation methods differ widely. Akinyemi et al. (2017) surveyed 120 participants using a multistage sampling technique and examined the market structure and performance of the banana supply chain in Nigeria. The paper sheds light on the diverse channels through which the farmers sell bananas in Nigeria, including intermediaries, direct-to-market structures, and roadside shops near the farm. While the authors point out that 85% of the respondents in their research mentioned that delays in transportation, poor road infrastructure, high transportation cost, and inadequate transportation facilities are major constraints for banana marketing, they did not focus on banana loss across the supply chain. Kuyu and Tola (2018) focused on banana loss due to fungal pathogens resulting from the improper handling of bananas in southwest Ethiopia. The results highlight physical injury to bananas, lack of sanitation and improper temperature management and packaging, and transportation problems as main drivers of banana spoilage. Similar results have been highlighted by Guo et al. (2020). Authors from the last reference mentioned that mechanical damages would lead to temporary storage and transportation time of bananas and thus reduce the economic value of bananas. They point out a study in Jamaica that shows that vibrations during transportation can cause mechanical damage to bananas.

The lack of transportation is sometimes an issue, leading to banana loss. For example, in Southwest Ethiopia, one study indicates that 52% of the respondents used a truck, 38% used their backs, and 10% used an animal to carry the bananas (Kuyu & Tola, 2018). In Nigeria, the banana production centers are highly fragmented and small-scale, and the infrastructure to transport bananas is not well developed (Akinyemi et al., 2017). Such inadequate transportation options also exist in Bangladesh (Mahfuzur Rahman et al., 2020). The authors studied 30 farmers and 30 traders in the Narsingdi district of Bangladesh, selected using convenience sampling. A survey was administered to collect the primary data. Eighty percent of the respondents indicated inadequate good transport, and 50% indicated inadequate storage facilities and packaging (Mahfuzur Rahman et al., 2020).

Furthermore, even if a good transportation option is available, how bananas are packed and transported can also affect banana loss. Eighty-five percent of the respondents transported bananas using a wooden box in Jimma market town, southwest Ethiopia and the remaining 15% were transported using a basket, plastic bin, and sack (Kuyu & Tola, 2018). These wooden boxes were too big and rough to protect bananas, and great mechanical damage was observed (Kuyu & Tola, 2018).

Few transporters overload the banana bunches in the vehicle to minimize the transportation cost, but unfortunately, this leads to greater damage and deterioration of banana quality (Kuyu & Tola, 2018). L-shaped banana frames can keep banana bunches upright to minimize mechanical damage (Guo et al., 2020). The mechanical damage to bananas during transportation makes bananas susceptible to pathogen attacks, and research shows that around 20-25% of bananas are wasted due to fungus attacks post-harvesting (Kuyu & Tola, 2018). It is worthwhile to study the accountability of banana transporters to such damages and the resulting cost-margin dynamics.

Another aspect that is not related to banana handling practices but is crucial to combat banana loss is credit access. Credit facilities could play an important role in the banana loss by providing monetary support at the right time to procure the equipment and build the necessary infrastructure. Unfortunately, research shows that 59% of farmers had the challenge of access to credit facilities in Nigeria (Akinyemi et al., 2017), and 68% indicated lack of access to capital as a main issue in the banana supply chain in Bangladesh (Mahfuzur Rahman et al., 2020).

According to Chaboud & Moustier (2021), food loss and waste (FLW) could indicate the supply chain's economic efficiency. A study conducted in Cali, Colombia, intended to identify the role of diverse distribution channels in reducing food loss and waste, found that the average FLW across the tomato supply chain in that city is 15-20%, with 13% located at the farm level. They also found that the farmers who sell to multiple stakeholders (supermarket and non-supermarket) in the supply chain are likely to witness lower FLW. Finally, they concluded that to effectively combat Food Loss and Waste (FLW), diverse distribution channels are the need of the hour (Chaboud & Moustier, 2021). For the above reasons, we find it important to examine the food loss at the farm level for Colombian bananas and to study the possibilities of diverse distribution channels and the use of regional food hubs in Colombia.

2.4 Retail Stage

Banana damage proportion seems to differ based on the supply chain actor that also sells the banana. The maximum damage was observed in the banana sample taken from the retail shop at 56%, while the least damage was observed in the bananas sold by farmers at 16% (Kuyu & Tola, 2018). This finding signifies and gives rise to the hypothesis that farmers are better at handling the product, and thus, educating retailers might bring down the damage level. Another hypothesis is that the banana sold by retailers might have undergone multiple transportation legs before reaching the retailer, whereas the farmers selling the banana directly in the market has not. Thus, the resulting damage at retail shops is disproportionately huge. Therefore, we find it relevant to investigate the use of regional food hubs mentioned by various authors (Koch & Hamm, 2015; Mejia & Garcia-Diaz, 2018; Morganti & Gonzalez-Feliu, 2015). Further, we aim to apply this knowledge in the Colombian banana supply chain because the existence of food hubs will reduce the number of transportation legs.

There has been extensive research on food waste at retail stores. Damaged packaging, inappropriate storage conditions, and demand uncertainty are the major causes of food loss and food waste at the retail level (Buzby & Hyman, 2012). The major source of waste in fruit and vegetables are phenomena of deterioration (Lebersorger & Schneider, 2014). A study of 600 Austrian retail outlets found that 67% of the food waste is due to the developed flaws in the product and deterioration. Those appear mainly due to the storage and transportation conditions at the retail levant across the supply chain from farm to retail stores (Lebersorger & Schneider, 2014). Thus, this result re-emphasizes the need to devise strategies for banana transportation.

While the regression model developed by Lebersorger and Schneider to explain the food loss and waste variation with explanatory variables such as sales volume, number of purchases, and sales area at the retail store offered insights into the food waste, much of the variance remained unexplained. Hence, the food loss rates must be influenced by the supply chain's logistics, behavioral, and situation-related aspects (Lebersorger & Schneider, 2014).

The organization of the supply process of retailers may influence waste production and, to truly understand the impact of logistic actions and food deterioration on the profit of the companies involved, modeling the interactions among supply chain parties, including how they reward each other, is necessary (Beullens & Ghiami, 2021). Beullens and Ghiami (2021) extended the research on waste at a retail store by interconnecting the entire supply chain actors with the retail store. They developed easy-to-apply operations research models with net present value to increase understanding of the links among operational conditions, profit-maximizing decisions, and waste production.

Collaboration can reduce in reduced food waste and better profit for stakeholders. Still, the dominant partner in the supply chain in terms of profit margin is likely not to be motivated to reduce food loss (Beullens & Ghiami, 2021). For example, suppliers delivering to large retailers will be asked to help prevent waste at the retailer. Smaller retailers delivered by large suppliers, however, may have to tackle waste prevention themselves because they have higher margins, are the dominating partner in the supply chain, and may lack the motivation for waste reduction. This finding implies that a system dynamics approach that integrates motivation and personal profit-maximizing decisions is a sine qua non to understand the banana loss in the supply chain. We see this as one of the major gaps in the literature.

2.5 Network Design

Food supply chains constantly evolve and are complex due to the perishable nature of the products, multi-product compatibility issues, and the time-sensitive nature of delivery (Nguyen et al., 2019). According to Nguyen et al. (2019), there are three design problems for delivery of any products: network design, distribution, and vehicle routing problems (VRP). Food network design has challenges, such as limited shelf life of products, the need for special handling during transportation, and many supply chain actors both upstream and downstream.

While VRPs have been successful since their introduction in 1959, research on transporting perishable products using VRP is more recent (Nguyen et al., 2019). The authors list recent works in VRP for perishable products such as Milk and dairy, dry/fresh products and frozen products, and multicommodity perishable food distribution (Tarantilis and Kiranoudis (2001), Ambrosino and Sciomachen (2007) and Song and Ko (2016) as cited in Nguyen et al., 2019). The Vehicle Routing Problem with Time Windows is suitable for the transportation of perishable products and has been studied by various authors (Belenguer et al., 2005; Hsu et al. (2007); Osvald and Stirn (2008); Li et al. (2015); Mahdavi et al. (2017) as cited in Nguyen et al., 2019).

Supply chain network design also is important in reducing food loss and has been studied by multiple scholars (Accorsi et al., 2016; Leat et al., 2013; Yu and Nagurney, 2013; Tsao, 2013; de Keizer et al., 2015 as cited in Nguyen et al., 2019). Distribution problems are also common for shipping decisions with objectives such as maximizing demand fulfillment, constraining the time product stays in inventory, and minimizing the cumulative deviation of actual deliveries to the facilities (Viergutz and Knust, 2014;

Nguyen et al., 2014; Lamsal et al., 2016 as cited in Nguyen et al., 2019). Nguyen et al. underscore network design's importance in reducing food loss.

2.6 Gaps and Contributions

In summary, the banana supply chain has been studied by various authors focusing on different issues in the value chain across geographies. The focus of the researchers has included fungal attacks, education and training of the farmers, post-harvest dip solutions to extend shelf life, transportation problems, use of technology and machine learning in post-harvest operations, retail waste, and differentiation between certified and non-certified banana plantations, to name a few. Also, most of the studies were focused only on a few aspects of the supply chain but did not cover the entire supply chain from a food loss perspective. Further, there have been studies by various authors about retail food waste. However, the complex interaction among the value chain actors in a system is not studied yet, at least in the Colombian banana supply chain context. Finally, the end-to-end mapping of the banana supply chain and the issues faced by supply chain actors, especially in the aftermath of COVID-19, has not been documented yet, particularly in emerging markets.

We thus aim to address this gap by mapping the banana supply chain from different locations in Antioquia to Medellín to provide a high-level overview of the value chain system and find the losses in each stage. To achieve the gap understanding, we will study the supply chain issues from a transportation perspective and apply the best practices in banana handling by analyzing the feasibility of those practices in the Colombian context.

A few of the research questions we want to address are: 1) How does the banana supply chain work from specific places in Antioquia to Medellín regarding the flow of goods, information, and resources? Who are the various supply chain actors? 2) What factors contribute to the banana loss variability in each of the supply chain stages? The factors could include but are not limited to cultivation practices, the type of transportation used, and the kind of retail outlets where bananas are sold. 3) How does the interaction of supply chain actors affect banana loss? 5) What are the issues in the transportation of bananas? Are transporters accountable for banana loss? Is there a difference in banana loss among the players? 6) Can storage facilities mitigate the food loss problem? 7) What are the diverse channels through which banana is sold? 8) How can innovative transportation business models bring down food loss? We will address these questions by analyzing semi-structured interviews and quantitative models.

3. Methodology

Originally, the study aimed to determine banana losses in the supply chain from Urabá to Medellín. Still, after analyzing information obtained through primary and secondary sources, we decided to focus our research on the area of Jardín, another municipality in the department of Antioquia, located 134 km southwest of Medellín. This decision took place because production in Urabá is almost entirely destined for export. The production, harvesting, and transport techniques use high technology that minimizes losses. Jardín, on the other hand, only produces bananas for the local market. While Urabá produces the Cavendish variety, Jardín produces the Gros Michel, also known locally as "criollo."

Regarding the distribution and storage of bananas before reaching the shops, the target area was the surrounding area of Jardín and the city of Medellín. Medellín was selected due to the proximity to the selected farms around Jardín's area and the banana distribution networks already in place. Due to the difficulty of addressing the whole chain, we focused our intervention on the specific problems of the post-harvest transport stage and did not explore the problems that cause farm-level losses.

Specifically, our research aimed to map the flows in the banana supply chain, understand the interactions between supply chain actors, and how their actions influence food loss. We sought to understand the transportation issues in the banana supply chain and evaluate a possible innovative and sustainable transportation business model to reduce banana loss.

3.1 Study Design

To understand the main problems in banana transportation and distribution that cause losses up to retail and how to address these problems, we designed our study as follows: The first part of the study involved primary and secondary data collection. The second part of the study consisted of evaluating the current situation through the analysis of the collected data and identifying the main problems causing food loss during the transportation and storage stages of the products along the supply chain. The third part consisted of conducting a simulation to predict the banana loss and tackle the problems at the root. Finally, based on the analysis and simulation results, we proposed solutions to build a business model for a Colombian transportation company willing to address the food loss issue. This company plans on using its fleets and provide best practices for farmers, transporters, warehouse service providers, and retailers to target food loss during the transport and storage of the products.

3.2 Data Collection

We first gathered both primary and secondary data. We analyzed the secondary data on production volumes, transport, and storage capacities from official entities such as the Ministry of Agriculture and AUGURA, the Colombian banana growers' association. We conducted semi-structured interviews with various stakeholders along the banana supply chain, such as farmers, wholesalers, retailers, transporters, and end consumers. Those interviews aimed to obtain primary data on production quantities, transport and storage capacities, demand, the choice of key partners, the main causes of product losses, the constraints, the pain points, and the stakeholders' expectations.

We chose to conduct semi-structured interviews for the following reasons. Firstly, we tried to understand the issues in the banana supply chain; hence, semi-structured interviews allowed us to be more open and follow up on the answers given by these stakeholders. Surveys would have been more rigid. Secondly, the surveys might have subconsciously biased these stakeholders toward the options in the survey. Thirdly, semi-structured interviews offer a more personalized feel and thus can help us get more insights into the state of the supply chain than a survey.

Four interview questionnaires were developed and tailored to the following stakeholders: transporters, wholesalers, retailers, and consumers. The interview questionnaires served to get information from the mentioned stakeholders as follows: transporters – type and capacity of vehicles available, average truck journey, and preservation methods used during transport; wholesalers and cooperatives - production volumes, varieties produced and sold by the farmers, preferred distribution channels, sales to the different distribution channels and production lost; retailers – supply chain strategy, product sales prices, storage conditions, information on demand planning, and product losses; end consumers – buying preferences in terms of varieties and ripening degree, banana consumption, and banana waste.

3.3 Data analysis and output

The data analysis consisted of two parts: 1) Analyzing the secondary data to get a big-picture view of the production and movements between Urabá and Jardín, and Medellín 2) Analyzing the primary data to understand the issues, pain points, and rationale for decisions such as transport mode selection, transport partner selection, etc. of the stakeholders.

These data were used to map the flows of bananas from the Urabá and Jardín to Medellín. With the help of primary data, we got estimates of the Food Loss (FL) as banana passes through each stage in the supply chain. We pinpointed the root causes of this FL and analyzed the data to gain a broader perspective on the issues and needs of the banana supply chain actors.

The simulation was instrumental in developing a business model that we will suggest to an identified Colombian transport company. This company is willing to use the additional vehicles or the returning vehicles from the back-haul to secure the transport of bananas.

We tried to build a logistic regression model to predict whether there is banana loss with independent variables such as banana ripeness preference, purchase frequency, purchase location, and factors influencing purchase location. However, the model did not yield a good prediction.

We used the data we obtained from the interviews with retailers and consumers to determine the factors leading to banana loss and use them to create a simulator to predict banana loss. We selected several factors we used to do the simulation in stages: farms, farms to DC transit, storage at DC, DC to Plaza Mayorista transit, and Storage at Plaza Mayorista. Some examples of those factors are Temperature, time since harvest, wait times, mechanical damage due to overloading, accidents or road blockage, and loading and unloading.

In summary, the input to our study is the primary and secondary data collected from various stakeholders and internal company data. The output is the Jardín-Medellín banana supply chain flow-map and a set of best practices for the supply chain actors, particularly for the identified transport company.

4. Results

The results from the information gathered from the different primary and secondary sources are presented below. The secondary information consists mainly of data from a study by the Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ), mainly due to the relevance and actuality of the data. The primary information consists of interviews with wholesalers from Plaza Mayorista de Medellín, retailers present in Medellín, a transportation company transporting bananas and other fruits between to Medellín, and end consumers living in Medellín.

4.1 Secondary data

According to the GIZ report (2021), over 1000 varieties of bananas are produced in the world, and ten different banana varieties are produced in Colombia. Gros Michel variety is majorly used for domestic consumption. Harton, Dominico (Dominican), Banana Comino (Cumin), Banana Guineo, and Murrapo are other varieties used for domestic consumption. The Cavendish variety is cultivated for export purposes. Around 47% of the banana produced in Colombia is of the Cavendish variety. This variety is resistant to Panama disease, has longevity during transport, gives high yields, and is preferred by the international market. Gran Enano, Williams, and Valery are the subgroups of the Cavendish variety. The Gros Michel Variety (Criollo) is grown in Valle del Cauca, Quindio, Santander, Antioquia, Cundinamarca, and Huila. This variety is also produced in mountainous terrain linked to coffee production areas, as per the report by GIZ.

Banana consumption in Colombia is 4 kilos per person per year. Out of the 32 departments in Colombia, banana is grown in 22 departments. Colombia produces 2.2 million metric tons of bananas annually, and 90% of the total production is exported, as indicated in Figure 3.

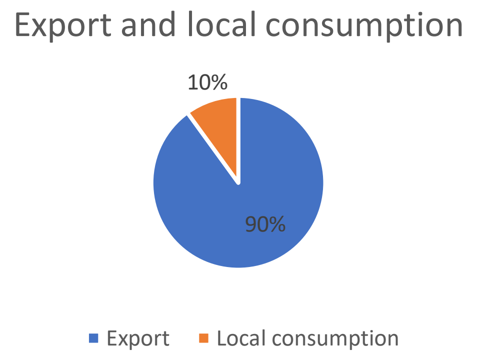


Figure 3. Banana Production, export, and local consumption quantity as of 2019 (GIZ, 2021).

AUGURA (Association of Colombian Banana Growers) is involved in 73% of the bananas exported. The rest 27% is managed by another organization called ASBAMA (Association of Banana Growers in Magdalena and La Guajira).

The top three departments in the number of banana producers are Magdalena, with 781 producers, Guajira, with 388 producers and Antioquia, with 344 producers. Figure 4 details the location of these departments along with the number of departments. Interestingly, the 344 producers in Antioquia own roughly 37,000 hectares of banana plantations, as detailed in Figure 5, accounting for more than 50% of Colombia's total banana production area. Thus, the Antioquia region is dominated by large producers. The proportion of producers who own >22 hectares is 38% in Antioquia, 18% in Magdalena, and 8% in Guajira, as explained in Table 1.

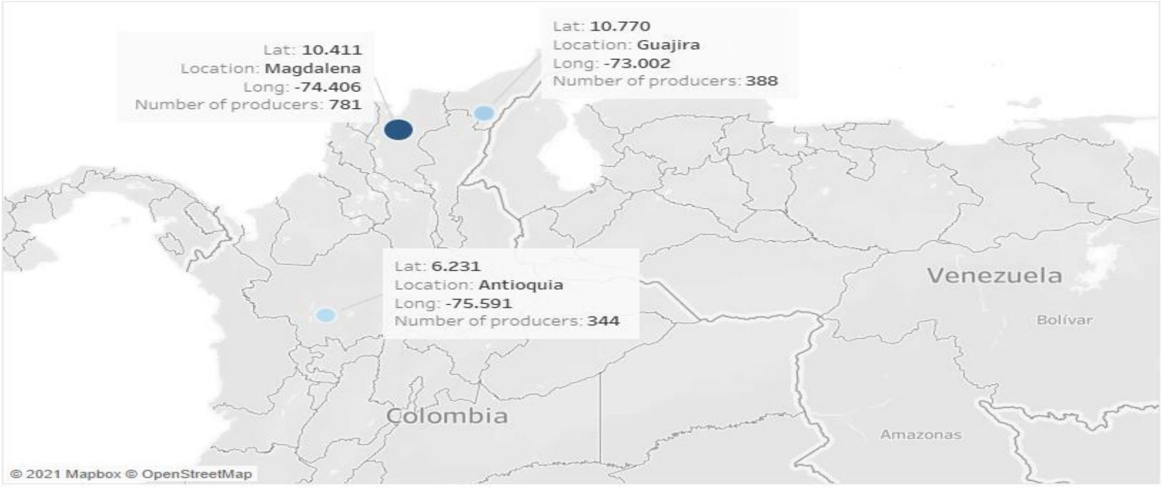


Figure 4. Total Number of Banana Producers by the department in Colombia

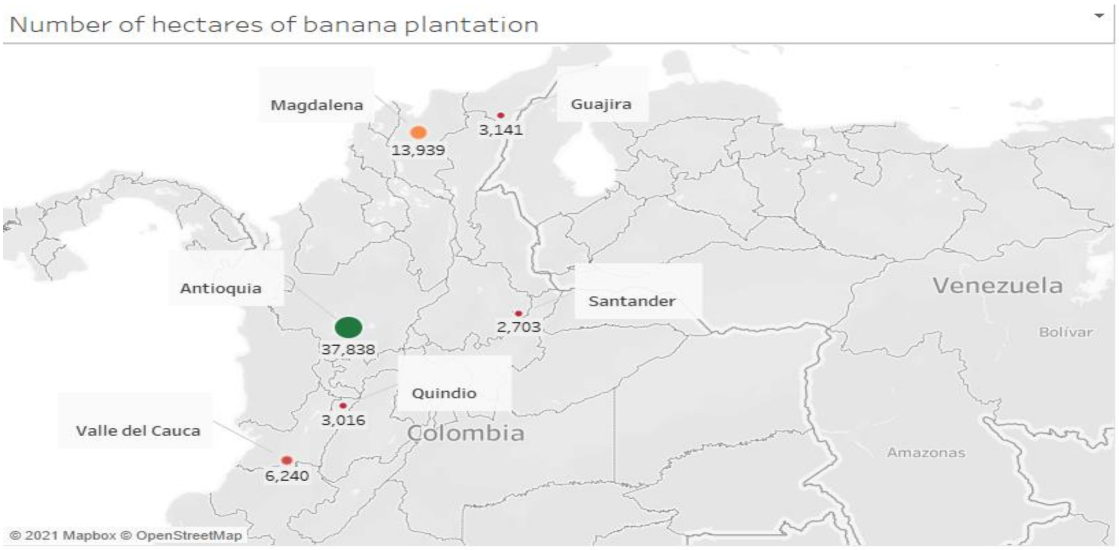


Figure 5. Number of Hectares of Banana Production (GIZ, 2021).

Table 1. Distribution of Producer Size in Colombian Departments (GIZ, 2021)

	Count			Percentage		
Producer size	**Antioquia**	**Magdalena**	**Guajira**	**Antioquia**	**Magdalena**	**Guajira**
Small (<22 Ha)	215	642	360	63%	82%	93%
Medium (22-80 Ha)	96	117	22	28%	15%	6%
Large (>80 Ha)	33	22	6	10%	3%	2%
Total	344	781	388	100%	100%	100%

As indicated in figure 6, Antioquia is Colombia's largest banana-producing region, with 1.2 million metric tons of banana production, accounting for more than 50% of the national banana production. Magdalena comes next with 423,538 metric tons, followed by Guajira with 122,587. However, table 2 shows that regarding the number of hectares of banana plantation, the department Valle del Cauca takes third place, replacing Guajira. Guajira cultivates in half the area that Valle del Cauca cultivates but produces 34,000 tons more bananas.

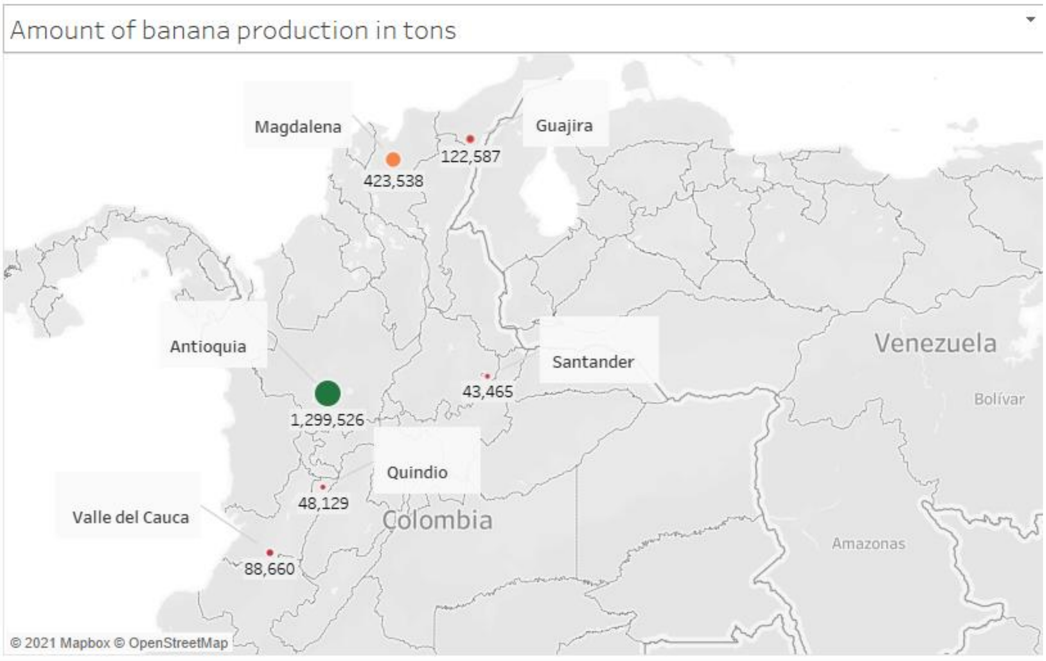


Figure 6. Amount of banana production (GIZ, 2021).

Table 2 indicates that although bananas are grown in 22 departments, Antioquia, Magdalena, Guajira, Valla del Cauca, Quindio, and Santander produce 2,025,905 tons of tons of bananas, accounting for 88.7% of the banana production in Colombia. Antioquia alone accounts for 56.9% of the national banana production. Interestingly, although the banana plantation area in Guajira is only 100 hectares more than that of Quindio, the total banana production is 2.54 times that of Quindio. The productivity of banana plantations in Guajira is the highest in Colombia. This indicator shows that there could be learnings from the Guajira region that can be applied to banana production in other departments in Colombia.

Table 2. Banana Productivity (GIZ, 2021)

Location	Production area (in ha)	Production (in tons)	Productivity (ton/ha/yr)
Antioquia	37838	1299526	34.34
Magdalena	13939	423538	30.39
Guajira	3141	122587	39.03
Valle del Cauca	6240	88660	14.21
Quindio	3016	48129	15.96
Santander	2703	43465	16.08

The GIZ report indicates that 1,871 boxes of banana per hectare per year are produced in Antioquia. This value informs that a box of bananas weighs 18.36 kg (including the weight of the box) because Antioquia produces 1.2 million tons of bananas and 37,838 hectares of a banana plantation. The report also indicates that 7.8 USD is the cost of producing one box of bananas, of which 2.3 USD is a variable cost. Forty percent of the variable cost goes to transportation. Thus, we could estimate the total addressable market size of Colombia's domestic banana transportation industry. While estimating the total addressable market, we assumed that the production cost is the same across Colombia's departments. Focusing on 88% of the total production area, 10.15 million USD is the maximum revenue a transportation service provider can expect to earn as of 2019. This number has been validated by the primary data we collected with CB. CB pays 200,000 Colombian Pesos (51.46 USD) to transport one ton of bananas. Given that Colombian domestic consumption is 200,000 tons, this works out to 10.29 million USD. Thus, the estimation in table 3 holds for 2021, although the cost details are for 2019.

Table 3. Total Addressable Market Size of the Domestic Banana Transportation

Location	Production (in tons)	Production Cost Per Kg in USD	Variable Production Cost Per kg in USD	Total Variable Cost (VC) in million USD	Total VC for domestic consumption in million USD *	Total variable cost for domestic transport in million USD **
Antioquia	1299526	0.42	0.13	162.83	16.28	6.51
Magdalena	423538	0.42	0.13	53.07	5.31	2.12
Guajira	122587	0.42	0.13	15.36	1.54	0.61
Valle del Cauca	88660	0.42	0.13	11.11	1.11	0.44
Quindio	48129	0.42	0.13	6.03	0.60	0.24
Santander	43465	0.42	0.13	5.45	0.54	0.22
Total Addressable Market value in million USD for the domestic banana transportation						**10.15**
* Total VC for domestic consumption = 10% of the Total VC						
** Total variable cost for domestic transport in million USD = 40% of Total VC for domestic consumption						

Based on the analysis, we have the following interpretations and inferences:

1) Six departments in Colombia account for 88% of the total banana production in Colombia. Antioquia is the largest department, accounting for more than 50% of banana production. The Urabá region, located in Antioquia, is the largest banana-producing subregion. The export-reject bananas are used for domestic consumption, estimated at 10% of the banana production in Urabá.
2) In Urabá, the Cavendish variety of bananas is grown; in other parts of Antioquia and other departments, Gros Michel Variety is grown. Gros Michel variety is the preferred banana for domestic consumption as it tastes better for the local population than that of export rejected Cavendish variety from Urabá. Thus, Urabá may not be the best region to target for the domestic consumption transportation business, but Jardin in Antioquia and other departments might be.
3) The total domestic banana transportation market value is 10 million USD per year.
4) The banana transportation for the nano stores might be less sophisticated, transporting bananas like loose cargo. Hence, the proportion of banana loss could be greater for the supermarkets, for which the transportation happens in boxes.
5) The Guajira region's banana productivity is so high that there could be learnings from there that we can apply to the other regions in Colombia.
6) The major reasons for the banana loss are mechanical damage during harvest, damage to the crown due to improper banana cleaning, and damage due to the insect.

4.2 Primary data

4.2.1 Supply chain map in the export market

Originally, the study aimed to determine banana losses in the supply chain from Urabá to Medellín; we collected primary data through semi-structured interviews with UNIBAN. The information obtained through these interviews was crucial, as it helped us to understand the details of the flow of bananas for export. It also showed us that, due to the high-quality requirements expected by overseas buyers and the production and handling techniques used to meet these requirements, there is a higher percentage loss in the supply chain of bananas for local consumption.

UNIBAN and BANACOL are the two largest banana exporting companies in the Urabá region of Antioquia. Banana producers are associated with AUGURA, and the production managed through these companies is exported. UNIBAN is a limited company and not a cooperative. Banana producers are associated with AUGURA; each producer sells through UNIBAN or BANACOL.

Almost all producers in Antioquia are part of AUGURA. There are three distinct banana marketing channels in Urabá. Each producer sells their banana through UNIBAN or BANACOL, but not both. If the product is of very bad quality, the producers sell the banana in the market. Figure 7 illustrates the banana marketing channels in Urabá.

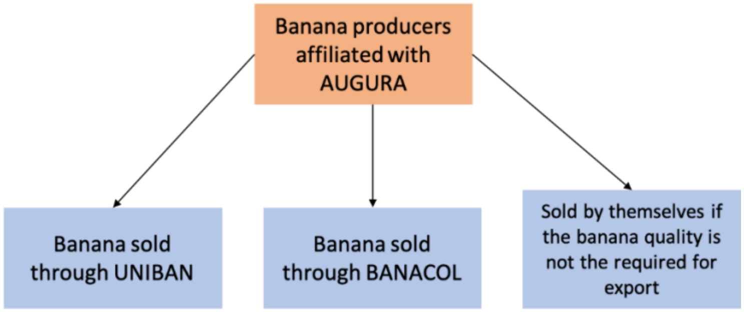


Figure 7. Banana Marketing Channels in Urabá. Data derived from the semi-structured interview with UNIBAN

The primary data collected through UNIBAN interviews offered insights into the banana supply chain flow in Urabá. The bananas, which are of Cavendish variety, are produced year around. They cannot be stored for long periods; once it completes its development cycle, it must be used or lost. The main challenge is the need to manage the marketing of these bananas to avoid loss with all the mechanisms to protect their quality and life so that it arrives in good condition at the shelves of the supermarkets and end consumers daily. Every day, the banana is cut and loaded into the trucks at the farms. The ripening process starts as soon as the banana is harvested and cannot be reversed. Although refrigeration of bananas is possible, it can only be used for 1 or 2 weeks, and storing the bananas for a long time is impossible. According to one of our interviewees, 15 to 20% of the bananas cannot be exported, and only 50% is used for domestic consumption. The other 50% is used as fertilizer or is wasted.

There are logistical, equipment, transport, pests, diseases, and climatic problems. All these affect the condition of the fruit and its quality. Bananas are produced and packed for the company daily from Monday to Friday. There may be delays due to the unavailability of vehicles for transport or because containers are unavailable, but the effect on losses is negligible. Losses may occur due to vehicle accidents or mishandling of loading and unloading, but these are not common. Bananas are distributed using contract vehicles, and UNIBAN does not own vehicles. Refrigerated transport or transport exclusively for food products is used to avoid cross-contamination. Bananas handling practices differ based on the destination market, so bananas are packed in boxes for large retail chains and other institutional markets. Bananas are stacked in a truck for less specialized markets as loose cargo. This fact indicates the possibility of more banana loss in the nano store domestic market. UNIBAN does not handle the nano store market, but other traders in Colombia do.

At the farm, the plants are tied with red, blue, and yellow plastic, depending on the number of weeks each plant has. Control of the fruit is carried out over time. Each export destination requires the harvest to take place at different periods. With this color coding at the farm, the producer knows when to harvest and deliver the banana. Workers take Bananas to the collection centers on the farm as soon as they are harvested. The fruit is checked, sorted by color according to the weeks and ripening degree at the collection centers, and checked for bruises. Any bruises that led to rejection and rejected products can be used to serve the domestic market (excluding Atlantic coast), Atlantic coast or as a fertilizer. Around 4-5% of the banana intended for the domestic market is sold along the Atlantic coast. These are mostly of very bad quality, and the traders sell them there because the low-income population is a majority along the Atlantic coast. Another export selection is made of bananas that pass the bruise test. The banana bunches are cut, and the smallest fruit is kept for the domestic market. The bananas that pass the bunch cut stage are taken to the ports where the third selection happens. The bananas that do not meet the quality requirement in the port are diverted to the domestic market. Figure 8 illustrates the supply chain flow of bananas produced in Antioquia.

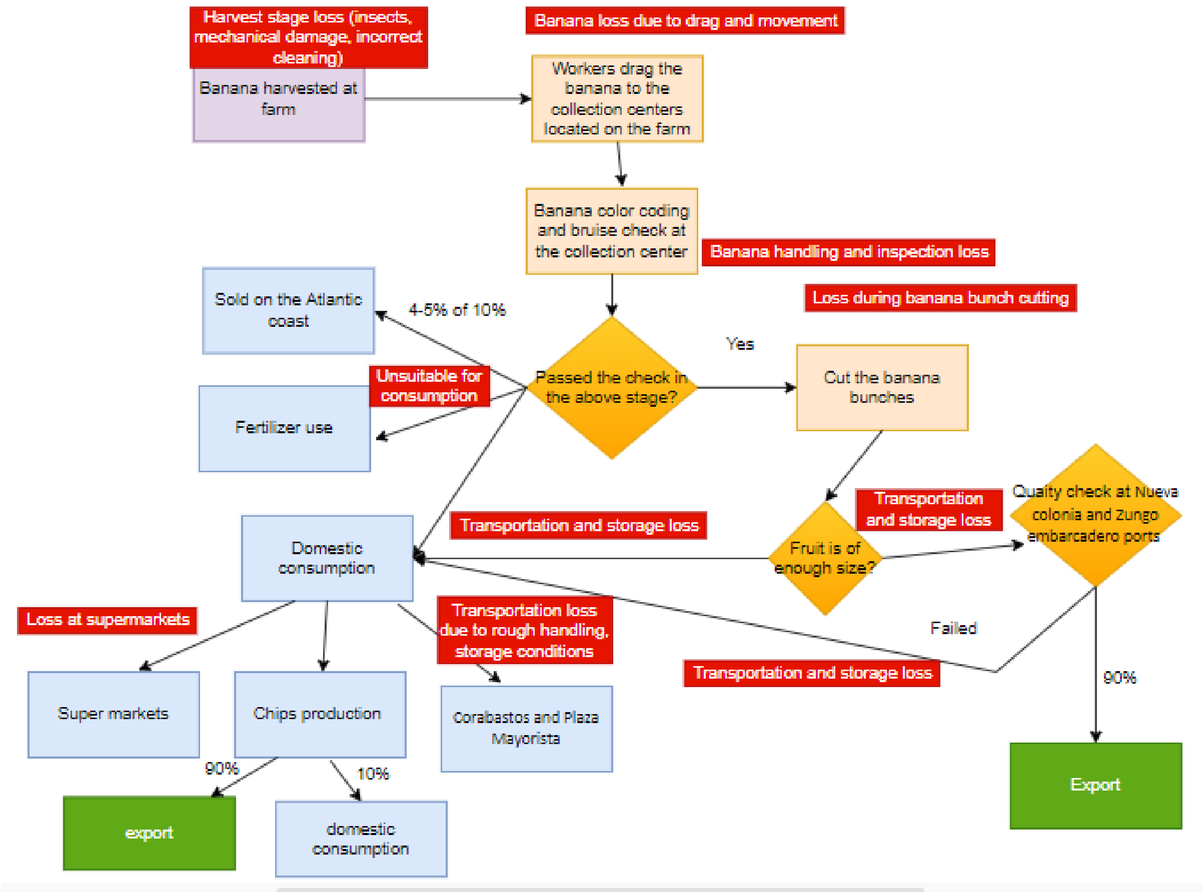


Figure 8. Banana supply chain flow in Antioquia. Data derived from the semi-structured interview with UNIBAN

4.2.2 Supply chain map in the domestic market

The domestic banana market consists majorly of three avenues: (1) The bananas sold through large retail chains; (2) Bananas sold in markets such as Corabastos and Plaza Mayorista, in the case of Medellín; (3) Chips produced through the company Turbana owned by UNIBAN. Of the Turbana chips production, 90% is exported, and 10% is used for domestic markets.

We conducted primary interviews with wholesalers in Plaza Mayorista in Medellin to understand the banana supply chain from the perspective of domestic retailers. They typically procure bananas from three organizations: 1) CB, a distribution company in Antioquia; 2) CS, a cooperative founded in 1994 by the small farmers in Southwest Antioquia; and 3) Gajos, a company involved in the Wholesale trade of food products.

All the banana of Plaza Mayorista of Medellín comes from the Southwest of Antioquia, including the towns of Jardin (CB) and Andes (CS). The banana variety produced in these regions is called Gros Michel but is widely known as "Criollo." The Criollo banana is sweeter and less white than the rejected banana Cavendish of exportation sort from Urabá (UNIBAN). Due to the bad quality of the rejected banana exportation, banana from UNIBAN or BANACOL is not very popular among local consumers. Eventually, some boxes of this kind arrive at Plaza Mayorista and are sold due to the lower price of it. It is common to find that the truck driver who brought other products, such as plantain, also brought a bad quality banana from UNIBAN and sold it to have extra money. However, this does not mean a major business for them, which indicates that the domestic market is not served by the Urabá region but in other regions where the native Gros Michel (Criollo) variety is grown.

We also conducted primary interviews with CB and CS, offering insights into Colombia's dynamic banana-growing landscape. To map the banana supply chain for domestic demand and find the losses in each stage, we focus our results on the interviews conducted with CB and Soycampo, from which we obtained more information.

When the CB business was started 17 years ago, Urabá produced Gros Michel Variety as well. Still, this variety is prone to Fusarium and other pests resistant to the Cavendish variety. Hence, Cavendish started to be grown for export in Urabá. These two varieties completely differ in sensory characteristics, such as taste and texture. If the Gros Michel seed is sown in Urabá now, the bush will not flower because the soil is contaminated with fusarium. In Jardín and other regions where there is a colder climate, the Gros Michel variety is planted. This variety performs better and can be marketed.

CB is a cooperative with 500 producers located within 100 km of the distribution center in Jardín, southwest of Antioquia. Four hundred producers are located within 5 km of the DC, while 100 producers are located at a distance of 80 to 100 km. CB uses four own and three third-party trucks with one to four tons capacity to transport the bananas from the close-by farms to the distribution center in Jardín. Similarly, they use one own and one third-party truck with one to four tons capacity to pick up the product from the farms far away and bring it to the DC.

Before the drivers arrive, the farmers have cut the bananas, made a first selection, washed them, and prepared them for collection. Drivers drive to the close-by farms as per a fixed route. Then, they select quality products and reject damaged or not complaint bananas. Following, they load their trucks, take note of the product's weight, and follow the route. This procedure replicates for 4 to 5 farms per trip and five daily trips, each lasting two hours.
Regarding the far-away farms, the product is collected by the owned and third-party trucks first in a 10-ton CB owns. The time taken to load a 10 tons truck with boxes of bananas is 20 minutes. The two small trucks carry out four trips per day, each lasting one hour after visiting three to four farms. The big truck and the two small trucks bring all the product collected during the day to the DC in Jardin on a trip that lasts approximately six hours.

Figure 9**.** CB distribution center in Jardin. Banana unloading operation and storage facility.
Photos were taken during the CB site visit.

The DC of CB in Jardín has a capacity of 102 metric tons of banana with the possibility to store 43 tons in a ripening cellar with controlled temperature conditions to accelerate or reduce the ripening process or to store 59 tons of product at room-temperature conditions (18ºC). Bananas can stay here from two to seven days, depending on the desired process (ripening/conservation) or destination. If a product needs to be ripened, it will be kept in the ripening cellar at 19.5ºC for two days; if the product is not yet needed, it will be kept in the conservation cellar at 13ºC for up to seven days. The usual level of volume they receive is 50 tons per day; loss is about 17 kg per day (0.03%), according to the CB employee interviewed. When there is high production, the DC receives 60 tons of bananas daily, and the loss can be about 300 kg per day (0.5%). As volume increases, the banana loss increases. In the case of the

DC of CB, doubling the banana handling volume increased the loss by 30 times. CB boxes the bananas as shown in the above pictures. Figure 10 summarizes the important data from the DC of CB in Jardin.

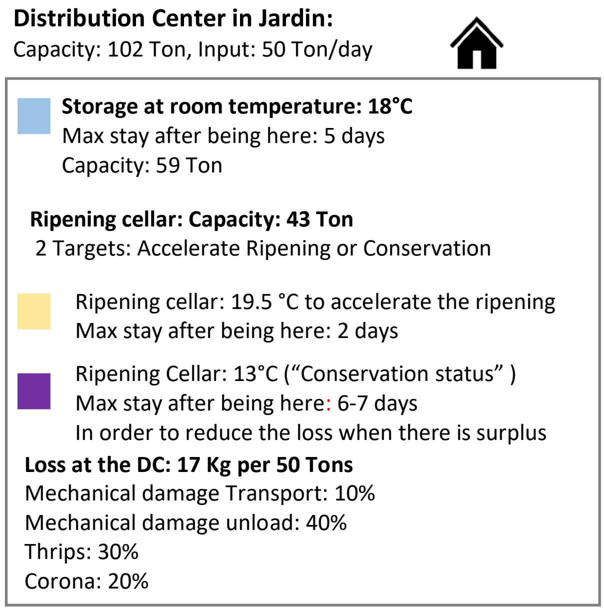


Figure 10. Summary for DC in Jardin.

The major reasons for the banana loss, according to CB, are due to the following:

1. Mechanical damage during transport and unloading: This damage is produced because of the blows received by bananas during the transport and handling operations. 10% of the total losses occurring at the DC are caused by mechanical damage in transport. 40% are caused by damage during the unloading of the product.
2. Mal de Corona (Damage of the Crown): This damage occurs because the farmers did not use the right product to clean the banana after harvesting. Figure 11 shows some products used to clean the banana. 20% of the losses occurring at the DC are due to the problem of "Mal de Corona."
3. Thrips: this problem is caused by an insect that damages the bananas. The way to protect the banana is by using a special type of bag that contains insecticide to protect the bananas. The problem could appear because either the farmer never used the bags or used the bags too late. A good moment to protect the banana with the bags is when the "bellota" (set of flowers) of the banana appears. Figure 12 illustrates how bananas need coverage from insects, with an example of a damaged banana and a picture of the insect that caused the damage. Thrips cause 30% of the total losses in the DC.

Figure 11. Products to Clean the Banana with to Prevent Mal de Corona (Banaspar and Mirage)
Photos were taken during the CB site visit.

Figures 12. Covering of bananas to protect from the insect causing Thrips, damaged banana, and insect that causes the damage. Primary data was collected during the CB site visit.

From the distribution center in Jardín, CB serves the cities of Bogota and Medellin with a 10-ton truck and Cali with a six-ton truck. The cost to serve per box from Jardin to Medellin is 1,000 Colombian Pesos. On the backhaul journey, the truck can transport 1200 empty boxes, costing 250 Colombian Pesos per empty box. The cost to serve from Jardin to Bogota or Jardin to Cali is 200,000 Colombian Pesos per ton of banana. The company pays 1,000 Colombian Pesos to transport per empty box on this route because the distance from Jardin to Bogota (467 km) or Jardin to Cali (333 km) is nearly 3 to 4 times the distance from Jardin to Medellin (132 km). The customer of CB in Bogota usually returns 800 boxes per trip, less than the Full Truckload Capacity of 1,200 boxes.

The distance between the DC in Jardin and the Plaza Mayorista in Medellín is 192 km. The capacity that Plaza Mayorista has is 17 tons. The plaza's storage conditions include room temperature (on average 27ºC), where the product stays a maximum of 24 hours, and a conservation chamber (13ºC), where the product stays up to two days. Figure 13 shows a summary of the information from Plaza Mayorista in Medellín.

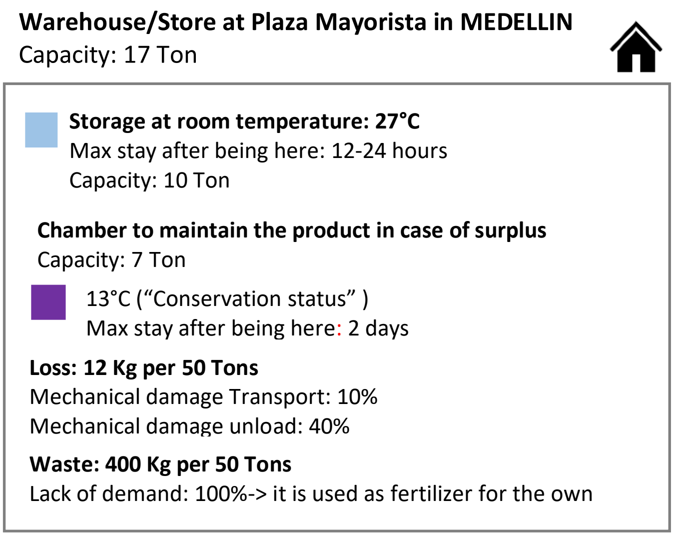


Figure 13. Summary of information from Plaza Mayorista in Medellín.

From the warehouse in Plaza Mayorista of Medellín, the banana is distributed to the warehouses of the retailers and stores in the city of Medellín using a six-ton truck owned by CB. Each retailer will then carry out their distribution from their warehouses to the stores in the city.

4.2.3. Banana waste at the retailers' stage

To understand the banana storage conditions that could lead to banana losses at the retail stage, we conducted interviews with 21 retailers and nano stores in Medellín and analyzed that data.

The majority of the stores interviewed order bananas daily, which could mean, on the one hand, that they have a high turnover or, on the other hand, that they have little storage space. Figure 14 shows the banana order frequency of the retailers interviewed.

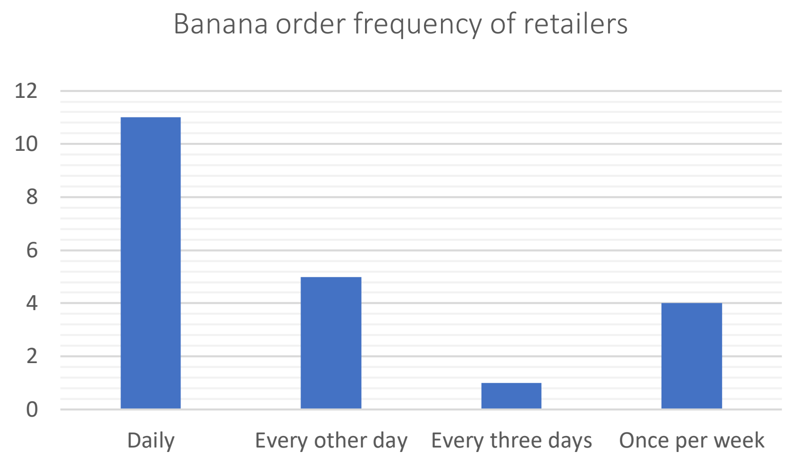
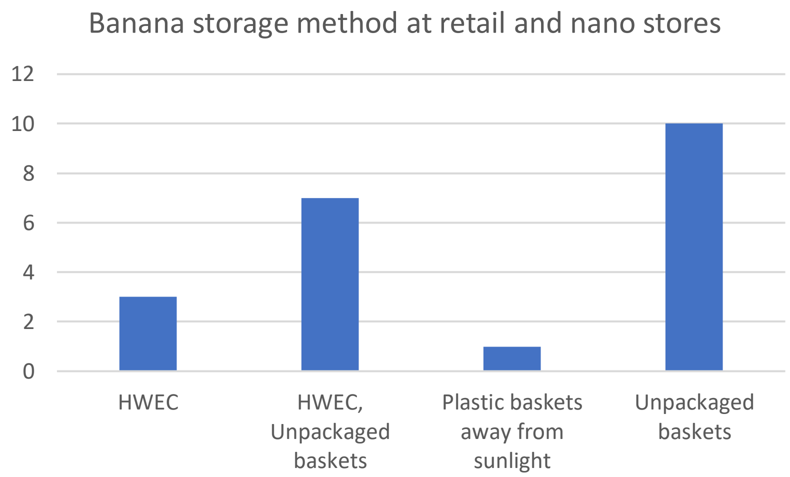


Figure 14. banana order frequency of retailers.

When asked what informs their supply chain strategy, 23% replied improving banana quality, and 20% said that solely reducing costs determine their strategy. 42% of the retailers mentioned that improving banana quality and reducing costs at least partially determine their supply chain strategy. Pineapple, orange, lemon, mango, and apple are the most common fruits co-transported with bananas.

Half of the retailers leave the bananas in the open air, as indicated in figure 15, allowing them to continue with the ripening process. Another half keep the bananas in unpackaged baskets, leaving them susceptible to the environment. Thus, it is clear that at the retail shops interviewed, bananas are not stored with proper temperature control, causing the ripening of the products to be accelerated if the ambient temperature is equal to or higher than 18ºC.



HWEC – Hanging without environmental control

Figure 15. Banana storage methods at retail and nano stores.

Figure 16 shows that most retailers mention that mechanical damage during transport is the cause of banana loss at retail stores. This mechanical damage could arise because of the co-transportation of bananas and other products, banana boxes breakdown, and banana crushing during transport. Other major reasons include insufficient temperature control and earlier ethylene application to accelerate the ripening process. Both cause a faster ripening of the product, leading to a softer texture and hence, easier to damage-products. Human touch during banana loading and unloading also leads to deterioration of quality. To bring down the banana loss, thus, we need to reduce the number of echelons in the supply chain to minimize human touch, avoid co-transporting other products, control the vehicle's temperature, and delay ethylene application to as close as possible to the consumption point.

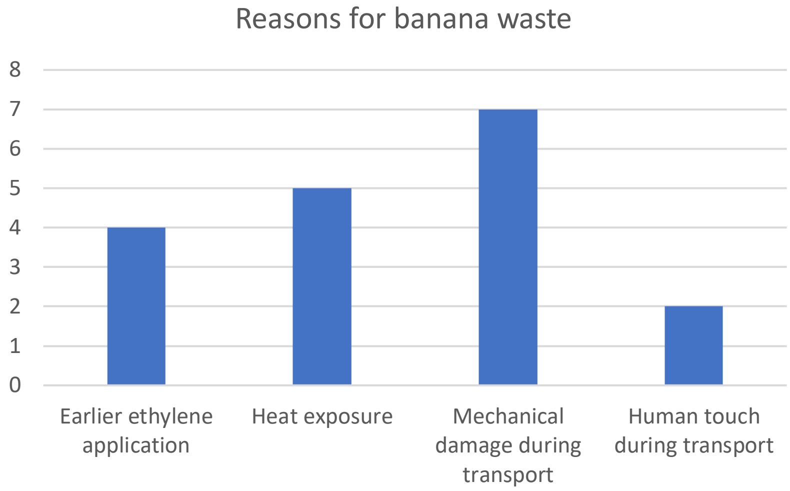


Figure 16. Reasons for banana waste at the retailer stage.

Retailers often give away damaged bananas as gifts to consumers or use them to feed birds and animals. 10% return the damaged bananas to suppliers. 20% throw away the bananas. When asked whether they would be willing to donate bananas that do not meet the required quality standards but are fit for human consumption to food banks, 85% said yes.

4.2.4. Consumers buying preferences and banana waste

To understand the consumers' buying preferences and the waste that can happen at the consumer level, we conducted primary interviews with 79 consumers. Consumers tend to purchase bananas from multiple places on different days. Table 4 offers a simplified view of the purchase location; hence, the total will be more than 100%. 48% of the respondents purchase the banana from Supermarkets, although not exclusively. 44% purchase from neighborhood stores. 10% purchase from wholesale markets. 5% purchase directly from farmers.

Table 4. Consumers' banana purchase location preference.

Purchase Location	Number of Respondents	Number of Respondents%
Supermarkets	38	48%
Neighborhood store	35	44%
Farmer	4	5%
Wholesale market	8	10%
Homegrown	1	1%
Street vendor	2	3%
Randomly	1	1%

Table 5. Factors deciding banana purchase location

Top Factors deciding purchase location	Number of Respondents	Number of Respondents%
Proximity	27	34%
Quality and freshness	17	22%
Price, quality, and freshness	9	11%
Price	9	11%
Proximity, Price	4	5%

As shown in table 5, proximity is the most influential decision variable for 34% of the respondents. For 22% of the respondents, quality is the most important factor, meaning they would be willing to travel to get quality bananas. The price factor comes at a distant third.

Table 6. Preference for ripening degree of bananas.

How do you prefer to buy bananas based on their ripeness?	Number of Respondents	Number of Respondents%
Light yellow, ready to be consumed the following day.	46	58%
Green, so that they mature slowly	24	30%
Mature, it doesn't matter if they have some black spots	9	11%

Based on the information from table 6, 58% of the respondents purchased yellow bananas to consume the following day. 30% purchase green, and 10% do not mind if the banana is mature.

Table 7. Relation among different factors.

Is Banana Quality a Factor when you choose the place of purchase?	How do you prefer to buy bananas based on their ripeness?)	Number of Respondents	Number of Respondents%
0	Green	16	20%
0	Light yellow	37	47%
0	Mature	5	6%
1	Green	8	10%
1	Light yellow	9	11%
1	Mature	4	5%

Among those who say banana quality determines their banana purchase location, about the same proportion of people purchase green and light-yellow color bananas. However, the proportion of people purchasing light yellow bananas immediately for consumption is more than double that of those purchasing green bananas, which implies that bananas with slight deterioration in quality can be marketed to consumers who would like to consume the banana the following day.

Table 8. Banana variety preference.

Banana Variety Preference	Number of Respondents
Not aware of banana varieties	48
No	15
Criollo	13
Uraba's patanconcito	2
Pinton	1

80% of the respondents do not prefer the banana variety. Of those who have a preference, 81% prefer the Criollo variety.

48% of the respondents have a preference for domestically grown bananas. 35% of them strictly prefer the banana grown in Antioquia. A majority of those who prefer local bananas do it to support the local economy, as seen below.

Table 9. Reason for banana origin preference.

Reason for Banana Origin Preference	Number of Respondents
No Preference	49
Local support	18
Taste	4
Fewer chemicals	1
Price	2
Freshness, Quality	1
The region is known for its banana	2
Other reasons	2

When asked whether they prefer certified bananas, only 6% said they prefer certified bananas. 58% say that they are not aware that certifications exist. 35% do not have a preference for certified bananas.

Table 10. Frequency of banana purchases.

How often do you buy bananas?	Number of Respondents	Number of Respondents %
More than once a week	10	13%
Once a week	30	38%
Twice a month	25	32%
Once a month	14	18%

13% of the respondents buy bananas more than once a week, and 18% buy them monthly. Most people buy once a week.

A family consumes 24 bananas on average, and the median consumption is 20.

Table 11. Monthly family banana consumption.

How often do you buy bananas?	Monthly family banana consumption
More than once a week	30
Once a week	29
Twice a month	19
Once a month	17

Table 12. Banana waste at the consumer level

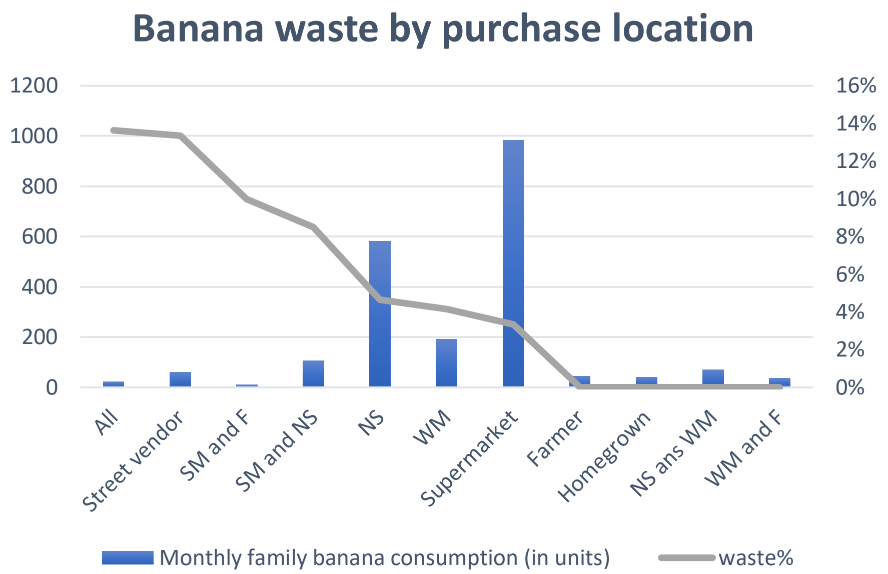
Banana waste	Number of Respondents	Number of Respondents %
No wastage	50	63%
At most, 5%	3	4%
5 to 10%	8	10%
10 to 20%	12	15%
>20%	6	8%

On average, one banana is wasted, thus indicating a 4% banana waste in households. 63% responded that they do not waste bananas at all. 8% of respondents waste more than 20% of what they purchase, assuming the monthly average consumption is nothing but the number of bananas purchased. Almost everyone throws away the banana because they are damaged. Two respondents (7% of those who discard the banana) do so because they purchased more than they needed.

Table 13. Banana by-products.

Would you purchase the following	Number of Respondents	Number of Respondents %
Banana chips	41	52%
Frozen bananas	40	51%
Banana Pulp	27	34%
Banana powder	23	29%

Nearly 50% of the respondents would purchase banana chips or frozen bananas. The household wastage of bananas is 4%, and there is a market for the by-products of bananas, as seen in the above table.



SM – Supermarkets; NS – Neighborhood stores; WM – Wholesale market; F - Farmer

Figure 17. Banana waste by purchase location.

Supermarkets and Neighborhood stores are the major channels through which bananas are purchased. Other important channels are street vendors, wholesale markets, and directly from farmers. Of the bananas purchased from neighborhood stores, 5% go to waste compared with the 3% waste for bananas purchased from supermarkets, indicating the possibility of better storage conditions available at supermarkets.

5. Simulation

The parameter for determining food loss was the degree of ripening of the banana. There are different ways to measure the degree of ripeness of a banana. We based information analysis used by one of the largest retailers in Colombia to determine the degree of ripeness and, thus, the acceptance or rejection of bananas in their storage centers for distribution and sale in their shops. According to this retailer, there are six degrees of ripening, going from 1 (completely green) to 6 (already with black spots) (Figure 18).

Figure 18. Banana ripening degrees used in retail in Colombia.

To estimate the level of ripening that the banana will have after a certain time at certain temperatures, we relied on the study by Chen and Ramaswamy (2002), in which they measured the changes in color and texture of the banana as a function of different storage temperatures. The authors did not inject ethylene to advance the ripening process but let the banana ripen naturally under different time and temperature conditions. Thus, we used the color data they obtained in terms of L, a, and b values for bananas stored for several days at 10, 16, 22, and 28 degrees Celsius. We used a converter from L, a, and b values to color from Nix Color Sensor (Nix Color Sensor, 2022). Based on the authors' definition of a fully ripe banana of *L=75.2, a=4.5, and b=41.2*, and information provided by the retailer (Figure 3), we estimated the degree of banana ripening for each of the combinations of L, a, and b. We developed three linear regression models to know the degree of ripening that a banana should have at a specific temperature after a certain time.

Table 14. Time required at a given temperature for the banana to advance to higher degrees when the initial degree is 1; Source: Chen and Ramaswamy (2002).

Temperature	Time in hours	Final banana degree
10	216	2
10	288	3
10	360	4
16	96	2
16	144	3
16	192	4
16	288	5
22	72	2
22	120	3
22	168	4
22	216	5
28	48	2
28	72	3
28	96	4

Table 15. Time required at a given temperature for the banana to advance to higher degrees when the initial degree is 2; Source: Chen and Ramaswamy (2002).

Temperature	Time in hours	Final banana degree
10	72	3
16	48	3
22	48	3
28	24	3
10	144	4
16	96	4
22	96	4
28	48	4
16	192	5
22	144	5

Table 16. Time required at a given temperature for the banana to advance to higher degrees when the initial degree is 3; Source: Chen and Ramaswamy (2002).

Temperature	Time in hours	Final banana degree
10	72	4
16	48	4
22	48	4
28	24	4
16	144	5
22	96	5

In the supply chain, banana goes through multiple echelons where the temperature and the length of stay differ. We need a method to account for these varied temperature controls to quantify the banana loss. One of the largest retailers in Colombia demands that the banana is in degree 3 when the bananas are delivered. We intend to predict the proportion of bananas that would be more than degree 3 by the time they are delivered with the help of the three linear regression models we have developed. The first linear regression model predicts the final degree of ripening given the temperature control and the length of the journey or stays if the initial degree of ripening was 1. The second linear regression model predicts the final degree of ripening given the temperature control and the length of the journey or stays if the initial degree of ripening was 2. The third linear regression model predicts the final degree of ripening given the temperature control and the length of the journey or stays if the initial degree of ripening was 3.

SUMMARY OUTPUT

Regression Statistics	
Multiple F	0.857359971
R Square	0.735066119
Adjusted I	0.686896323
Standard I	0.598191252
Observati	14

ANOVA

	df	SS	MS	F	Significance F
Regressio	2	10.92098235	5.460491173	15.2599	0.000671825
Residual	11	3.936160511	0.357832774		
Total	13	14.85714286			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-2.579571363	1.176541382	-2.192503725	0.050746	-5.169121486	0.00997876	-5.16912149	0.009978759
temp	0.171910625	0.040119925	4.284918875	0.001288	0.083607265	0.26021398	0.083607265	0.260213985
time	0.015313877	0.002772007	5.524472234	0.00018	0.009212731	0.02141502	0.009212731	0.021415024

Figure 19. Linear regression model to predict the final ripening degree when the initial degree is 1

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.956829506
R Square	0.915522703
Adjusted R Sq	0.891386333
Standard Erroı	0.25996507
Observations	10

ANOVA

	df	SS	MS	F	Significance F
Regression	2	5.126927138	2.563464	37.93125	0.000175223
Residual	7	0.473072862	0.067582		
Total	9	5.6			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	1.230552622	0.397903612	3.09259	0.017503	0.289660093	2.17144515	0.28966009	2.171445152
temp	0.059838085	0.015032845	3.98049	0.005321	0.024291055	0.09538512	0.02429106	0.095385115
time	0.015707497	0.001803406	8.709908	5.28E-05	0.011443121	0.01997187	0.01144312	0.019971874

Figure 20. Linear regression model to predict the final ripening degree when the initial degree is 2

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.95742711
R Square	0.91666667
Adjusted R Squ	0.86111111
Standard Error	0.19245009
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	1.222222222	0.611111	16.5	0.024056261
Residual	3	0.111111111	0.037037		
Total	5	1.333333333			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	2.71296296	0.391488957	6.929858	0.006161	1.46707038	3.958855546	1.46707038	3.95885555
temp	0.03703704	0.015120307	2.44949	0.091721	-0.01108253	0.085156602	-0.0110825	0.0851566
time	0.01273148	0.002216266	5.744563	0.010477	0.005678332	0.01978463	0.00567833	0.01978463

Figure 21. Linear regression model to predict the final ripening degree when the initial degree is 3

We built a simulation to quantify the banana loss. We considered the following stages: Farm, Farm to DC transit, DC, DC to Plaza Mayorista transit, and Plaza Mayorista in that order. We simulate the percentage of banana loss in a fully loaded truck with a one-ton capacity. We assume that bananas are transported in boxes, simulate the banana loss at the box level, and aggregate it to the truck level. Each banana box can hold 15kgs of bananas, and hence we assume that 1 ton of banana transportation needs 67 boxes, in simplistic terms, disregarding the own weight of the boxes.

We first simulate the initial degree of ripening of the banana in each of the boxes when it is at the farm. The underlying assumption is that all the bananas in a box will have the same degree of ripening, but the degree of ripening can differ among the boxes. Retailers generally do not accept bananas with more than three or four degrees of ripening because the bananas would stay at the retail stores before the consumer purchases them bananas. Anything that arrives at the retail store with a degree above three or four is lost. Thus, we simulate the degree of ripening of each banana box as a function of time and temperature at each of the five stages listed earlier. At the Plaza Mayorista, the final stage, if the banana degree of ripening is greater than three or four, we consider all the bananas in that box are lost.
If not, we consider all the bananas in that box in good condition. The proportion of lost boxes is then the proportion of the banana loss for the whole truck. We separately estimate the banana loss due to mechanical damage for the whole truck.

Table 17. Variables and their distributions in the simulation

Stage	Variable	Description	Distribution	Reasons for choosing the distribution parameters
Farm	farm_stay_temp_in_celcius	Temperature at the farm	uniform between 12 and 26	Based on the farm locations and information provided by the distributor in Antioquia
Farm	farm_stay_time_in_hrs	Time the banana stays at the farm	poisson with mean of 0.5 hours	There is a fixed time for banana collection at the farm and average delay is 0.5 hours; information obtained from the interview with the distributor in Antioquia
Farm	farm_stay_mechanical_damage	Proportion of bananas lost due to mechanical damage at the farm	triangular with min=0.1%,mode=5% and max=10%	Interviews with the retailers
Farm To DC	farmtodc_loading_time_in_hrs	Time to load banana in the truck at the farm to transport to DC	normal with mean 1.67 hours and standard deviation 0.167 hour	It takes 10 minutes to load 100 kg of banana in the truck and hence 1.67 hours to load 1 ton of banana; information obtained from the distributor in Antioquia
Farm To DC	farmtodc_loading_temp_in_celcius	Temperature at the farm when banana is loaded in the truck	uniform between 12 and 26	Based on the farm locations and information provided by the distributor in Antioquia
Farm To DC	farmtodc_transit_time_in_hrs	Transit time between farm and DC	normal with mean 1 hour and standard deviation 0.25 hour	The farms are located close to DC and the mean travel time is 1 hour; information obtained from the distributor n Antioquia
Farm To DC	farmtodc_transit_temp_in_celcius	Temperature in the truck during the transit	uniform between 10 and 31	Temperature in the truck will be higher than the atmospheric temperature due to heat generated by the vehicle and hence the range between 10 degrees and 31 degrees
Farm To DC	farmtodc_accident_or_road_blockage	Whether there was an interruption during the transit in terms of road blockage or accident	uniform between 0 and 101; if the generated number is greater than 98 then this flag is set to 1. This is done to simulate the real world where the probability of transit disruption happening is very low.	
Farm To DC	farmtodc_transit_mechanical_damage	Proportion of bananas lost due to mechanical damage at the transit between farm and DC	triangular with min=0.1%,mode=5% and max=10%	Interviews with the retailers
DC	indc_unloading_time_in_hrs	Time to unload the banana in DC	normal with mean 1.67 hours and standard deviation 0.167 hour	Assuming loading and unloading takes same amount of time
DC	indc_unloading_temp_in_celcius	Temperature when banana is unloaded at the DC	uniform between 9 and 20	Assuming DC is located in Jardin and the temperature in Jardin varies between 9 and 20 degree celcius
DC	indc_stay_temp_in_celcius	Storage temperature at DC	uniform between 13 and 19.5	DC has temperature control between 13 degree celcius and 19.5 degree celcius; information obtained from the distributor in Antioquia
DC	indc_stay_time_in_hrs	storage time at DC	poisson with mean 48 hours	On average the banana stays in DC for 48 hours; information obtained from the distributor in Antioquia
DC To Plaza Mayorista	dctoplaza_loading_time_in_hrs	Time to load banana in the truck at the DC to transport to plaza mayorista	normal with mean 1.67 hours and standard deviation 0.167 hour	It takes 10 minutes to load 100 kg of banana in the truck and hence 1.67 hours to load 1 ton of banana; information obtained from the distributor in Antioquia
DC To Plaza Mayorista	dctoplaza_loading_temp_in_celcius	Temperature at the DC when banana is loaded in the truck	uniform between 9 and 20	Assuming DC is located in Jardin and the temperature in Jardin varies between 9 and 20 degree celcius
DC To Plaza Mayorista	dctoplaza_transit_time_in_hrs	Transit time between DC and plaza mayorista	normal with mean 4 hours and standard deviation 1 hour	Considering that DC is in Jardin and Plaza mayorista is in Medellin; information obtained from the distributor
DC To Plaza Mayorista	dctoplaza_transit_temp_in_celcius	Temperature in the truck during the transit	uniform between 10 and 31	Temperature in the truck will be higher than the atmospheric temperature due to heat generated by the vehicle and hence the range between 10 degrees and 31 degrees
DC To Plaza Mayorista	dctoplaza_mechanical_damage	Proportion of bananas lost due to mechanical damage at the transit between DC and plaza mayorista	triangular with min=0.1%,mode=5% and max=10%	Interviews with the retailers
Plaza Mayorista	plaza_unloading_time_in_hrs	Time to unload the banana in plaza mayorista	normal with mean 1.67 hours and standard deviation 0.167 hour	Assuming loading and unloading takes same amount of time
Plaza Mayorista	plaza_unloading_temp_in_celcius	Temperature at the plaza mayorista when banana is unloaded	uniform between 17 and 26	Assuming Plaza mayorista is in Medellin and the temperature in Medellin varies between 17 and 26 degree celcius
Plaza Mayorista	plaza_stay_temp_in_celcius	Storage temperature at plaza mayorista	uniform between 13 and 26	Plaza mayorista has temperature control mechanism and hence the lowest temperature could be as low as 13
Plaza Mayorista	plaza_stay_time_in_hrs	storage time at plaza mayorista	poisson with mean 12 hours	Banana stays in plaza mayorista on average for 12 hours and can be as high as 2 days; information obtained from the distributor in Antioquia

The delays due to road accidents, road blockage, etc., are incorporated into the transit time between Farm and DC and the stay time at the Farm. At each stage, we compute the End of stage degree of ripening: The regression equation we have developed to predict the banana ripening earlier is specific when the banana ripeness degrees are integers. An intermediate stage exists between banana ripeness degrees one and two, two and three, and so on. Thus, using the same regression equation when the banana ripening degree is one vs. when the banana ripening degree is 1.6 is incorrect. If the banana ripening degree is less than 1.4, we use regression equation 1. If it is between 1.9 and 2.4, we use regression equation 2; if it is between 2.9 and 3.4, we use regression equation 3. If the degree of ripening is between 1.4 and 1.9, we simulate the regression coefficients using the standard error of regression equation 1. If the degree of ripening is between 2.4 and 2.9, we simulate the regression coefficients using the standard error of regression equation 2. We use the normal distribution to simulate the regression coefficients and set the probability percentile to a floor value of 51 to ensure that the bananas with ripening degrees between 1.4 and 1.9 will ripen faster than those with ripening degrees <1.4. We choose the regression equation and the coefficients to use at the current stage considering the end of the stage ripening of the previous stage, which is the initial ripening of the current stage.

We used 22 variables in the simulation across five stages. Their distribution is summarized in Table 18. We ran this simulation 1000 times. The python script to run the simulation is written in the annexure. The simulation yielded a mean loss of 30%, and the median loss was 25%. The range of losses was from 0% to 100%.

Table 18. Analysis of simulation data

Variable	Mean value when the loss due to temperature and time is 0%	Mean value when the loss due to temperature and time is 100%
farm_stay_temp_in_celcius	17.41	16.34
farm_stay_time_in_hrs	1.06	1.00
farmtodc_loading_time_in_hrs	1.68	1.57
farmtodc_loading_temp_in_celcius	17.62	18.41
farmtodc_transit_time_in_hrs	3.04	2.48
farmtodc_transit_temp_in_celcius	16.73	29.94
farmtodc_accident_or_road_blockage	0.01	0.00
indc_unloading_time_in_hrs	1.68	1.79
indc_unloading_temp_in_celcius	14.22	15.15
indc_stay_temp_in_celcius	15.95	17.56
indc_stay_time_in_hrs	47.85	60.00
dctoplaza_loading_time_in_hrs	1.68	1.82
dctoplaza_loading_temp_in_celcius	14.45	18.16
dctoplaza_transit_time_in_hrs	3.97	4.20
dctoplaza_transit_temp_in_celcius	18.45	17.83
plaza_unloading_time_in_hrs	1.66	1.77
plaza_unloading_temp_in_celcius	20.76	20.91
plaza_stay_temp_in_celcius	18.47	25.35
plaza_stay_time_in_hrs	12.41	18.00

We analyzed the simulation data and specifically sought to understand what causes no loss and what causes full loss. To do this, we compared the mean values of the variables for the scenarios with 0% loss and 100% loss. This analysis indicated that the temperature in the truck during the farm to DC transit stays time at the DC. The temperature at the DC when we load the truck is the parameter that could have contributed most to the loss, and such scenarios must be avoided to reduce banana loss. Based on the results of the simulation and the data obtained from the interviews we have conducted so far, we conclude that:

1) The banana must pass through as few intermediary points as possible between the farm and the end consumer, which will reduce the banana loss due to mechanical damage caused by human touch
2) The bananas must be harvested at the ripening degree 1, and ethylene should be injected as close to the end consumer consumption point as possible and not earlier in the supply chain
3) There must be strict temperature control across all the points in the supply chain, such as the transport and the DC storage
4) More consumers must be encouraged to buy bananas with a degree of ripening of two or less to minimize waste at retail stores

5) If improved further with real data, the simulation tool we have developed can create a system that monitors the banana quality of shipments and automatically prioritize the bananas about to go to waste.
6) This simulation tool has limitations in terms of accurate data availability.

6. Conclusions

Bananas, being climacteric fruits, continue their ripening process after being cut from the plant. Bananas release ethylene, a hormone-like gas, which promotes the ripening of the fruit. Temperatures above 18ºC favor ethylene production and, therefore, accelerate the ripening of bananas. Ripening in bananas implies changes in the color of the fruit but also in its physicochemical, nutritional, and sensory characteristics.

A product that arrives at the retailers with a high degree of ripeness will not be accepted by them because of the possibility that it has to reach its ideal ripening point for consumption before the consumer can buy it. Similarly, consumers will not purchase an overripe product or, if purchased at a high degree of ripeness, will ripen after a short time in their homes. Whatever the case, the product will have a high probability of being wasted.

Besides the obvious changes in the fruit color, the bananas' ripening led to a change in the texture of the banana flesh and the skin covering it. The banana skin softens, making it more susceptible to mechanical damage. Mechanical damage in bananas may be caused by blows during transport, especially if the roads are not in good condition; by contact with other heavier or more resistant fruits; by pressure from boxes and packaging; by the handling of the actors in the supply chain; or even by the touch of the consumers in the shops. A product that arrives at retailers with some damage will be rejected. If it is not rejected, there is little probability that a consumer will pay for a damaged product.

Based on the information provided through interviews, the fruit loading and unloading times, and the time the fruit waits on the farm to be picked up by the collectors, are relatively low. Therefore, temperature changes during these times do not significantly affect the ripening of the product. In contrast, there may be more variations in transport time between the farms and the distribution center, between the distribution center and Plaza Mayorista in Medellín, or between the Plaza Mayorista and the retailer's warehouses in Medellín. These variations may be due to accidents, poor road conditions, or changes in traffic on the route at that time.

For the above reasons, the temperature must be controlled and stable during transport and storage until the product reaches the point of sale to ensure that the percentage of losses is as low as possible. For this, we suggest the transport vehicles used for the banana distribution from the farm to the retailers' shops be temperature controlled and kept in the range of 13-18ºC.

If further improvised, the simulation tool we have developed can be used to create an automated system to track the health of bananas and automatically prioritize the bananas about to go bad for consumption. The simulation can be improved by gathering additional quantitative data to validate the data distributions and the distribution parameters we have used for the variables.

The regression equations can also be improved by conducting experiments to determine the relationship between time, temperature, and the banana's degrees of ripening.

Acknowledgments

We are very grateful to all our advisors, Dr. Chris Mejía, Dr. Claudia Antonini, and Dr. José Larco, for all their support and advice during the Capstone project process. This work would not have been possible without their help, guidance, and patience.

Thanks to Fabio and Jorge from the sponsor company for all their help. Especially with the face-to-face interviews in different parts of Colombia due to our inability to travel there.

Many thanks to Dr. Juan Guillermo Villegas from the University of Antioquia, Jaime from U.B., and Catalina from C.B. We thank them for their support through interviews or data and valuable information that helped us understand the banana supply chain in Colombia and its opportunities.

Finally, thank you very much for the help of the students of the research group at Universidad EAFIT and Dr. Juan Gregorio Arrieta for their help in collecting data through interviews with transporters, retailers and shopkeepers, and final consumers.

References

Akinyemi, S. O. S., Adejoro, M. A., Layade, A. A., & Adegbite, O. O. (2017). Market Structure and Performance for Plantain and Banana. *International Journal of Fruit Science*, *17*(4), 440-450. https://doi.org/10.1080/15538362.2017.1360231

Baez-Sañudo, M., Siller-Cepeda, J., Muy-Rangel, D., & Heredia, J. B. (2009). Extending the shelf-life of bananas with 1-methylcyclopropene and a chitosan-based edible coating. *Journal of the Science of Food and Agriculture*, *89*(14), 2343-2349. https://doi.org/10.1002/jsfa.3715

Barham, J., Tropp, D., Enterline, K., Farbman, J., Fisk, J., & Kiraly, S. (2012). *Regional Food Hub Resource Guide*. U.S. Department of Agriculture, Agricultural Marketing Service. https://doi.org/10.9752/MS046.04-2012

Beekman, G., Dekkers, M., & Koster, T. (2019). *Towards a sustainable banana supply chain in Colombia: Rainforest Alliance Certification and economic, social and environment conditions on small-scale banana plantations in Magdalena, Colombia*. Wageningen Economic Research. https://doi.org/10.18174/466678

Beullens, P., & Ghiami, Y. (2021). Waste reduction in the supply chain of a deteriorating food item – Impact of supply structure on retailer performance. *European Journal of Operational Research*, S0377221721007748. https://doi.org/10.1016/j.ejor.2021.09.015

Blay-Palmer, A., Landman, K., Knezevic, I., & Hayhurst, R. (2013). Constructing resilient, transformative communities through sustainable “food hubs”. *Local Environment*, *18*(5), 521-528. https://doi.org/10.1080/13549839.2013.797156

Blomme, G., Dita, M., Jacobsen, K. S., Pérez Vicente, L., Molina, A., Ocimati, W., Poussier, S., & Prior, P. (2017). Bacterial Diseases of Bananas and Enset: Current State of Knowledge and Integrated Approaches Toward Sustainable Management. *Frontiers in Plant Science*, *8*, 1290. https://doi.org/10.3389/fpls.2017.01290

Broad Leib, E. M., Shapiro, M., Jagdagdorj, N., Hill, J., & Giguere, M. (2021). Colombia Legal Guide food donation law and policy. *The global food donation policy atlas*. https://www.foodbanking.org/wp-content/uploads/2021/01/Colombia-Legal-Guide.pdf

Buzby, J. C., & Hyman, J. (2012). Total and per capita value of food loss in the United States. *Food Policy*, *37*(5), 561-570. https://doi.org/10.1016/j.foodpol.2012.06.002

Cattaneo, A., Sánchez, M. V., Torero, M., & Vos, R. (2021). Reducing food loss and waste: Five challenges for policy and research. *Food Policy*, *98*, 101974. https://doi.org/10.1016/j.foodpol.2020.101974

Chaboud, G., & Moustier, P. (2021). The role of diverse distribution channels in reducing food loss and waste: The case of the Cali tomato supply chain in Colombia. *Food Policy*, *98*, 101881. https://doi.org/10.1016/j.foodpol.2020.101881

Chen and Ramaswamy (2002). Color and Texture Change Kinetics in Ripening Banana. Lebensm.-Wiss. u.-Technol., 35, 415–419

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH (2021). Cost of Production in the Banana Sector. https://www.bananenbuendnis.org/wp-content/uploads/Production-Costs-Colombia-1.pdf

FAO. (2021a). *12.3.1 Global food losses | Sustainable Development Goals* |. https://www.fao.org/sustainable-development-goals/indicators/12.3.1/en/

FAO. (2021b). *Banana market review – Preliminary results 2020. Rome.* 18.

FAO. (2021c). *¡El Rescate! Nada se pierde, todo se transforma*. https://www.fao.org/colombia/noticias/detail-events/es/c/1400577/

FAO. (2021d). *Food Loss and Food Waste*. Food and Agriculture Organization of the United Nations. http://www.fao.org/food-loss-and-food-waste/en/

FAO. (2021e). *Hunger and food insecurity*. Food and Agriculture Organization of the United Nations. http://www.fao.org/hunger/en/

GIZ. (2021). *Cost of Production in the Banana Sector. Study of Production Costs in the Banana Sector in Colombia.* https://www.bananenbuendnis.org/wp-content/uploads/Production-Costs-Colombia.pdf

Goldy, R. (2019). *All fruit and vegetables are not created equal regarding proper storage conditions*. Food

Preservation. https://www.canr.msu.edu/news/all-fruit-and-vegetables-are-not-created-equal-when-it-comes-to-proper-storage-conditions

Guo, J., Duan, J., Li, J., & Yang, Z. (2020). Mechanized Technology Research and Equipment Application of Banana Post-Harvesting: A Review. *Agronomy*, *10*(3), 374. https://doi.org/10.3390/agronomy10030374

Gustavsson, J. (Ed.). (2011). *Global food losses and food waste: Extent, causes and prevention; study conducted for the International Congress Save Food! at Interpack 2011, [16 - 17 May], Düsseldorf, Germany*. Food and Agriculture Organization of the United Nations.

Hammond, S. T., Brown, J. H., Burger, J. R., Flanagan, T. P., Fristoe, T. S., Mercado-Silva, N., Nekola, J. C., & Okie, J. G. (2015). Food Spoilage, Storage, and Transport: Implications for a Sustainable Future. *BioScience*, *65*(8), 758-768. https://doi.org/10.1093/biosci/biv081

Harvard school of public health. (2018, agosto 15). *Bananas*. The Nutrition Source. https://www.hsph.harvard.edu/nutritionsource/food-features/bananas/

Hegnsholt, E., Unnikrishnan, S., Pollmann-Larsen, M., Askelsdottir, B., & Gerard, M. (2018). *Tackling the 1.6-Billion-Ton Food Loss and Waste Crisis*. 10.

Huang, P., Zhu, L., Zhang, Z., & Yang, C. (2021). Row End Detection and Headland Turning Control for an Autonomous Banana-Picking Robot. *Machines*, *9*(5), 103. https://doi.org/10.3390/machines9050103

Koch, K., & Hamm, M. W. (2015). The Role of Values in Food Hub Sourcing and Distributing Practices. *Journal of Hunger & Environmental Nutrition*, *10*(4), 483-495. https://doi.org/10.1080/19320248.2015.1045668

Kuyu, C. G., & Tola, Y. B. (2018). Assessment of banana fruit handling practices and associated fungal pathogens in Jimma town market, southwest Ethiopia. *Food Science & Nutrition*, *6*(3), 609-616. https://doi.org/10.1002/fsn3.591

Lebersorger, S., & Schneider, F. (2014). Food loss rates at the food retail, influencing factors and reasons as a basis for waste prevention measures. *Waste Management*, *34*(11), 1911-1919. https://doi.org/10.1016/j.wasman.2014.06.013

Li, M., Slaughter, D. C., & Thompson, J. F. (1997). Optical chlorophyll sensing system for banana ripening. *Postharvest Biology and Technology*, *12*(3), 273-283. https://doi.org/10.1016/S0925-5214(97)00059-8

Liu, G. (2014). *Food Losses and Food Waste in China: A First Estimate* (OECD Food, Agriculture and Fisheries Papers N.º 66; OECD Food, Agriculture and Fisheries Papers, Vol. 66). https://doi.org/10.1787/5jz5sq5173lq-en

Maduwanthi, S. D. T., & Marapana, R. A. U. J. (2019). Induced Ripening Agents and Their Effect on Fruit Quality of Banana. *International Journal of Food Science*, *2019*, 1-8. https://doi.org/10.1155/2019/2520179

Mahfuzur Rahman, Mukta, F. A., & Md. Wahidul Islam. (2020). Value Chain Analysis of Banana in Some Areas of Narsingdi District. *International Journal of Multidisciplinary Informative Research and Review*. https://doi.org/10.5281/ZENODO.4309644

Martínez Z., N., Menacho P., Z., & Pachón-Ariza, F. (2014). Food loss in a hungry world, a problem? *Agronomía Colombiana*, *32*(2), 283-293. https://doi.org/10.15446/agron.colomb.v32n2.43470

Mattsson, L., Williams, H., & Berghel, J. (2018). Waste of fresh fruit and vegetables at retailers in Sweden – Measuring and calculation of mass, economic cost and climate impact. *Resources, Conservation and Recycling*, *130*, 118-126. https://doi.org/10.1016/j.resconrec.2017.10.037

Medical news today. (2020, enero 13). *Bananas: Health benefits, tips, and risks*. https://www.medicalnewstoday.com/articles/271157

Mejia, G., & Garcia-Diaz, C. (2018). Market-level effects of firm-level adaptation and intermediation in networked markets of fresh foods: A case study in Colombia. *Agricultural Systems*, *160*, 132-142. https://doi.org/10.1016/j.agsy.2017.06.003

Mejía, G., Granados-Rivera, D., Jarrín, J. A., Castellanos, A., Mayorquín, N., & Molano, E. (2021). Strategic Supply Chain Planning for Food Hubs in Central Colombia: An Approach for Sustainable Food Supply and Distribution. *Applied Sciences*, *11*(4), 1792. https://doi.org/10.3390/app11041792

Morganti, E., & Gonzalez-Feliu, J. (2015). City logistics for perishable products. The case of the Parma's Food Hub. *Case Studies on Transport Policy*, *3*(2), 120-128. https://doi.org/10.1016/j.cstp.2014.08.003

Nix Color Sensor (2022). Retrieved February 27, 2022, from https://www.nixsensor.com/free-color-converter/

Nguyen, C., Goff, Z., & Accorsi, R. (2019). Mathematical modeling of food and agriculture distribution. En *Sustainable Food Supply Chains* (pp. 145-158). Elsevier. https://doi.org/10.1016/B978-0-12-813411-5.00010-7

Noleppa, S., Gornott, C., Lüttringhaus, S., Hackenberg, I., & Gleixner, S. (2020). *Climate change and its effects on banana production in Colombia, Costa Rica, the Dominican Republic, and Ecuador*. 199.

OECD & FAO. (2020). *OECD-FAO Agricultural Outlook 2020-2029*. OECD. https://doi.org/10.1787/1112c23b-en

Ostertag, C. F., Sandoval, O. A., Barona, J. F., & Mancilla, C. (2014). *(CODER) to Max Havelaar – The Netherlands*. 122.
Paul, V., Pandey, R., & Srivastava, G. C. (2012). The fading distinctions between classical patterns of ripening in climacteric and non-climacteric fruit and the ubiquity of ethylene—An overview. *Journal of Food Science and Technology*, *49*(1), 1-21. https://doi.org/10.1007/s13197-011-0293-4
Rajkumar, P., Rani, C. I., Wang, N., & Raghavan, G. S. V. (2015). *Classification of banana fruit maturity using zNose*. *17*(4), 8.
Rajkumar, P., Wang, N., Elmasry, G., Raghavan, G. S. V., & Gariepy, Y. (2012). Studies on banana fruit quality and maturity stages using hyperspectral imaging. *Journal of Food Engineering*, *108*(1), 194-200. https://doi.org/10.1016/j.jfoodeng.2011.05.002
Ramadhan, Y. A., Djamal, E. C., Kasyidi, F., & Bon, A. T. (2020). *Identification of Cavendish Banana Maturity Using Convolutional Neural Networks*. 9.
Rangel, V. (2016). *Supply Chain Frontiers #61: Using Logistics to Cut Food Waste in Colombia | Center for Transportation and Logistics*. https://ctl.mit.edu/pub/newsletter/supply-chain-frontiers-61-using-logistics-cut-food-waste-colombia
Rolle, S., Rosa, Asian Productivity Organization, & Food and Agriculture Organization of the United Nations. (2006). *Postharvest management of fruit and vegetables in the Asia-Pacific region*. Asian Productivity Organization ; Food an Agricultural Organization. http://books.google.com/books?id=zVgjAQAAMAAJ
Selvaraj, M. G., Vergara, A., Ruiz, H., Safari, N., Elayabalan, S., Ocimati, W., & Blomme, G. (2019). AI-powered banana diseases and pest detection. *Plant Methods*, *15*(1), 92. https://doi.org/10.1186/s13007-019-0475-z
Venkatachalam, K., Muthuvel, I., Sundaresan, S., Subramanian, K. S., Janaki, J. G., Sullivan, J. A., Paliyath, G., & Subramanian, J. (2018). Post-harvest dip of enhanced freshness formulation to extend the shelf life of banana (Musa acuminata cv. Grand Naine) in India. *Tropical Agriculture*, *95*(11), 13. https://journals.sta.uwi.edu/ojs/index.php/ta/article/view/6686
Wang, H. J., Huang, G. G., Zou, X. J., & Chen, Y. (2013). Modeling and Performance Simulation for a Picking Manipulator Based on Modelica. *Key Engineering Materials*, *579-580*, 467-475. https://doi.org/10.4028/www.scientific.net/KEM.579-580.467
World Bank. (2021). *Data for Colombia, Upper middle income | Data*. https://data.worldbank.org/?locations=CO-XT
World Food Programme. (2020). *5 facts about food waste and hunger* [World Food Programme]. https://www.wfp.org/stories/5-facts-about-food-waste-and-hunger
World Resources Institute. (2021). *Food Loss & Waste Protocol*. World Resources Institute. https://www.wri.org/initiatives/food-loss-waste-protocol
WWF-UK. (2021). *Driven to waste: The global impact of food loss and waste on farms*. https://wwfint.awsassets.panda.org/downloads/wwf_uk__driven_to_waste___the_global_impact_of_food_loss_and_waste_on_farms.pdf

Annexes

Annex 1 – questionnaires for transporters, retailers, and consumers

a. **Transportistas:**
https://docs.google.com/forms/d/e/1FAIpQLSctrBhGfrD-dMm1h_llyoEXfZKZuIa-uYnwkZkgohANM4FR_Q/viewform?usp=sf_link

b. **Minoristas:**
https://docs.google.com/forms/d/e/1FAIpQLSfc7-QIUW5u5cBZnyb5V9FrcGi0eJHBAOyVnqfJxtYZjG1u_A/viewform?usp=sf_link

c. **Consumidores finales:**
https://docs.google.com/forms/d/e/1FAIpQLSfEcc92MnoLdgulJHYv4qAiHri1Rlg03_6HjzxFxhx9n74XGQ/viewform?usp=sf_link

Annex 2 – python code used for the simulation

```
import pandas as pd
import numpy as np
```

```
pd.set_option('display.max_columns', None)
pd.set_option('display.max_rows', None)

from scipy.stats import poisson

import scipy.stats as sct

#regression coefficients to evaluate the banana ripeness degree
r1_intercept=-2.579571363
r1_temp_coef=0.171910625
r1_time_coef=0.015313877

r1_intercept_stderror=1.176541382
r1_temp_coef_stderror=0.040119925
r1_time_coef_stderror=0.002772007


r2_intercept=1.230552622
r2_temp_coef=0.059838085
r2_time_coef=0.015707497

r2_intercept_stderror=0.397903612
r2_temp_coef_stderror=0.015032845
r2_time_coef_stderror=0.001803406


r3_intercept=2.712962963
r3_temp_coef=0.037037037
r3_time_coef=0.012731481


r3_intercept_stderror=0.391488957
r3_temp_coef_stderror=0.015120307
r3_time_coef_stderror=0.002216266

simulated=pd.DataFrame()

for i in range(0,1000): #simulate 1000 times

   #simulate the variables across the journey of a one-ton truck from Farm to Plaza
Mayorista
   farm_stay_temp=np.random.uniform(low=12,high=26, size=1)
   farm_stay_time=poisson.rvs(mu=0.5, size=1)
   farm_stay_mechanical_damage=np.random.triangular(left=0.1, mode=5, right=10, size=1)

   farmtodc_loading_time=np.random.normal(loc=1.67, scale=0.167, size=1)
   farmtodc_loading_temp=np.random.uniform(low=12,high=26, size=1)
```

```
    farmtodc_transit_time=np.random.normal(loc=1, scale=0.25, size=1)
    farmtodc_transit_temp=np.random.uniform(low=10,high=31, size=1)
    farmtodc_accident_or_road_blockage=np.random.uniform(low=0,high=101, size=1)
    if farmtodc_accident_or_road_blockage>98:
        farmtodc_accident_or_road_blockage=[1]
    else:
        farmtodc_accident_or_road_blockage=[0]
    farmtodc_transit_mechanical_damage=np.random.triangular(left=0.1, mode=5, right=10,
size=1)

    indc_unloading_time=np.random.normal(loc=1.67, scale=0.167, size=1)
    indc_unloading_temp=np.random.uniform(low=9,high=20, size=1)
    indc_stay_temp=np.random.uniform(low=13,high=19.5, size=1)
    indc_stay_time=poisson.rvs(mu=48, size=1)

    dctoplaza_loading_time=np.random.normal(loc=1.67, scale=0.167, size=1)
    dctoplaza_loading_temp=np.random.uniform(low=9,high=20, size=1)
    dctoplaza_transit_time=np.random.normal(loc=4, scale=1, size=1)
    dctoplaza_transit_temp=np.random.uniform(low=10,high=31, size=1)
    dctoplaza_mechanical_damage=np.random.triangular(left=0.1, mode=5, right=10, size=1)

    plaza_unloading_time=np.random.normal(loc=1.67, scale=0.167, size=1)
    plaza_unloading_temp=np.random.uniform(low=17,high=26, size=1)
    plaza_stay_temp=np.random.uniform(low=13,high=26, size=1)
    plaza_stay_time=poisson.rvs(mu=12, size=1)

    #if an accident or road blockage happens, farm stay time and transit time are updated
    if farmtodc_accident_or_road_blockage==0:
        pass
    else:
        farmtodc_transit_time=farmtodc_transit_time+np.random.normal(loc=1, scale=0.25,
size=1)+np.random.normal(loc=1, scale=0.25, size=1)
        farm_stay_time= farm_stay_time+poisson.rvs(mu=0.5, size=1)

    '''simulate the initial degree of ripeness for each
of the boxes in the truck. Assuming one box weighs 15kg,
    Sixty-seven boxes are required in one tun truck. '''

    l=np.random.normal(loc=0,scale=0.25, size=67)
    l=[abs(i) for i in l]

    initial_degree_of_ripening_banana_boxes=[i+1 for i in l]

    #delete this delete this
    initial_degree_of_ripening_banana_boxes=[1 for i in l]
```

```
    '''creating empty lists to store ripening degrees at the end of each stage in the truck
journey for each box.
    Each list will have 67 values, one for each box'''

    final_farm_ripening_degree_list=[]
    final_farmdctransit_ripening_degree_list=[]
    final_dc_ripening_degree_list=[]
    final_dcplazatransit_ripening_degree_list=[]
    final_plaza_ripening_degree_list=[]

    ''' For each of the 67 boxes, simulate and calculate the banana ripening degree at each
stage'''
    for i in range(0,len(initial_degree_of_ripening_banana_boxes)):


simulated_r1_intercept=sct.norm.ppf(q=np.random.randint(low=51,high=100)/100,loc=r1_i
ntercept,scale=r1_intercept_stderror)

simulated_r1_temp_coef=sct.norm.ppf(q=np.random.randint(low=51,high=100)/100,loc=r1
_temp_coef,scale=r1_temp_coef_stderror)

simulated_r1_time_coef=sct.norm.ppf(q=np.random.randint(low=51,high=100)/100,loc=r1_
time_coef,scale=r1_time_coef_stderror)


simulated_r2_intercept=sct.norm.ppf(q=np.random.randint(low=51,high=100)/100,loc=r2_i
ntercept,scale=r2_intercept_stderror)

simulated_r2_temp_coef=sct.norm.ppf(q=np.random.randint(low=51,high=100)/100,loc=r2
_temp_coef,scale=r2_temp_coef_stderror)

simulated_r2_time_coef=sct.norm.ppf(q=np.random.randint(low=51,high=100)/100,loc=r2_
time_coef,scale=r2_time_coef_stderror)


simulated_r3_intercept=sct.norm.ppf(q=np.random.randint(low=51,high=100)/100,loc=r3_i
ntercept,scale=r3_intercept_stderror)

simulated_r3_temp_coef=sct.norm.ppf(q=np.random.randint(low=51,high=100)/100,loc=r3
_temp_coef,scale=r3_temp_coef_stderror)

simulated_r3_time_coef=sct.norm.ppf(q=np.random.randint(low=51,high=100)/100,loc=r3_
time_coef,scale=r3_time_coef_stderror)
        #FARM STAGE

        if initial_degree_of_ripening_banana_boxes[i]<=1.4:
```

```
final_farm_ripening_degree=r1_intercept+r1_temp_coef*farm_stay_temp+r1_time_coef*f
arm_stay_time
        elif initial_degree_of_ripening_banana_boxes[i]>1.4 and
initial_degree_of_ripening_banana_boxes[i]<=1.9:

final_farm_ripening_degree=simulated_r1_intercept+simulated_r1_temp_coef*farm_stay_
temp+simulated_r1_time_coef*farm_stay_time
        elif initial_degree_of_ripening_banana_boxes[i]>1.9 and
initial_degree_of_ripening_banana_boxes[i]<=2.4:

final_farm_ripening_degree=r2_intercept+r2_temp_coef*farm_stay_temp+r2_time_coef*f
arm_stay_time
        elif initial_degree_of_ripening_banana_boxes[i]>2.4 and
initial_degree_of_ripening_banana_boxes[i]<=2.9:

final_farm_ripening_degree=simulated_r2_intercept+simulated_r2_temp_coef*farm_stay_
temp+simulated_r2_time_coef*farm_stay_time
        elif initial_degree_of_ripening_banana_boxes[i]>2.9 and
initial_degree_of_ripening_banana_boxes[i]<=3.4:

final_farm_ripening_degree=r3_intercept+r3_temp_coef*farm_stay_temp+r3_time_coef*f
arm_stay_time
        else:

final_farm_ripening_degree=simulated_r3_intercept+simulated_r3_temp_coef*farm_stay_
temp+simulated_r3_time_coef*farm_stay_time

        final_farm_ripening_degree=max(1,final_farm_ripening_degree[0])
        #FARM TO DC TRANSIT STAGE
        #loading operation
        if final_farm_ripening_degree<=1.4:

final_farmdctransit_ripening_degree=r1_intercept+r1_temp_coef*farmtodc_loading_temp
+r1_time_coef*farmtodc_loading_time
        elif final_farm_ripening_degree>1.4 and final_farm_ripening_degree<=1.9:

final_farmdctransit_ripening_degree=simulated_r1_intercept+simulated_r1_temp_coef*far
mtodc_loading_temp+simulated_r1_time_coef*farmtodc_loading_time
        elif final_farm_ripening_degree>1.9 and final_farm_ripening_degree<=2.4:

final_farmdctransit_ripening_degree=r2_intercept+r2_temp_coef*farmtodc_loading_temp
+r2_time_coef*farmtodc_loading_time
        elif final_farm_ripening_degree>2.4 and final_farm_ripening_degree<=2.9:

final_farmdctransit_ripening_degree=simulated_r2_intercept+simulated_r2_temp_coef*far
mtodc_loading_temp+simulated_r2_time_coef*farmtodc_loading_time
```

```
    elif final_farm_ripening_degree>2.9 and final_farm_ripening_degree<=3.4:

final_farmdctransit_ripening_degree=r3_intercept+r3_temp_coef*farmtodc_loading_temp
+r3_time_coef*farmtodc_loading_time
    else:

final_farmdctransit_ripening_degree=simulated_r3_intercept+simulated_r3_temp_coef*far
mtodc_loading_temp+simulated_r3_time_coef*farmtodc_loading_time


    #transit operation
    if final_farmdctransit_ripening_degree<=1.4:

final_farmdctransit_ripening_degree=r1_intercept+r1_temp_coef*farmtodc_transit_temp+
r1_time_coef*farmtodc_transit_time
    elif final_farmdctransit_ripening_degree>1.4 and
final_farmdctransit_ripening_degree<=1.9:

final_farmdctransit_ripening_degree=simulated_r1_intercept+simulated_r1_temp_coef*far
mtodc_transit_temp+simulated_r1_time_coef*farmtodc_transit_time
    elif final_farmdctransit_ripening_degree>1.9 and
final_farmdctransit_ripening_degree<=2.4:

final_farmdctransit_ripening_degree=r2_intercept+r2_temp_coef*farmtodc_transit_temp+
r2_time_coef*farmtodc_transit_time
    elif final_farmdctransit_ripening_degree>2.4 and
final_farmdctransit_ripening_degree<=2.9:

final_farmdctransit_ripening_degree=simulated_r2_intercept+simulated_r2_temp_coef*far
mtodc_transit_temp+simulated_r2_time_coef*farmtodc_transit_time
    elif final_farmdctransit_ripening_degree>2.9 and
final_farmdctransit_ripening_degree<=3.4:

final_farmdctransit_ripening_degree=r3_intercept+r3_temp_coef*farmtodc_transit_temp+
r3_time_coef*farmtodc_transit_time
    else:

final_farmdctransit_ripening_degree=simulated_r3_intercept+simulated_r3_temp_coef*far
mtodc_transit_temp+simulated_r3_time_coef*farmtodc_transit_time

    ##IN DC STAGE
    #unloading operation
    if final_farmdctransit_ripening_degree<=1.4:

final_dc_ripening_degree=r1_intercept+r1_temp_coef*indc_unloading_temp+r1_time_coef
*indc_unloading_time
```

```
    elif final_farmdctransit_ripening_degree>1.4 and
final_farmdctransit_ripening_degree<=1.9:

final_dc_ripening_degree=simulated_r1_intercept+simulated_r1_temp_coef*indc_unloadin
g_temp+simulated_r1_time_coef*indc_unloading_time
    elif final_farmdctransit_ripening_degree>1.9 and
final_farmdctransit_ripening_degree<=2.4:

final_dc_ripening_degree=r2_intercept+r2_temp_coef*indc_unloading_temp+r2_time_coef
*indc_unloading_time
    elif final_farmdctransit_ripening_degree>2.4 and
final_farmdctransit_ripening_degree<=2.9:

final_dc_ripening_degree=simulated_r2_intercept+simulated_r2_temp_coef*indc_unloadin
g_temp+simulated_r2_time_coef*indc_unloading_time
    elif final_farmdctransit_ripening_degree>2.9 and
final_farmdctransit_ripening_degree<=3.4:

final_dc_ripening_degree=r3_intercept+r3_temp_coef*indc_unloading_temp+r3_time_coef
*indc_unloading_time
    else:

final_dc_ripening_degree=simulated_r3_intercept+simulated_r3_temp_coef*indc_unloadin
g_temp+simulated_r3_time_coef*indc_unloading_time

    #stay operation
    if final_dc_ripening_degree<=1.4:

final_dc_ripening_degree=r1_intercept+r1_temp_coef*indc_stay_temp+r1_time_coef*indc
_stay_time
    elif final_dc_ripening_degree>1.4 and final_dc_ripening_degree<=1.9:

final_dc_ripening_degree=simulated_r1_intercept+simulated_r1_temp_coef*indc_stay_te
mp+simulated_r1_time_coef*indc_stay_time
    elif final_dc_ripening_degree>1.9 and final_dc_ripening_degree<=2.4:

final_dc_ripening_degree=r2_intercept+r2_temp_coef*indc_stay_temp+r2_time_coef*indc
_stay_time
    elif final_dc_ripening_degree>2.4 and final_dc_ripening_degree<=2.9:

final_dc_ripening_degree=simulated_r2_intercept+simulated_r2_temp_coef*indc_stay_te
mp+simulated_r2_time_coef*indc_stay_time
    elif final_dc_ripening_degree>2.9 and final_dc_ripening_degree<=3.4:

final_dc_ripening_degree=r3_intercept+r3_temp_coef*indc_stay_temp+r3_time_coef*indc
_stay_time
    else:
```

```
final_dc_ripening_degree=simulated_r3_intercept+simulated_r3_temp_coef*indc_stay_te
mp+simulated_r3_time_coef*indc_stay_time

    #DC TO PLAZA TRANSIT STAGE
    #loading operation
    if final_dc_ripening_degree<=1.4:

final_dcplazatransit_ripening_degree=r1_intercept+r1_temp_coef*dctoplaza_loading_temp
+r1_time_coef*dctoplaza_loading_time
    elif final_dc_ripening_degree>1.4 and final_dc_ripening_degree<=1.9:

final_dcplazatransit_ripening_degree=simulated_r1_intercept+simulated_r1_temp_coef*dc
toplaza_loading_temp+simulated_r1_time_coef*dctoplaza_loading_time
    elif final_dc_ripening_degree>1.9 and final_dc_ripening_degree<=2.4:

final_dcplazatransit_ripening_degree=r2_intercept+r2_temp_coef*dctoplaza_loading_temp
+r2_time_coef*dctoplaza_loading_time
    elif final_dc_ripening_degree>2.4 and final_dc_ripening_degree<=2.9:

final_dcplazatransit_ripening_degree=simulated_r2_intercept+simulated_r2_temp_coef*dc
toplaza_loading_temp+simulated_r2_time_coef*dctoplaza_loading_time
    elif final_dc_ripening_degree>2.9 and final_dc_ripening_degree<=3.4:

final_dcplazatransit_ripening_degree=r3_intercept+r3_temp_coef*dctoplaza_loading_temp
+r3_time_coef*dctoplaza_loading_time
    else:

final_dcplazatransit_ripening_degree=simulated_r3_intercept+simulated_r3_temp_coef*dc
toplaza_loading_temp+simulated_r3_time_coef*dctoplaza_loading_time

    #transit operation
    if final_dcplazatransit_ripening_degree<=1.4:

final_dcplazatransit_ripening_degree=r1_intercept+r1_temp_coef*dctoplaza_transit_temp
+r1_time_coef*dctoplaza_transit_time
    elif final_dcplazatransit_ripening_degree>1.4 and
final_dcplazatransit_ripening_degree<=1.9:

final_dcplazatransit_ripening_degree=simulated_r1_intercept+simulated_r1_temp_coef*dc
toplaza_transit_temp+simulated_r1_time_coef*dctoplaza_transit_time
    elif final_dcplazatransit_ripening_degree>1.9 and
final_dcplazatransit_ripening_degree<=2.4:

final_dcplazatransit_ripening_degree=r2_intercept+r2_temp_coef*dctoplaza_transit_temp
+r2_time_coef*dctoplaza_transit_time
```

```
    elif final_dcplazatransit_ripening_degree>2.4 and
final_dcplazatransit_ripening_degree<=2.9:

final_dcplazatransit_ripening_degree=simulated_r2_intercept+simulated_r2_temp_coef*dc
toplaza_transit_temp+simulated_r2_time_coef*dctoplaza_transit_time
    elif final_dcplazatransit_ripening_degree>2.9 and
final_dcplazatransit_ripening_degree<=3.4:

final_dcplazatransit_ripening_degree=r3_intercept+r3_temp_coef*dctoplaza_transit_temp
+r3_time_coef*dctoplaza_transit_time
    else:

final_dcplazatransit_ripening_degree=simulated_r3_intercept+simulated_r3_temp_coef*dc
toplaza_transit_temp+simulated_r3_time_coef*dctoplaza_transit_time

    #PLAZA STAGE
    #unloading stage
    if final_dcplazatransit_ripening_degree<=1.4:

final_plaza_ripening_degree=r1_intercept+r1_temp_coef*plaza_unloading_temp+r1_time_
coef*plaza_unloading_time
    elif final_dcplazatransit_ripening_degree>1.4 and
final_dcplazatransit_ripening_degree<=1.9:

final_plaza_ripening_degree=simulated_r1_intercept+simulated_r1_temp_coef*plaza_unlo
ading_temp+simulated_r1_time_coef*plaza_unloading_time
    elif final_dcplazatransit_ripening_degree>1.9 and
final_dcplazatransit_ripening_degree<=2.4:

final_plaza_ripening_degree=r2_intercept+r2_temp_coef*plaza_unloading_temp+r2_time_
coef*plaza_unloading_time
    elif final_dcplazatransit_ripening_degree>2.4 and
final_dcplazatransit_ripening_degree<=2.9:

final_plaza_ripening_degree=simulated_r2_intercept+simulated_r2_temp_coef*plaza_unlo
ading_temp+simulated_r2_time_coef*plaza_unloading_time
    elif final_dcplazatransit_ripening_degree>2.9 and
final_dcplazatransit_ripening_degree<=3.4:

final_plaza_ripening_degree=r3_intercept+r3_temp_coef*plaza_unloading_temp+r3_time_
coef*plaza_unloading_time
    else:

final_plaza_ripening_degree=simulated_r3_intercept+simulated_r3_temp_coef*plaza_unlo
ading_temp+simulated_r3_time_coef*plaza_unloading_time

    #stay operation
```

```
        if final_plaza_ripening_degree<=1.4:

final_plaza_ripening_degree=r1_intercept+r1_temp_coef*plaza_stay_temp+r1_time_coef*
plaza_stay_time
        elif final_plaza_ripening_degree>1.4 and final_plaza_ripening_degree<=1.9:

final_plaza_ripening_degree=simulated_r1_intercept+simulated_r1_temp_coef*plaza_stay
_temp+simulated_r1_time_coef*plaza_stay_time
        elif final_plaza_ripening_degree>1.9 and final_plaza_ripening_degree<=2.4:

final_plaza_ripening_degree=r2_intercept+r2_temp_coef*plaza_stay_temp+r2_time_coef*
plaza_stay_time
        elif final_plaza_ripening_degree>2.4 and final_plaza_ripening_degree<=2.9:

final_plaza_ripening_degree=simulated_r2_intercept+simulated_r2_temp_coef*plaza_stay
_temp+simulated_r2_time_coef*plaza_stay_time
        elif final_plaza_ripening_degree>2.9 and final_plaza_ripening_degree<=3.4:

final_plaza_ripening_degree=r3_intercept+r3_temp_coef*plaza_stay_temp+r3_time_coef*
plaza_stay_time
        else:

final_plaza_ripening_degree=simulated_r3_intercept+simulated_r3_temp_coef*plaza_stay
_temp+simulated_r3_time_coef*plaza_stay_time

        final_farm_ripening_degree_list.append(final_farm_ripening_degree)
        final_farmdctransit_ripening_degree_list.append(final_farmdctransit_ripening_degree)
        final_dc_ripening_degree_list.append(final_dc_ripening_degree)

final_dcplazatransit_ripening_degree_list.append(final_dcplazatransit_ripening_degree)
        final_plaza_ripening_degree_list.append(final_plaza_ripening_degree)

    #once we have simulated the banana ripening stage for each box, store it in a data frame
and calculate the loss
    a=pd.DataFrame(final_farm_ripening_degree_list)
    b=pd.DataFrame(final_farmdctransit_ripening_degree_list)
    c=pd.DataFrame(final_dc_ripening_degree_list)
    d=pd.DataFrame(final_dcplazatransit_ripening_degree_list)
    e=pd.DataFrame(final_plaza_ripening_degree_list)
    f=pd.concat([a,b,c,d,e],axis=1)


f.columns=['final_farm_ripening_degree','final_farmdctransit_ripening_degree','final_dc_rip
ening_degree',\
            'final_dcplazatransit_ripening_degree','final_plaza_ripening_degree']
```

```
    f['loss_flag']=f['final_plaza_ripening_degree']>4 #anything with a degree >4 is considered
loss

    loss_due_to_temp_time=f['loss_flag'].sum()*100/67
    loss_due_to_mechanical_damage=100*(1-((100-farm_stay_mechanical_damage)*(100-
farmtodc_transit_mechanical_damage)*(100-dctoplaza_mechanical_damage)/1000000))
    x=pd.DataFrame([loss_due_to_temp_time,loss_due_to_mechanical_damage[0]]).T
    x.columns=['Loss% due to temperature and transit time','Loss% due to mechanical
damage']


y=pd.DataFrame([farm_stay_temp,farm_stay_time,farm_stay_mechanical_damage,farmtod
c_loading_time,farmtodc_loading_temp,

farmtodc_transit_time,farmtodc_transit_temp,farmtodc_accident_or_road_blockage,farmt
odc_transit_mechanical_damage,

indc_unloading_time,indc_unloading_temp,indc_stay_temp,indc_stay_time,dctoplaza_load
ing_time,

dctoplaza_loading_temp,dctoplaza_transit_time,dctoplaza_transit_temp,dctoplaza_mechan
ical_damage,
            plaza_unloading_time,plaza_unloading_temp,plaza_stay_temp,plaza_stay_time])
    y=y.T

y.columns=['farm_stay_temp_in_celcius','farm_stay_time_in_hrs','farm_stay_mechanical_d
amage','farmtodc_loading_time_in_hrs','farmtodc_loading_temp_in_celcius',

'farmtodc_transit_time_in_hrs','farmtodc_transit_temp_in_celcius','farmtodc_accident_or_
road_blockage','farmtodc_transit_mechanical_damage',

'indc_unloading_time_in_hrs','indc_unloading_temp_in_celcius','indc_stay_temp_in_celcius
','indc_stay_time_in_hrs','dctoplaza_loading_time_in_hrs',

'dctoplaza_loading_temp_in_celcius','dctoplaza_transit_time_in_hrs','dctoplaza_transit_te
mp_in_celcius','dctoplaza_mechanical_damage',

'plaza_unloading_time_in_hrs','plaza_unloading_temp_in_celcius','plaza_stay_temp_in_cel
cius','plaza_stay_time_in_hrs']
    y=pd.concat([y,x],axis=1)

    simulated=pd.concat([simulated,y])

simulated.to_csv('simulation_runs.csv',index=False)
```