Prevention schemes for future fresh agricultural products (FAPs) supply chain: mathematical model and experience of guaranteeing the supply of FAPs during the COVID-19 pandemic

Shi Yin, Lan Bai and Runqing Zhang

Abstract

BACKGROUND: The COVID-19 outbreak caused short-term disruptions in the supply chain of fresh agricultural products (FAPs), which exposed the vulnerability of the existing FAP supply chain. With pandemic control being widely coordinated, the supply chain of FAPs was gradually optimized and improved. However, after the outbreak of COVID-19, achieving an effective supply of FAPs in future pandemics has become a key issue. The present work therefore aimed to construct a three-level supply chain based on the Stackelberg game model, consisting of suppliers, third-party logistics (TPL), and retailers, to guarantee the supply of FAPs. COVID-19 pandemic factors such as virus infection coefficients and pandemic prevention efforts were fully integrated into the model.

RESULTS: Compared with the wholesale prices of FAPs, preservation efforts and pandemic prevention efforts have huge impacts on the retail prices of FAPs. When suppliers are in the leading position, the quality assurance effort level is positively correlated with the optimal profit. Compared with this situation, when FAP retailers are in the leading position, TPL providers show higher levels of pandemic prevention effort and FAP preservation effort. With an increase in consumer preference for pandemic prevention, the profits of supply-chain members when FAP retailers are in the leading position will gradually increase.

CONCLUSION: This study reveals an effective supply mechanism for FAPs in metropolitan areas during the COVID-19 pandemic and describes the authors’ experience of guaranteeing the quality and safety of FAPs for future pandemic cases.

Keywords: fresh agricultural products; COVID-19; pandemic prevention; supply-chain coordination; Stackelberg game

INTRODUCTION

In 2002, the first case of SARS was found in Guangdong, China. According to a report released by the World Health Organization (WHO), as of 7 August 2003, there had been 8422 cases of SARS worldwide, involving 32 countries and regions. The sudden disaster of SARS not only caused huge economic losses but also had a profound impact on the lives of metropolitan residents in terms of the supply of fresh agricultural products (FAPs).1 According to the latest real-time statistics from the WHO, as of 15:58 Central European time on 28 October 2020, there have been 43,766,712 confirmed cases of COVID-19 globally and 1,163,459 cumulative deaths. On 28 October, there were 404,159 new confirmed cases of COVID-19 worldwide and 5,780 new deaths. In October 2020, France and Germany again sealed their cities. These phenomena indicate that the COVID-19 virus is likely to sweep across the world again this winter. COVID-19 has had a serious impact on the lives of metropolitan residents in terms of their supply of FAPs.

In the Beijing Xinfadi Market, a novel coronavirus nucleic acid test administered to FAPs was found to be positive. Subsequently, novel coronavirus nucleic acid was detected in packaging samples of frozen white shrimp produced in South America in Dalian, Xiamen, and Qingdao. Table 1 shows the detection results of COVID-19 associated with FAPs over the last 6 months. Fresh agricultural products mainly refer to the primary products of vegetables, fruits, meat, eggs, milk, and seafood, which are the main food sources consumed in people’s daily lives.2 The degree of freshness is an important standard that measures agricultural product value. The biggest drawback of fresh produce is that it is perishable. Cold-chain logistics requires the use of temperature control to ensure the safety and quality of FAPs. As the pandemic...
intensifies, the demand for FAPs in the lives of metropolitan residents increases gradually. This also causes the market demand for FAPs such as vegetables, fruits, and meat to expand. The distribution of FAPs in China is extremely uneven. Inner Mongolia is rich in beef and mutton, and the fishing industry is concentrated around the coastal zone. Cold-chain transportation in the supply chain of FAPs is fragmented. In general, the FAP supply chain in China mainly has the following characteristics. First, the FAP logistics system is not perfect; the fresh loss rate is high, and there is an insufficient input of cold-chain logistics facilities and equipment, such as refrigerated trucks and warehouses. Second, due to the lack of facilities and equipment for cold-chain logistics, most FAP supply chains in China cover a regional area, and the circulation radius of FAPs is small. In addition, the FAP supply chains are also too dispersed at both ends. Due to the highly dispersed production and consumption markets, the organization of FAPs is difficult, and a multi-level supply-chain structure is hard to avoid. The COVID-19 outbreak caused short-term disruptions in the supply chain of FAPs, which exposed the vulnerability of the existing FAP supply chain.

It should be emphasized that the cold-chain transportation of FAPs could easily become a means of spreading the novel coronavirus as it provides an appropriate temperature. Most viruses can survive for a long time at low temperatures in cold-chain transportation. The sequential flow of the cold supply chain is shown in Fig. 1. The entire cold-chain transportation system should meet the needs of metropolitan residents in the COVID-19 pandemic. From the production and processing of FAPs to their cold storage; to the cold chain transport vehicles, containers, and ships used; to the destination of the cold storage; and then through the destination of the cold chain transport vehicles to the market, each step involves a large number of practitioners. If the outbreak is still

| Event time  | Event content                                                                                                                                 |
|-------------|----------------------------------------------------------------------------------------------------------------------------------------------|
| 10 July     | Novel coronavirus was detected in three batches of frozen shrimp containers imported from Ecuador by Dalian customs and Xiamen customs.     |
| 14 July     | Some consumers in Pingxiang City, Jiangxi province, bought Ecuadorian frozen shrimp through a group-buying platform. The inner wall and outer package of the same batch of products tested positive for nucleic acid from the novel coronavirus. |
| 15 July     | Novel coronavirus nucleic acid test of some Ecuadorian frozen shrimp packaging was found positive in a frozen warehouse in Western Chongqing logistics park in Shapingba District, Chongqing. |
| 16 July     | Yunnan province reported that the outer surface of the packing cases of three samples of Ecuadorian frozen shrimp tested positive for novel coronavirus nucleic acid. |
| 23 July     | Novel coronavirus was detected in a number of samples from Dalian Kaiyang seafood refrigerator, processing workshop, dormitory, cafeteria, and environment. |
| 11 August   | Novel coronavirus nucleic acid test results of packaged samples of frozen seafood products imported from Dalian port by three enterprises in Yantai, Shandong province, were found to be positive. |
| 12 August   | Novel coronavirus nucleic acid test of a packaging sample of Ecuadorian frozen shrimp imported from a restaurant in Wuhu, Anhui province, was found to be positive. |
| 12 August   | Two samples of Brazilian frozen chickens submitted by The Center for Disease Control and Prevention in Longgang District, Shenzhen, tested positive for novel coronavirus nucleic acid. |
| 24 September| In Qingdao, 1440 samples of cold chain products and environmental samples were collected, and a total of 51 samples were positive. |

**Figure 1.** The sequential flow of the cold supply chain of FAPs.
ongoing in the places where food is produced, there is a risk that workers will become infected. Once one link of the FAPs chain becomes contaminated with the novel coronavirus, the risk of the whole system becoming contaminated will be high. Many institutions and scholars believe that the source of the virus that caused the epidemic situation in Xinfadi, Beijing, is most likely to have been food imported in the cold chain from regions with a high COVID-19 incidence outside China. If FAPs carry the virus, it can easily be transported through the cold-chain to large cities and then directly infect residents.

Many studies have explored the operational problems of the FAP supply chain, such as sowing, production, harvesting, transportation, distribution, inventory, sales, and returns. The aim of these studies is mostly to optimize the operation efficiency of the FAP supply chain. The circulation modes of FAPs can be divided into two types: single-channel supply chains and double-channel supply chains. In the context of COVID-19, the single-channel supply chain was used as the research scenario in this study to reduce unnecessary exposure effectively. Table 2 shows recent research references on FAPs supply chains.

The above studies mainly analyzed the optimization management of the supply chain of FAPs, but there are several studies that have focused on the supply chain of FAPs under emergencies. Emergencies require supply chain coordination or the original plan will no longer be feasible, and affect the operation decisions of FAPs supply chains. To this end, Rabbani et al. found that the initial amount bought by the purchaser is negatively correlated with the strike price of the option in an option contract application in relief material supply chains. Saputra et al. studied the impact of the average interval of sudden disasters between the emergency drug reserve and established the emergency drug reserve model. Some scholars have also emphasized the importance of quantitative flexible contracts. He and Yang reduced the buyer’s profit risk in the supply chain through the implementation of a quantity elastic contract. Nikkhoo et al. used a quantity flexible contract to coordinate procurement activities in a three-level supply chain.

In the context of the COVID-19 pandemic, the above topics have received extensive attention from many scholars.

- From an integrated perspective, Everstine argued that the global food supply chain has seen major disruptions due to the COVID-19 pandemic. Boughton et al. stated that COVID-19 health restrictions disrupted every aspect of the agri-food system. Torero et al. believed that the greatest concern in the context of the COVID-19 pandemic is the disruption to the food system and the impact on food security.
- From a functional perspective, Zhang et al. used an economy-wide multisector model to assess the impact of COVID-19 on China’s agri-food system in terms of value added and employment. Kumar et al. believed that the COVID-19 crisis exposed the fragility of India’s agri-food system and highlighted the need for agricultural market reforms and digital solutions to improve the agri-food system. Bhavani and Gopinath argued that establishing region-specific agricultural systems based on local agri-food value chains can help improve the diversity of households’ diets to meet the challenges posed by the COVID-19 pandemic. Weersink et al. stated that the outbreak of the COVID-19 pandemic exposed the fragility of the agribusiness system, and that the continued spread of the pandemic is likely to push the supply chain towards a higher degree of integration and product diversification.
- From the factor perspective, Coluccia et al. studied the risk level of the agri-food sector with regard to the coronavirus pandemic and concluded that fresh and perishable products produced or harvested during COVID-19 are affected by the price level. Mussell et al. argued that COVID-19 brings different situations and risks of its own to the agri-food system, where workplace absences due to disease and fear of disease affect the viability and continuity of certain businesses. Hussain highlighted the potential risks facing the agri-food sector due to the COVID-19 pandemic and noted that many countries have emphasized the need for key agricultural inputs, such as fertilizers and safe, high-quality seeds, to mitigate the impact of COVID-19 on food security. Heck et al. argued that the restrictions on the movement of people and goods in developing countries due to COVID-19 have impaired access to markets, services, and food, and they highlighted that connectivity is at the heart of agri-food systems. Snow et al. conducted a quantitative and qualitative assessment of the impact, adaptation, and opportunities of agricultural systems in Australia and New Zealand to improve the resilience of agricultural systems, arguing that the COVID-19 pandemic impacted agri-food systems through labor, goods and services, value chains, and markets. Stephens et al. believed that, in the context of the COVID-19 pandemic, fresh vegetables, fruits, and milk are wasted because farmers or entrepreneurs are unable to transport fresh vegetables, fruits, and milk from the place of production to local markets or supermarkets in nearby towns or cities. Poppe stated that the COVID-19 pandemic has highlighted the fragility of the agri-food system and wider society while promoting the development of supply chains and multifunctional agriculture, and that the ‘green high-tech transformation’ has played a major role in changing the lifestyles of residents. Hobbs studied the impact of demand-side and supply-side shocks on the food supply chain in the context of the COVID-19 pandemic, and concluded that the panic-buying behavior of consumers and sudden changes in consumption patterns were important factors affecting the demand side, while labor shortage and transportation network disruption were important factors affecting the supply side. Kumar and Singh argued that, during the COVID-19 pandemic, increasing the resilience of the agricultural supply chain in handling perishable items could help farmers, food processors, distributors, and retailers maintain an uninterrupted flow of food from farmers to end users in an uncertain business environment.
- In the COVID-19 pandemic, technologies such as artificial intelligence (AI), blockchains, and sensors should also be integrated into the agri-food supply chain in applications such as smart proactive packaging and advanced traceability systems that can directly track food and goods from farm to fork. Rowan and Galanakis believed that the post-COVID-19 era of the agri-food supply chain should be more intensive while meeting the high demand for new green trading innovations, with digital technology playing an important role. Galanakis et al. investigated the four issues of the food sector (food safety, bioactive food compounds, food security, and sustainability) in the context of the COVID-19 pandemic and concluded that the integrated application of digital technologies such as big data, AI, Internet of Things, and blockchain in the food supply chain has redefined the way we consume food and has the highest innovation potential in the new era. Di Vaio et al. investigated the application of AI in the agri-food supply chain and argued that considering AI in the context of the COVID-19 pandemic.
## Table 2. Recent research references on FAPs supply chains

| Supply-chain structure | Supply-chain process | Critical factors | Research objectives | References |
|------------------------|---------------------|-----------------|------------------|-----------|
| Producer–seller        | Harvest–sales       | Quality loss    | The mixed-response model after harvest can effectively reduce the quality loss of the supply chain. | Blackburn and Scudder2 |
| Manufacturer–distributor | Production–transportation–sales | Quantity and quality loss | The design of an incentive mechanism can realize the coordination of the interests of both sides. | Cai et al.4 |
| Manufacturer–third-party logistics (TPL)–distributor | Production–transportation–sales | Quantity and quality loss | TPL has a significant impact on supply-chain performance. | Cai et al.5 |
| Producer–export–local market | Production–transportation–sales | The number of losses | Replenishment by order and replenishment by stock will have different effects on product loss. | Cai and Zhou6 |
| Producer–seller        | Production–sales    | Uncertainty about output, demand, and prices | To manage uncertainty, vendors need to strike a balance between resource inputs and revenue. | Gokarn et al.7 |
| Fresh e-commerce– Offline physical stores | Online–offline sales | Circulation channel, loss | Online and offline dynamic pricing strategies influence each other. | He et al.8 |
| Manufacturer–processing center–distributor | Harvest–processing–distribution | Seasonality, demand and harvest uncertainty, loss | Customization of supply chain around the uncertainty of FAPs can improve the operation performance of the supply chain. | Jonkman et al.9 |
| Supplier–TPL–retailer  | Supply–transportation–sales | Quantity and quality loss | The revenue-sharing contract and the fresh-keeping effort level sharing contract can realize the supply-chain coordination and Pareto improvement. | Ma et al.10 |
| Supplier–seller        | Production–sales    | Cost in quantity and quality | The design of revenue-sharing and technology investment contract sharing can help to achieve coordination. | Mohammadi et al.11 |
| Manufacturer–retailer   | Production–distribution–inventory | Quality of whipped consumption | A method involving using a building quality loss model for production and distribution decisions was proposed. | Rong et al.12 |
| Supplier–retailer       | Production–transportation–sales | Random output and random demand | The contract was designed to increase the profit of supply-chain members under a controllable transport time. | Su et al.13 |
| Distributor–logistics service provider | Transportation–sales | Quantity and quality loss | The power structure affects contract design, enterprise decision behavior, and system performance. | Wu et al.14 |
| Manufacturer–distributor | Production–transportation–sales | The number of losses | Using the pull model can make both parties perform better. | Xiao and Chen15 |
| Supplier–TPL–retailer  | Production–transportation–sales | The number of losses | Cold chain service price and service sensitivity will affect the profit of supply-chain members. | Yu and Xiao16 |
| Supplier–TPL–retailer  | Supply–production–sales | Random output and random demand, quality loss | Wholesale price and logistics service price clearing contracts are introduced to realize supply-chain coordination. | Feng et al.17 |
| Supplier–retailer       | Supply–sales        | Quality loss     | Purchase price contract and wholesale price–fresh-keeping cost sharing contract can help the supply chain to improve the freshness of products. | Wang and Dan18 |
| Producer–wholesale market | Production–transportation–sales | Cost in quantity and quality | Different business models have a great impact on the decision-making and coordination mechanism of supply-chain members. | Xiao et al.19 |
| Manufacturer–distributor | Production–sales    | Cost in quantity and quality | Adjusting the strategy used for freshness preservation can affect both supply-chain members. | Zheng et al.20 |
pandemic could help achieve a sustainable and responsible business model. Galanakis\textsuperscript{53} believed that, in the context of the COVID-19 pandemic, to ensure food safety, Industry 4.0 tools should be introduced to reduce food losses and develop functional foods containing bioactive compounds and antioxidants to promote health and support the immune systems of consumers.

Although many studies have been carried out on agri-food value chains and COVID-19, there are still three points that need to be further explored: (i) The essential factors of COVID-19, such as the virus infection coefficient, pandemic prevention efforts, and preservation efforts, have not been considered effectively in the previous literature; (ii) there is a lack of research on how to guarantee the supply of FAPs to urban residents after the COVID-19 outbreak in metropolitan areas, and (iii) in the context of the COVID-19 pandemic, most studies have used methods such as theoretical overviews and literature summaries and have rarely used game theory to explore the guaranteed supply of FAPs in this scenario.

To make up for the deficiencies in existing research, this study mainly considers the COVID-19 outbreak in a metropolis. On the one hand, the perishable nature of FAPs determines that the logistics process should be efficient and rapid. How can suppliers, retailers, and third-party logistics (TPL) providers leverage their advantages to ensure the safety of FAPs to the greatest extent? On the other hand, in such a future scenario, how can we guarantee the quality and safety of FAPs in future pandemics for people in metropolitan areas? These two aspects need to be studied to reveal the optimal supply mechanism of FAPs for future urban responses to pandemics. Virus infection coefficients and pandemic prevention efforts were therefore introduced into our game model, which was established for the FAP supply chain with a background of COVID-19, consisting of suppliers, TPL providers, and retailers. Stackelberg game theory was used to find the optimal preservation effort level, wholesale price, retail price, and optimal profit result. This study not only reveals an effective supply mechanism for FAPs in the context of the COVID-19 pandemic but also provides experience of guaranteeing the quality and safety of FAPs for future pandemic cases. This study also enriches our theoretical understanding of the three-level supply chain of FAPs in the context of the COVID-19 pandemic.

The rest of this study is as follows. The theoretical basis and preservation model are analyzed in the next section. The article then shows the quality assurance strategy of FAPs and presents a comparative analysis of the control strategies of FAPs. Our conclusions and the future research directions are presented in the final section.

**THEORETICAL BASIS AND PRESERVATION MODEL**

**Theoretical basis**

The operation mechanism of FAPs supply chain

The FAP supply chain can be divided into five operation modes, with agricultural cooperatives, processing enterprises, wholesale FAP markets, supermarkets, and online platforms as the core.\textsuperscript{4,27} The agricultural cooperative model centered on connecting farmers and markets. The FAP wholesale market is the main way to supply FAPs to urban residents. The FAP wholesale market has a strong distribution function but its supporting facilities are not complete, which aggravates the loss of FAPs and reduces the logistics efficiency.\textsuperscript{17,20,27} In the context of COVID-19, the operational efficiency of the FAP supply chain needs to be improved rapidly.

To model the circular efficiency of FAPs, this study builds a supply chain model of FAPs based on the intelligent environment of big data, as shown in Fig. 2. The core values of FAP supply-chain innovation driven by big data technology include the digital management of channel sales business, omni-channel collaborative retail, and the digital intelligence of whole-process business processing. Based on the platform support of the FAP supply chain, big data intelligent technology can create small platforms designed to improve the operational efficiency of FAPs in the context of COVID-19 and other pandemic-level diseases.\textsuperscript{35,37,39,48}

The supply chain model of FAPs based on big data intelligence shown in Fig. 2 is different from the traditional supply chain of FAPs. This model is based on information technology and runs through the whole process of the supply, circulation, and sales of FAPs. The COVID-19 outbreak forced a rapid flow of information...
in the FAPs supply chain. The Internet, big data, cloud computing, and other methods are used to ensure the flow and smoothness of information and realize data sharing. In the upper reaches of the supply chain are the producers of FAPs, including farmers, agricultural production bases, and agricultural cooperatives. Cooperation between self-operation and TPL can optimize the warehousing and distribution mode. A combination of self-support and TPL is used to deliver products to consumers through multiple points of demand. Throughout the whole process, all members of the supply chain are closely connected, based on big data intelligence, to control the quality of FAPs in future pandemics effectively.

The emergency mechanism of FAPs supply chain
In the context of COVID-19, the supply chain of FAPs is not coordinated and smooth. On the one hand, consumers face structural supply constraints of FAPs, such as panic buying and hoarding. On the other hand, FAPs are unmarketable in some rural areas, and some livestock and poultry products cannot be sold. At the same time, due to the shortage of rework personnel in agricultural production areas, farmers cannot finish packing FAPs in a short time. Unsaleable FAPs in many regions lead to shortages of FAPs within short periods of time. The measures taken to close the cities and rural areas have a great impact on the external logistics transportation of the supply chain. If there is a COVID-19 outbreak, it is necessary to acquire professional manpower, facilities, technology, information, and other resources within a short period of time to control and deal with the emergency effectively. In this study, Fig. 3 shows the emergency mechanism of the FAP supply chain based on big data intelligence.

Figure 3 shows that the FAP information-sharing platform built by digital technologies is utilized and can organize the whole process quickly from the production to sales of FAPs. This model helps FAP supply-chain members to complete a series of operations such as procurement, sales, logistics, and finance. The model can also promote the improvement of FAP efficiency effectively. Big data intelligence allows the FAP supply-chain platform to connect a collection of retailers and suppliers to help them meet customer demand. The novelty of this model lies in its realization of a low-cost and fast-response FAP supply-chain operation. This study proposed a third-party emergency mode based on a FAPs emergency. If an outbreak of COVID-19 occurs and the farmers’ alliance is unable to respond, work can be outsourced to a professional third-party emergency response organization. Third-party emergency organizations can take advantage of their professional advantages to provide farmers with low-cost and efficient emergency services to provide sales networks and sales channels of FAPs in time for future pandemic cases.

Preservation model
Preservation strategy of FAPs
Compared with normal times, during the COVID-19 pandemic the TPL providers of FAPs have relatively high requirements in terms of cleanliness levels and preservation levels. The cold-chain logistics provided by TPL providers can not only greatly reduce the loss of FAPs in terms of quality and quantity in the processes of transportation, storage, distribution, and sales, but they can also greatly improve the cleanliness level of FAPs. In the context of COVID-19, TPL providers not only provide an important guarantee of the distribution efficiency of FAPs but also guarantee the quality and safety of FAPs. In addition to suppliers and retailers, TPL providers are also very important and necessary for the research subjects of the FAP supply chain. Hence, third parties are at risk of contracting the COVID-19 virus during the distribution of FAPs. The research methods used for the supply-chain optimization of FAPs mainly include mathematical modeling, the Nash game, the Stalberg game, the evolutionary game, and the cooperative game. Relevant game theory methods were therefore used in this study to describe the competition and cooperation relationship among the main bodies of the FAPs supply chain with...
the background of the COVID-19 pandemic. In the context of COVID-19, the Stackelberg game was used in this study to investigate the coordination of a FAPs three-level supply chain composed of suppliers, TPL providers, and retailers to ensure the supply of FAPs to metropolitan residents. The reasons why this approach was considered more suitable for this study than other methods are as follows.

In terms of research content, the COVID-19 outbreak led to a shortage of FAPs in metropolitan areas. In this context, there are two scenarios. In scenario 1, once a supplier of FAPs from outside the metropolitan area has a business opportunity, it may offer to supply FAPs to the metropolitan area to the retailer. As access to metropolitan areas would be restricted, FAP profits would increase. In scenario 2, FAP retailers in metropolitan areas are unable to meet residents’ demands for FAPs and may take the initiative to request FAPs from suppliers. Due to the virus risk in metropolitan areas, suppliers and retailers will consider their own interests and cannot reach an agreement. Therefore, the two scenarios in this study are in line with the application scenarios of the Stackelberg game.

In terms of research methods, in the context of the COVID-19 pandemic many scholars have discussed the supply-chain management of FAPs using qualitative or empirical methods. These studies focus on macro perspectives, such as how future policies can be developed to cope with long-term pandemics or to prevent future health emergencies. There is a lack of literature specifically using the Stackelberg game to explore how the preservation effort level, pandemic prevention effort level, and dominant maintenance status affect the optimal decisions about the three under different power structures. In the context of the COVID-19 pandemic, there are few studies that have analyzed the supply-chain management of FAPs with the Stackelberg game.

**Preservation scenario of FAPs**

In this study, a metropolitan outbreak of new crown pneumonia was set as the scenario. A good pandemic prevention effect has been maintained outside the metropolitan area, and the effect of this is that the new crown pneumonia pandemic has been effectively controlled. Under such circumstances, ensuring the quality and safety of FAPs in metropolitan areas is the problem to be solved in this study.

In this study, a three-echelon supply chain composed of a single supplier, a single TPL service provider, and a single retailer was used to ensure the quality and safety of FAPs in metropolitan areas in the case of a sudden new crown pneumonia outbreak. The specific operation process to protect the FAPs in metropolitan areas in the case of such an outbreak is the process by which the supplier of FAP determines the wholesale price $\pi_s$ of FAP based on the unit cost $c_w$ of FAPs and the demand $D$ for FAP; they also receive the total payment from the retailer of the FAPs. The fresh produce retailer determines the retail price $p_r$ of fresh produce. The demand for FAPs in the life of metropolitan residents is affected by the retail price $p_r$ and freshness $\theta$ of FAPs. Third-party logistics service providers provide a FAP cold-chain transport service. The unit cost is $c_p$ and the freshness preservation effort level and pandemic prevention effort level are $e_1$ and $e_2$, respectively. A certain freshness preservation and pandemic prevention cost $C$ is generated. The prices of FAP preservation and pandemic prevention services charged by the TPL service provider to the retailer are $P_1$ and $P_2$, respectively. Different Stackelberg master–slave game models were constructed according to a situation where the suppliers and retailers of FAPs are in the dominant position of guaranteed supply. In this study, Fig. 4 shows the quality- and safety-oriented strategy of FAPs in metropolitan areas with the participation of third-party logistics.

In the context of COVID-19, the short-term interruption of the cold-chain supply of FAPs has an impact on both supply and demand. The outbreak exposed the vulnerability of the existing FAP supply chain. After long-distance transportation, FAPs will deteriorate to a certain extent. This deterioration is not only reflected in a deterioration in the quality of FAPs caused by the decrease in the level of freshness but also in the reduction in the quantity caused by prior treatment due to putrefaction and deterioration. This will inevitably result in the number of FAPs arriving at the retailers in less than the quantity ordered, which causes the physical loss. Due to COVID-19 and other factors, the loss rate of FAPs was higher than in the previous transportation situation. Moreover, due to the sudden occurrence of COVID-19 in metropolitan areas, FAPs transported through the cold chain should be protected against COVID-19. Third-party logistics providers invest in preservation and pandemic prevention, including the use of...
professional cold chain equipment, advanced cold chain technology, and effective pandemic prevention strategies. These strategies provide professional cold-chain logistics services for FAPs, which can reduce the deterioration of FAPs and ensure the safety of FAPs to a certain extent. Due to the quantity loss of FAPs, the quantity of FAPs arriving at retailers will be smaller than the quantity ordered. It is therefore assumed that there is a spot market in which suppliers of FAPs can purchase sufficient FAPs from the market at market prices to replace the FAPs that have decomposed and deteriorated during transportation.

Table 3. Model symbols for the quality assurance strategy of FAPs

| Symbol type | Symbol form | Symbolic meaning |
|-------------|-------------|------------------|
| Parameter   | a           | Demand scale of FAPs |
|             | b           | Sensitivity of the demand for FAPs to retail priced in metropolitan areas |
|             | β           | Sensitivity of the demand for FAPs in metropolitan areas to the level of preservation and pandemic prevention effort |
|             | c_w         | Unit production cost of the FAPs of suppliers |
|             | c_l         | Unit fresh agricultural product service cost of TPL |
|             | p_w, i = 1, 2 | The price of keeping produce fresh and the pandemic prevention price of the unit FAPs of TPL |
|             | t           | Market price of FAPs in metropolitan areas |
|             | L, i = 1, 2  | Quantity loss rate and virus infection coefficient |
|             | θ           | Quality assurance of FAPs |
|             | θ_0, i = 1, 2 | Initial level of effort required for keeping products fresh and initial pandemic prevention level |
|             | C           | Quality assurance cost of cold chain transportation provided by TPL service provider |
|             | D           | Demand for FAPs in metropolitan areas |
|             | σ           | Infection coefficient of COVID-19 |
| Decision variables | ε, i = 1, 2 | The level of effort required for keeping products fresh and pandemic prevention efforts of FAPs |
|                | (0 < ε < 1) | Contributed by TPL |
|                | p_w         | Wholesale price of units of FAPs from suppliers |
|                | p_r         | Retail price of units of FAPs from retailers |
| Objective variable | π_t         | Profit of TPL |
|                | π_w         | Profit of FAP suppliers |
|                | π_r         | Profit of FAP retailers |

Based on the above analysis, the relevant symbols and variable descriptions are shown in Table 3.

Preservation conditions of FAPs

Assumption 1: In the context of COVID-19, the members of the FAP supply chain at all levels in metropolitan areas are rational and their risk preferences are neutral. In the process of
cooperation, information is symmetrical and each pursues profit maximization. The TPL provider’s freshness and pandemic prevention efforts can be improved and measured.

Assumption 2: The market demand for FAPs in metropolitan areas is mainly affected by price, freshness, and safety. We assume that the market demand function is \( D = a - bp_t + (k_1 + k_2)\theta_t \), where \( a, b, \) and \( k \) are all greater than 0 and constant, where \( a \) represents the initial demand for FAPs in metropolitan areas in the context of COVID-19, and \( b, k_1, \) and \( k_2 \) represent the sensitivity coefficient of the market demand of FAPs in metropolitan areas to retail price, freshness, and safety. The degree \( \theta_t = (\theta_{t1} + \theta_{t2})(e_t + e_2) \) of preservation of FAPs indicates the quality level of FAPs, which is affected by the level of preservation effort and the level of pandemic prevention effort, where \( \theta_{t1} \) and \( \theta_{t2} \) are the initial freshness and pandemic prevention degree of FAPs, and \( e_t \) and \( e_2 \) are the efforts made in preservation and pandemic prevention for TPL service providers. Let \( \beta = (k_1 + k_2)(\theta_{t1} + \theta_{t2}) \) represent the sensitivity coefficient of the demand for FAPs in metropolitan areas to the level of preservation efforts and pandemic prevention efforts made. In the context of the COVID-19 pandemic, the market demand function of FAPs in metropolitan areas is therefore \( D = a - bp_t + \beta(e_t + e_2) \).

Assumption 3: In the context of COVID-19, the relationship between the cost of FAPs in metropolitan areas and the level of preservation efforts and pandemic prevention efforts made is \( C = \frac{1 + \sigma}{2} \lambda(e_t + e_2)^2 \). This shows that the improvement in the TPL quality-assurance effort level can lead to an increase in the quality assurance cost, and the quality assurance cost shows a marginal increasing trend.

Assumption 4: The parameter satisfies the relation \( p_t > p_w + p_{t1} + p_{t2} \), indicating that the retailer’s retail price of a unit of FAPs is greater than the sum of the supplier’s unit wholesale price of FAPs and the TPL service provider’s guaranteed delivery price. \( p_w > c_w + tL_1 + tL_2 \) means that when the TPL service provider does not provide quality assurance services, the wholesale price per unit of FAPs of the supplier is greater than the sum of the cost per unit of FAPs and the cost of quantity loss. \( a - b(c_w + tL_1 + tL_2 + p_{t1} + p_{t2}) > 0 \) indicates that in the context of COVID-19, when TPL providers do not provide quality assurance services, the market demand for FAPs in metropolitan areas is positively correlated with the profits of supply-chain members at all levels.

RESULTS AND DISCUSSION
Quality assurance strategy of FAPs
Quality assurance strategy of FAPs under the guidance of suppliers
With the background of a new crown pneumonia outbreak, suppliers play a leading role in the three-level supply-chain structure of FAPs with good quality in metropolitan areas. When the supplier of FAPs is in the leading position of supply guarantee, first the supplier of FAPs formulates the optimal unit wholesale price of FAPs \( p_w \). The TPL service providers then make decisions to maximize their own profits. Third-party logistics service providers select level \( e_t \) of effort made to keep products fresh and level \( e_2 \) of pandemic prevention effort and reports to retailers the fresh keeping price \( p_{t1} \) and pandemic prevention price \( p_{t2} \). Finally, depending on the wholesale price of FAPs given by the supplier and the quality assurance level given by the TPL service provider, the best retail price \( p_r \) of FAPs is finally determined by FAPs retailers based on their own profit maximization conditions.

According to the above game process, the Stackelberg game model of the supplier allows a supply guarantee to be constructed in a situation where the level of quality assurance efforts affects the market demand. In the context of the outbreak of new crown pneumonia, the profit function of suppliers in the three-level supply-chain structure of FAPs with good quality in metropolitan areas can be expressed as follows:

\[
\pi_s = (p_w - c_w)(a - bp_t + \beta(e_t + e_2)) - (tL_1 + tL_2)(1 - e_t - e_2)(a - bp_t + \beta(e_t + e_2))
\]  

(1)

In Eqn (1), \((p_w - c_w)(a - bp_t + \beta(e_t + e_2))\) represents the income of FAPs suppliers. \((tL_1 + tL_2)(1 - e_t - e_2)(a - bp_t + \beta(e_t + e_2))\) represents the consumption cost and pandemic prevention cost paid by the suppliers of FAPs to meet the demand for FAPs. The profit function of TPL service providers can be expressed as follows:

\[
\pi_t = (p_{t1} + p_{t2} - c)(a - bp_t + \beta(e_t + e_2)) - \frac{1 + \sigma}{2} \lambda(e_t + e_2)^2
\]  

(2)

In Eqn (2), \((p_{t1} + p_{t2} - c)(a - bp_t + \beta(e_t + e_2))\) represents the income obtained by the TPL service provider from the transportation of FAPs. \(\frac{1 + \sigma}{2} \lambda(e_t + e_2)^2\) represents the cost of keeping products fresh and the pandemic prevention cost of FAPs invested by the TPL service provider. The profit function of fresh produce retailers can be expressed as in Eqn (3):

\[
\pi_r = (p_r - p_w - p_{t1} - p_{t2})(a - bp_t + \beta(e_t + e_2))
\]  

(3)

According to the above game model, the reverse order method is used to solve the above profit function. For the convenience of the solution, let \( p_r = p_w + \delta \), where \( \delta \) is the increased price of FAPs retailers. Then, the profit function of fresh produce retailers can be expressed as follows:

\[
\pi_r = (\delta - p_{t1} - p_{t2})(a - bp_w + \lambda(e_t + e_2))
\]  

(4)

For the first partial derivative of Eqn (4) with respect to \( \delta \),

\[
\frac{\partial \pi_r}{\partial \delta} = a - b(p_w + \lambda e_t + e_2) + (\delta - p_{t1} - p_{t2})(-b) \quad \text{As} \quad \frac{\partial \pi_r}{\partial \delta} = -2b < 0, \quad \pi_r \text{ is a convex function of } \delta. \text{ For FAP retailers, there is only one optimal retail price to maximize profit. If } \frac{\partial \pi_r}{\partial \delta} = 0, \text{ the relationship between the price } \delta \text{ increased by the best FAPs retailer and the wholesale price } p_w \text{ as well as the level of preservation effort required } e_t \text{ and the level of pandemic prevention effort made } e_2 \text{ can be expressed as follows:}
\]

\[
\delta = \frac{a - bp_w + \beta(e_t + e_2) + (p_{t1} + p_{t2})b}{2b}
\]  

(5)

Based on the above analysis, \( p_r = p_w + \delta \). The profit function of TPL service providers can be expressed as follows:

\[
\pi_t = (p_{t1} + p_{t2} - c)[a - b(p_w + \lambda) + \beta(e_t + e_2)] - \frac{1 + \sigma}{2} \lambda(e_t + e_2)^2
\]  

(6)
In Eqn (5) and substituting Eqn (6), under the condition that the best FAPs retailer increases the price, the profit function of the TPL service provider can be expressed as follows:

$$\pi_r = (\rho_1 + \rho_2 - C) \left[ \frac{a + b\rho_2 + \beta(e_1 + e_2) + (\rho_1 + \rho_2)b}{2b} + \beta(e_1 + e_2) \right] \frac{1 + \sigma}{2} \lambda(e_1 + e_2)^2$$

(7)

For the first partial derivatives of Eqn (7) for $e_1$ and $e_2$,

$$\frac{\partial \pi_r}{\partial e_1} = (\rho_1 + \rho_2 - C) \left( \frac{a + b\rho_2 + \beta(e_1 + e_2)}{2b} + \beta(e_1 + e_2) \right) \frac{1 + \sigma}{2} \lambda(e_1 + e_2)^2$$

As $\frac{\partial \pi_r}{\partial e_1} \neq 0$, $\pi_r$ is a convex function of $e_1$ and $e_2$. It can be seen that, for TPL service providers, there is only one optimal level of preservation effort and pandemic prevention effort made to maximize profits. If $\frac{\partial \pi_r}{\partial e_1} = 0$, the level of FAP preservation and pandemic prevention effort made by the TPL under the guidance of FAP suppliers can be expressed as follows:

$$\pi_r^* = \left( \frac{\beta(\rho_1 + \rho_2 - C)}{2(1 + \sigma)\lambda} \right) \frac{\partial \pi_r}{\partial e_1}$$

(8)

When $\rho_r = \rho_w + \delta$, the profit function of fresh produce suppliers can be expressed as follows:

$$\pi_w = \left( \rho_w - C_w \right) \left[ a - b(p_w + \delta) + \beta(e_1 + e_2) \right]$$

(9)

Substituting Eqn (5) and Eqn (8) into Eqn (9), the profit function of the FAPs supplier is $\pi_w(\rho_w)$ under the conditions of the increased price of the best FAPs retailer, the best effort level being made to keep products fresh, and the best pandemic prevention effort level being made. The first partial derivative of $\rho_w$ is solved

$$\frac{\partial \pi_w}{\partial \rho_w} = \frac{\beta(\rho_1 + \rho_2 - C)}{2(1 + \sigma)\lambda} \left( \frac{a + b\rho_2 + \beta(e_1 + e_2)}{2} \right)$$

(10)

The results of Eqns (5), (8), and (10) are substituted into $\rho_r = \rho_w + \delta$. In the case of the optimal fresh agricultural product retailer's increased price, optimal effort level to keep products fresh, optimal pandemic prevention effort level, and optimal wholesale price, the optimal retail price for the retailer under the fresh agricultural product supplier-led supply guarantee can be expressed as follows:

$$\pi_r^* = \left( \frac{\beta(\rho_1 + \rho_2 - C)}{2(1 + \sigma)\lambda} \right) \frac{\partial \pi_w}{\partial \rho_w}$$

(11)

Novel coronavirus pneumonia ($D = a - bp_r + \beta(e_1 + e_2)$) Eqns (8) and (11) were applied to the market demand function of FAPs in the background of the new crown pneumonia pandemic. In the case of the optimal TPL quality (preservation and pandemic prevention) effort level and the retailer’s optimal retail price, the optimal order quantity of the FAPs retailer (metropolitan FAPs demand) under the supplier-led supply guarantee can be expressed as follows:

$$\pi_f^* = \frac{2(1 + \sigma)(\rho_1 + \rho_2 - C)}{8(\rho_1 + \rho_2 - C)} \left( \frac{\beta(\rho_1 + \rho_2 - C)}{2(1 + \sigma)\lambda} \right) \frac{\partial \pi_r}{\partial \rho_r}$$

(12)

The results of Eqns (8), (10) and (11), are substituted into Eqns (1)–(3), respectively. Under the background of novel coronavirus pneumonia, the optimal profit of the three suppliers $\pi_1$, TPL service providers $\pi_r$, and retailers $\pi_n$ of the dominant suppliers in the metropolitan FAPs suppliers can be expressed as follows:

$$\pi_1^* = \frac{2(1 + \sigma)(\rho_1 + \rho_2 - C)}{8(\rho_1 + \rho_2 - C)} \left( \frac{\beta(\rho_1 + \rho_2 - C)}{2(1 + \sigma)\lambda} \right) \frac{\partial \pi_r}{\partial \rho_r}$$

(13)

$$\pi_r^* = \left( \frac{\beta(\rho_1 + \rho_2 - C)}{2(1 + \sigma)\lambda} \right) \frac{\partial \pi_w}{\partial \rho_w}$$

(14)

$$\pi_n^* = \frac{2(1 + \sigma)(\rho_1 + \rho_2 - C)}{8(\rho_1 + \rho_2 - C)} \left( \frac{\beta(\rho_1 + \rho_2 - C)}{2(1 + \sigma)\lambda} \right) \frac{\partial \pi_r}{\partial \rho_r}$$

(15)

It can be seen from the above that Eqns (13)–(15), respectively represent the optimal profits of suppliers, TPL service providers, and retailers under the conditions of optimal retailer price increase, optimal preservation effort level, optimal pandemic prevention effort level, and optimal wholesale price of suppliers.

Quality assurance strategy of FAPs under the guidance of retailers

In the context of the COVID-19 pandemic, retailers are leading the supply of FAPs in a three-tier supply-chain structure for quality assurance in metropolitan areas. When FAP retailers are in the leading position of supply guarantee, first metropolitan FAP retailers decide the appropriate retail price $\rho_r$. The TPL service provider then makes decisions based on profit maximization. The TPL service provider determines the optimal freshness preservation effort level $e_1$ and pandemic prevention effort level $e_2$, and reports to the retailer the FAPs freshness service price $\rho_1$ and pandemic prevention service value $\rho_2$. Finally, suppliers of FAPs combine their profit maximization conditions according to the retail price given by retailers and the quality assurance effort level given by TPL. On this basis, FAP suppliers decide the optimal wholesale price $\rho_w$ of FAPs.

According to the above game process, a Stackelberg game model of retailer-led guarantee can be built for cases where the level of preservation effort affects the market demand. The reverse order method is used to solve the Stackelberg game.
model. The first partial derivative of Eqn (9) with respect to \( p_w \) is solved, and the results can be expressed as follows:

\[
\frac{\partial \pi_w}{\partial p_w} = a - b(p_w + \delta) + \beta(e_1 + e_2) + |p_w - c_1 - (t_L + t_L_2)(1 - (e_1 + e_2))|(-b)
\]

(16)

As \( \frac{\partial^2 \pi_w}{\partial p_w^2} = -2b < 0 \), \( \pi_w \) is a convex function of \( p_w \). Suppliers of FAPs have a single optimal wholesale price to maximize their profits. With \( \frac{\partial \pi_w}{\partial p_w} = 0 \), the relationship between the optimal wholesale price \( p_w \) and the retailer’s markup of FAPs, as well as the freshness preservation effort level \( e_1 \) and the pandemic prevention effort level \( e_2 \), can be expressed as follows:

\[
(p_w)_2 = \frac{a - b\delta + \beta(e_1 + e_2) + bc_1 + b(t_L + t_L_2)(1 - (e_1 + e_2))}{2b}
\]

(17)

Equation (17) is substituted into Eqn (6) to obtain the profit function of TPL service providers under the optimal wholesale price. The profit function of TPL service providers can be expressed as follows:

\[
(p_w)_2 = \frac{2\lambda(1 + \sigma)(a - b(p_1 + p_2) + 3bc_1 + 3b(t_L + t_L_2)) + (p_1 + p_2 - c_1) \left( \beta^2 - 3b^2(t_L + t_L_2)^2 t^2 - 2b(b(t_L + t_L_2)) \right)}{8b}(1 + \sigma)
\]

(18)

Equations (20) and (21) are substituted into \( p_* = p_w + \delta \). In the case of optimal price increase and optimal wholesale price, the retailer’s optimal retail price can be expressed as follows when the retailer of FAPs leads the guarantee of supply:

\[
(p_2)_2 = \frac{2\lambda(1 + \sigma)(3a + bc_1 + b(t_L + t_L_2) + b(p_1 + p_2)) + (p_1 + p_2 - c_1) \left( 3b^2 + 2b(b(t_L + t_L_2) - b^2(t_L + t_L_2))^2 \right)}{8b}(1 + \sigma)
\]

(22)

To solve the first partial derivative of Eqn (18) with respect to \( e_1 \) and \( e_2 \), there exists \( \frac{\partial \pi_w}{\partial (e_1 + e_2)} = \frac{1}{2}(p_1 + p_2 - c_1)(\beta + b(t_L + t_L_2))(1 + \sigma) \lambda < 0 \). \( \pi_i \) is a convex function of \( e_1 \) and \( e_2 \). Third-party logistics service providers of FAPs have a unique level of quality-assurance efforts to maximize their profits. If \( \frac{\partial \pi_i}{\partial (e_1 + e_2)} = 0 \), the optimal quality assurance effort level of TPL under the retailer-led guarantee of FAPs can be expressed as follows:

\[
(e_1 + e_2)_2 = \frac{\beta + b(t_L + t_L_2)(p_1 + p_2 - c_1)}{2\lambda(1 + \sigma)}
\]

(19)

Equations (17) and (19) are substituted into Eqn (4) to obtain the profit function \( \pi_i(\delta) \) of FAP retailers under the condition of the optimal wholesale price and the optimal quality assurance effort level of TPL. The first partial derivative with respect to \( \delta \) is solved, and there is

\[
\frac{\partial \pi_i}{\partial \delta} = \frac{8\delta}{b(1 + \sigma)} - \frac{2b(b(t_L + t_L_2))^2}{4b(1 + \sigma)}.
\]

As \( \frac{\partial^2 \pi_i}{\partial \delta^2} = -b < 0 \), \( \pi_i \) is a convex function of \( \delta \). Fresh produce retailers have a single optimal retail price to maximize their profits. Let \( \frac{\partial \pi_i}{\partial \delta} = 0 \) to obtain the optimal fresh agricultural product retail price increase under the leading guarantee of FAPs, which can be expressed as follows:

\[
\delta = \frac{2\lambda(1 + \sigma)(a - b(p_1 + p_2) + b(t_L + t_L_2)) + (p_1 + p_2 - c_1) \left( \beta^2 - 3b^2(t_L + t_L_2)^2 t^2 - 2b(b(t_L + t_L_2)) \right)}{2b(1 + \sigma)}
\]

(20)

The results of Eqns (19) and (20) are substituted into Eqn (17). In the case of the TPL optimal quality effort level and optimal retailer markup, the supplier’s optimal wholesale price, when fresh agricultural product retailers dominate the guarantee, can be expressed as follows:

\[
\delta_1 = \frac{2\lambda(1 + \sigma)(a - b(p_1 + p_2) + b(t_L + t_L_2)) + (p_1 + p_2 - c_1) \left( \beta^2 - 3b^2(t_L + t_L_2)^2 t^2 - 2b(b(t_L + t_L_2)) \right)}{2b(1 + \sigma)}
\]

(21)

Equations (20) and (21) are substituted into \( p_* = p_w + \delta \). In the case of optimal price increase and optimal wholesale price, the retailer’s optimal retail price can be expressed as follows when the retailer of FAPs leads the guarantee of supply:

\[
(p_2)_2 = \frac{2\lambda(1 + \sigma)(3a + bc_1 + b(t_L + t_L_2) + b(p_1 + p_2)) + (p_1 + p_2 - c_1) \left( 3b^2 + 2b(b(t_L + t_L_2) - b^2(t_L + t_L_2))^2 \right)}{8b}(1 + \sigma)
\]

Equations (19) and (22) were substituted into the market demand function \( D = a - bp + \beta(e_1 + e_2) \) for FAPs in metropolitan areas in the context of a COVID-19 outbreak. In the case of the TPL’s optimal quality (fresh and pandemic prevention) effort level and the retailer’s optimal retail price, the retailer’s optimal order quantity (metropolitan area fresh produce demand) for fresh produce under the retailer’s leading guarantee can be expressed as follows:

\[
D_* = \frac{2\lambda(1 + \sigma)(a - b(p_1 + p_2) - bc_1 - b(t_L + t_L_2)) + (p_1 + p_2 - c_1) \left( \beta + b(t_L + t_L_2) \right)^2}{8b(1 + \sigma)}
\]

(23)

Equations (19), (21), and (22) are substituted into Eqns (1)–(3), respectively. The optimal profits of the supplier \( \pi_w \), TPL service

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Proposition 1: Equations (8) and (19) are compared by \( p_1 + p_2 > c_1 \). The optimal quality assurance effort level (freshness effort level and pandemic prevention effort level) of TPL service providers under the two game models satisfies \( e_1 + e_2_1 \leq (e_1 + e_2) \).

Proposition 1 shows that TPL service providers show a higher level of pandemic prevention effort and preservation effort for FAPs when FAP retailers are in the leading position of guarantee and supply compared with FAP suppliers. Compared with FAP suppliers and TPL service providers, FAP retailers have more decision-making power regarding FAP quality. Third-party logistics service providers can only cooperate by maintaining a higher level of prevention effort and preservation effort than fresh produce retailers. Third-party logistics service providers can also meet consumers’ high requirements for the quality of FAPs. At the same time, this proposition indicates that, in the context of the COVID-19 pandemic, the sensitivity of the market demand for FAPs in metropolitan areas to the level of pandemic prevention efforts and preservation efforts will, to a certain extent, offset the impact of the dominant position of supply and demand. When FAP suppliers are in the leading position of guarantee and supply, the relative size of the pandemic prevention efforts and preservation efforts depends on the sensitivity of the FAP market demand to the TPL preservation efforts made in metropolitan areas.

Proposition 2: For the optimal wholesale price of FAP suppliers, the wholesale price under the supplier-led guarantee is higher than the wholesale price under the retailer-led guarantee – namely, \( (p_w)^s_1 < (p_w)^r_1 \).

Proof. From hypothesis \( p_1 + p_2 > c_1 \) and \( a - b(c_1 + tL_1 + L_2) + p_1 + p_2 > 0 \), it can be found that:

\[
\begin{align*}
(p_w)^s_1 - (p_w)^r_1 &= \frac{2(1+\sigma)(a-b(p_1+p_2)+bc_w+b(tL_1+L_2))+(p_1+p_2-c_1)(\beta^2-b(tL_1+L_2)\beta)}{4\beta(1+\sigma)} \quad \text{if } \beta \geq b(tL_1+L_2) \\frac{c_1}{tL_1+L_2} \\
&\quad - \frac{2(1+\sigma)((a-b(p_1+p_2)+3bc_1+3b(tL_1+L_2))+(p_1+p_2-c_1)(\beta^2-3b^2(L_1+L_2)^2t^2-2\beta(b(tL_1+L_2)))}{8\beta b(1+\sigma)} > 0
\end{align*}
\]

Therefore, \( (p_w)^s_1 < (p_w)^r_1 \).

Proposition 2 shows that the wholesale price of FAPs under the supplier-led guarantee is higher than the wholesale price of FAPs under the retailer-led guarantee. When FAP suppliers have the dominant guarantee advantage, FAP suppliers have stronger bargaining power than retailers. The profits for suppliers of fresh produce increase with higher pricing.

Proposition 3: For the retailer’s optimal retail price under three game models, if \( \frac{b(tL_1+L_2)}{tL_1+L_2} \leq \beta \), then \( (p_r)^s_1 < (p_r)^r_1 \). If \( \frac{b(tL_1+L_2)}{tL_1+L_2} > \beta \), retailers of FAPs tend to set a higher retail price when they are in the leading guarantee position, compared with suppliers of FAPs who lead the guarantee. When \( \beta < \frac{b(tL_1+L_2)}{tL_1+L_2} \), retailers of FAPs tend to set a higher retail price when the supplier is in the leading guarantee position, compared with FAP retailers in the leading guarantee position. According to the retailer response expression obtained above, the optimal retail price is related to the supplier’s wholesale price and the TPL’s quality assurance effort level. If the level of quality assurance effort remains consistent, the comparative analysis of the wholesale price (proposition 2) shows that \( (p_w)^s_1 < (p_w)^r_1 \) and \( (p_r)^s_1 < (p_r)^r_1 \). According to proposition 1, if the condition of
Proposition 4: In the context of the COVID-19 pandemic, the optimal order quantity of the metropolitan FAPs system is $D^*_t < D^*_s$ based on hypothesis $p_{11} + p_{12} > c_t$ and $a - b(c_t + t(L_1 + L_2) + p_{11} + p_{12}) > 0$.

The conclusion of proposition 4 is similar to that of propositions 1 and 3. According to the demand function, the market demand for FAPs in metropolitan areas is related to the retail price, the level of effort made to keep produce fresh, and the level of pandemic prevention effort made. The retail price of FAPs in metropolitan areas has the following relationship: $(p_{11} + p_{12})_t < (p_{11} + p_{12})_s$, where the level of preservation efforts and pandemic prevention efforts meet the level of $(e_1 + e_2)_t < (e_1 + e_2)_s$. The market demand for FAPs in metropolitan areas is negatively correlated with the retail price and positively correlated with the quality assurance effort level. The relation with the level of preservation effort is therefore consistent with the conclusion of this thesis. In general, the optimal order quantity of FAPs in metropolitan areas is related to the retail price and positively correlated with the quality assurance effort level. The sensitivity coefficient of the preservation effort level and pandemic prevention effort level.

Proposition 5: When fresh produce suppliers are in the leading position of guarantee, the profit of fresh produce suppliers is twice that of retailers. When fresh produce retailers are in the leading position of the guarantee, fresh produce retailers' profit is twice that of their suppliers. Then, $\pi_{w1} = 2\pi_{r1}$ and $2\pi_{w2} = \pi_{r2}$.

Proposition 6: By assuming $p_{11} + p_{12} > c_r$, Eqns (15) and (26) are compared. Compared with the leading guarantee and supply of FAPs, the profit of FAPs retailers is larger when the retailers are in the leading guarantee and supply position – that is, $\pi_{r1} < \pi_{r2}$.

The conclusion of proposition 6 is consistent with those of propositions 1, 3, and 4, indicating that there is a certain relationship between the relative size of retailers' profits and the sensitivity of their quality assurance efforts. If the sensitivity coefficient of the quality assurance effort level is low enough, the quality assurance effort level and market demand are greater under the retailer-led guarantee than under the supplier-led guarantee. When $\beta > \beta_{rt}$, compared with the supplier-led guarantee, the quality assurance effort level, market demand, and retail price are all greater under the retailer-led guarantee. As increased demand leads to higher revenue, retail prices are higher, leading to higher margins. The profits of retailers of FAPs are affected by the sensitivity coefficient of the preservation efforts, pandemic prevention efforts, and dominant guarantee status.

Proposition 7: In the context of the COVID-19 pandemic, with the increase in the preference of FAP consumers for pandemic prevention efforts and preservation efforts in metropolitan areas, the profits of TPL service providers led by FAP retailers remain unchanged. Under the leading guarantee of FAPs suppliers, the profit level of the guarantee members will be increased – that is $\frac{\partial \pi_{w1}}{\partial \beta} > 0$, $\frac{\partial \pi_{r1}}{\partial \beta} > 0$, and $\frac{\partial \pi_{r2}}{\partial \beta} > 0$.

Proof. Under the leading guarantee of FAP suppliers, the derivative results of the optimal profits of members at all levels with respect to the sensitivity coefficient of preservation efforts can be expressed as follows:

$$\frac{\partial \pi_{w1}}{\partial \beta} = \frac{2[2\lambda a(1+\sigma) - 2\lambda b(1+\sigma)(c_t + p_{11} + p_{12} + tL_1 + tL_2) + (\beta^2 + b(tL_1 + tL_2) \beta)(p_{11} + p_{12} - c_t)](p_{11} + p_{12} - c_t)(2\beta + b(tL_1 + tL_2))}{32b\lambda^2(1+\sigma)^2}$$

$\frac{\partial \pi_{r1}}{\partial \beta} = \frac{b(p_{11} + p_{12} - c_t)^2(tL_1 + tL_2)}{8\lambda(1+\sigma)}$

$\frac{\partial \pi_{r2}}{\partial \beta} = 2[2\lambda a(1+\sigma) - 2\lambda b(1+\sigma)(c_t + p_{11} + p_{12} + tL_1 + tL_2) + (\beta^2 + b(tL_1 + tL_2) \beta)(p_{11} + p_{12} - c_t)](p_{11} + p_{12} - c_t)(2\beta + b(tL_1 + tL_2))}{64b\lambda^2(1+\sigma)^2}$

Proposition 5 shows that the profit ratio between FAP suppliers and retailers is 2:1 under the supplier-led guarantee. Under the retailer-led guarantee, the profit ratio of FAP suppliers and retailers is 1:2. When the guarantee subject is in the dominant guarantee position, it has a stronger control ability and decision-making ability compared with other members, so its own profit is greater than that of other members.
The implications of this study are as follows. At the micro level, the broken chain caused by the pandemic shows that, to fully ensure the effective supply of FAPs, it is necessary to infiltrate and participate in the upstream and downstream of the supply chain. The upstream part of the chain should extend to the supply end, with suppliers of FAPs developing their own sources of supply. The downstream part of the chain should strengthen logistics, and a rapid logistics platform needs to be built on an appropriate scale. Only when self-run logistics rise to a certain
scale can they reduce costs and increase profits. At the macro level, first the inventory and quality status of FAP areas should be sorted to open up the market for FAPs. Second, local government departments should coordinate to open up green channels for such FAPs. Third, logistics resources should be coordinated to ensure that FAPs can reach consumers.

Although this study has achieved the research goal of this paper, this paper still has some limitations. Fresh agricultural produce suppliers and retailer, respectively, led the study on FAP supply protection in metropolitan areas in the context of a COVID-19 outbreak. The guaranteed supply system led by TPL providers should be studied in the future. In addition, in the context of COVID-19 the members of the FAP supply chain are often one-to-many, many-to-one, or many-to-many in reality. In the future, the problem can be considered to ensure the effective supply of FAPs in metropolitan areas.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable.

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