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Enhancing economic and environmental sustainability in fruit and vegetable distribution through collaborative digital platforms

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ABSTRACT

Addressing environmental challenges has become increasingly urgent due to the significant impact of carbon emissions on our lives. Among the major contributors to these emissions is the food sector, where logistics plays a pivotal role and represents a key area for intervention. In response, recent literature has begun to explore digital and collaborative logistics solutions as promising alternatives to traditional models. Collaborative digital platforms are analysed but the debate is still in its early stages. This paper aims to contribute to this emerging discussion by first identifying the opportunities and barriers associated with this solution and then assessing its performance impacts. Through a combination of literature review, grey literature analysis, and expert interviews, the study investigates the practical implementation of these innovative solutions. An integrated economic and environmental assessment is then conducted to quantify their associated costs and emissions, providing insights to support informed decision-making. The findings reveal that, while the adoption of collaborative digital platforms remains limited, they have significant potential to deliver win–win outcomes from both economic and environmental standpoints. Indeed, they offer potential to reduce emissions produced and costs, despite the needed initial investments. The paper offers a twofold contribution: academically, by advancing the debate with concrete evidence and proposed pathways; and practically, by encouraging managers to rethink logistics strategies in support of decarbonization. Future research could refine the proposed model or explore its applicability to other sectors.

1. Introduction

The agri-food industry is one of the most significant in the Italian economy. Focusing specifically on the fruit and vegetable supply chain, its importance is reflected in its contribution to GDP employment, accounting for 25 % of the total [1]. Italy is also among the leading exporters of fresh produce, owing to the quality and variety of its products [2].

However, food systems generate considerable environmental impacts [3]. Agriculture is responsible for 20–25 % of global greenhouse gas (GHG) emissions [4], and the current food supply chain produces approximately 13.7 billion metric tons of CO_2-equivalent emissions, contributing to 78 % of global freshwater and ocean eutrophication [5]. Within this context, transportation—particularly in the fruit and vegetable sector—is a great contributor [6] and accounts for about 36 % of food-related GHG emissions [7]. The last-mile phase is especially impactful, being one of the most emission-intensive and operationally complex stages of distribution. Moreover, with urbanization, last mile is becoming increasingly polluting [8], and new solutions are emerging to improve the liveability of urban areas [9].

Green Logistics practices—defined as "the part of the activities of an enterprise aimed at measuring and minimizing the impact of logistics activities on the environment" [10]—are therefore essential for mitigating emissions in the distribution phase of agri-food products.

Digitalization is emerging as a pivotal enabler of green logistics practices. Technological innovation is transforming the Italian food industry, enhancing efficiency from production to distribution. Extant literature increasingly recognizes the strong link between digitalization and sustainability, which is also reflected in national investment priorities. For instance, Italy's National Recovery and Resilience Plan (PNRR), part of the EU's NextGenerationEU programme [11], has allocated €1.15 billion to support the ecological and digital transition of the

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agri-food sector.

Collaboration is another crucial lever for emission reduction. The Italian fruit and vegetable supply chain is highly fragmented, comprising a multitude of actors such as small producers, cooperatives (which consolidate supply and connect it to demand), producer organizations, large trade groups, agri-food centres, purchasing consortia, and retailers. Although the HoReCa channel is also involved, this study focuses on the retail segment, which represents a significant share of fruit and vegetable distribution in Italy. Within such a complex and fragmented system, collaboration is essential to improve efficiency and reduce emissions.

The food sector is therefore highly relevant in the Italian landscape, but it also strongly contributes to emissions, and logistics plays a key role. Practices of green logistics are on the rise, and the main trends are digitalization and collaboration. The positioning of this work is thus in the stream of sustainability of the distribution phase of the food supply chain, specifically the delivery of fruits and vegetables. A central solution explored is the use of collaborative digital platforms to foster horizontal collaboration and enhance sustainability within the food logistics sector.

However, the current literature does not extensively analyse the application and impact of such platforms. Their use in contexts characterised by fragmented demand and by the presence of small and medium-sized enterprises (SMEs) is underexplored and emerged as a critical gap to address. Additionally, while existing studies primarily focus on vertical collaboration, this solution targets horizontal collaboration—an area that remains largely overlooked.

Addressing these gaps is especially relevant for Italy, a country that is characterized by fragmented demand and lots of SMEs acting as producers or retailers. The focus of the paper will therefore be horizontal collaboration through digital platform to improve the sustainability of the distribution of food products in Italy. The chosen region is Emilia Romagna, as it entails the characteristics described in the introduction (i.e., fragmented demand, lots of SMEs).

This paper therefore aims to answer the following research questions:

- RQ1: What are the criticalities and opportunities in the implementation of collaborative digital platforms in the transportation phase of fresh products in Emilia Romagna?
- RQ2: What are the expected economic and environmental impacts of the implementation of a multi-actor collaborative digital platform in Emilia Romagna?

These RQs align with the objective of the work, which is understanding the current application of collaborative and digital solution ant their potential expansion to a larger scale.

2. Literature review

The literature highlights two primary trends: digitalization and collaboration. The concept of collaborative digital platforms intersects both trends, forming a critical area of analysis. Below, we delve into the exploration of these three interconnected topics. Starting from digitalization, we describe the main trends in the food sector. Moving to collaboration, we define how it can improve efficiency in fresh food supply chains. In literature, a stream is already present that intersects the two topics: collaborative digital platforms are studied, even though, as explained below, there are some gaps in literature that are addressed and filled with the present study.

2.1. Digitalization

One of the main themes in the literature is the adoption of Industry 4.0 technologies—such as the Internet of Things (IoT), Artificial Intelligence (AI), Digital Twin, Blockchain, and Information and Communication Technologies (ICT)—to optimise logistics processes and develop so-called smart cold chains [12]. Table 1 outlines the primary applications of these technologies, along with their associated economic and environmental impacts.

Advancements in IoT technologies have enabled wireless, real-time monitoring of environmental parameters throughout the fresh fruit and vegetable supply chain, significantly reducing product loss and waste [12]. IoT also supports warehousing applications [30]. Artificial Intelligence (AI) and machine learning also play a critical role, particularly in enhancing cold chain efficiency. These technologies support the development of more sustainable agri-food supply chains by offering innovative methods for coordinating various stakeholders [13,27].

In addition, Digital Twin technology can replicate individual fruits or vegetables, product packages, or entire refrigerated units within the agri-food supply chain [21,31]. This capability facilitates the analysis of food waste mechanisms and changes in environmental parameters during production and distribution [12]. A key advantage of digital twins is their ability to map entities across each stage of the supply chain, providing comprehensive indicators—economic, logistical, environmental, safety, and nutritional [32].

Blockchain technology further enhances supply chain management by ensuring secure and transparent data handling [33]. It improves traceability, supports product certification and authentication, and contributes to the digital transformation of agri-food supply chains [34]. In logistics, blockchain applications include the management of transport documents, goods traceability, fleet and delivery monitoring, geolocation, and real-time delivery statistics [16].

Finally, in the area of ICT, [35] identify four key success factors for a Food Integrity Information Sharing System (FI-ISS): (1) the selection of participating actors, (2) the type of information to be shared, (3) the third-party entity responsible for managing the system, and (4) the involvement of food safety authorities.

All these paradigms lead to the development of logistics, that is reaching the new form of logistics 4.0 [36].

2.2. Collaboration

Another key theme explored in the literature is collaboration, which is recognised as one of the most critical factors in designing efficient food retail networks. Vertical collaboration, particularly in upstream supply chain stages, is widely addressed. It enhances service levels and is often facilitated by digital innovation [37]. For instance, the consolidation of fresh agricultural products within multi-temperature joint distribution systems—with controlled temperature and humidity—can help preserve product quality and extend shelf life. The importance of integrated supply chain scheduling to support such initiatives is also well established. Collaboration can also be found in other stages of the product life cycle, such as the marketing phase [38].

Moreover, collaboration is increasingly seen as a key enabler of both sustainability [39] and circularity within supply chains [40,41]. However, horizontal collaboration—such as practices involving multi-pick and multi-drop logistics—is less frequently studied in the literature [42], despite its potential to optimise resources and reduce environmental impact.

There is a strong interconnection between digitalisation and collaboration [38]. Digital technologies play a central role in facilitating collaborative efforts, positioning themselves at the core of strategies aimed at reducing emissions and optimising costs. These technologies enable the adoption of integrated distribution models that blend online and offline channels [43], forming the foundation for economically and environmentally sustainable supply chains.

2.3. Collaboration and digitalisation merged: collaborative digital platforms

The intersection of the two previously discussed

Table 1
Digitalization strategies in logistics.

Technology	Logistics solution	Economic impact	Environmental impact
Internet of Things	- Real time monitoring [13] - Tracking and visibility [14] - [15]	- Cost reduction, improved efficiency [16] - Increased reliability [17] - High initial investment cost [12]	- Food waste reduction [12] - Energy optimization balancing consumption with efficiency [18] - e-waste reduction [19]
Artificial Intelligence	- Route optimization [16] - Truck and driver reduction [16] - Automatic detection (ML) [13]	- Cost reduction (waste, energy, transport) [13]	- Food waste reduction [13] - Energy efficiency [20]
Digital Twin	- Tracking product quality [21] - Optimizing logistics [16,20]	- Improved decision-making [16,20] - Outcome predictions (scenario analysis) [12] - Product quality improvement [21]	- Waste reduction [20,21] - Lifecycle assessment [22] - Emission reduction [20,21]
Blockchain	- Traceability system [16] - Smart contracts [12] - Fleet monitoring [16] - Document exchange [18]	- Reduced intermediaries [12] - Lower transaction costs [23] - Improved efficiency [12] - Faster transactions [18]	- Emission monitoring - Sustainability data collectio [24] - Waste reduction [23] - Energy consumption [23]
ICT	- Data sharing platforms [14] - Supply chain visibility [25] - Collaboration tools [26] - Smart logistics [26]	- Operational and cost efficiency [16,27] - Enhanced competitiveness [27]	- Waste reduction [28] - Lower emissions [29] - Optimized resource use (e.g. energy) [29] - Sustainable operational practices [29]

themes—collaboration and digitalisation—leads to the emerging topic of *collaborative digital platforms*. While this topic has been addressed in the literature [44], it remains underexplored, particularly in relation to the logistics phase of the supply chain within contexts characterised by fragmented demand and the presence of numerous small and medium-sized enterprises (SMEs) acting as both producers and retailers.

Existing research has examined collaborative smart farming [45], which applies similar principles to the production stage of the food supply chain. The concept has also been extended to the consumption phase through digital collaborative consumption, where consumers share rather than own products [46–48]. However, in the transportation domain, studies tend to focus on scenarios involving large-scale, consolidated production [49], limiting their applicability to more fragmented and SME-driven contexts.

Additionally, the concept has been applied to cooperatives [50], which are particularly relevant in the geographic and economic context under analysis. Collaborative computing has also emerged as a key tool for managing private data across the supply chain [51], ensuring secure and efficient information sharing among stakeholders.

Beyond logistical and operational benefits, the combination of collaboration and digitalisation can address broader social needs [52, 53] and enhance stakeholder engagement across the supply chain [53]. These insights highlight the potential of collaborative digital platforms not only to improve logistics efficiency but also to foster systemic innovation in agri-food networks.

2.4. Gaps and objectives

Some gaps have emerged from literature. The analysis of the main criticalities and opportunities in the application of collaborative and digital solution lacks a comprehensiveness that would allow operators to understand if and how to apply such strategies. Moreover, the economic and environmental implications of collaborative digital platforms are not agreed upon. Indeed, while some studies highlight the benefits of such practices [44] other studies emphasise their limitations [49]. Additionally, horizontal collaboration is less studied than vertical collaboration [37] and even in the studies that address this practice, a significant number has concentrated on countries with a more consolidated market [49], with limited attention to contexts with fragmented demand and lots of SMEs acting as producers or retailers [49].

Therefore, it is crucial to deepen our understanding of the potential of these models to support food operators in enhancing their performance while simultaneously reducing emissions and costs. In particular, if the adoption of collaborative and digital solutions is to increase in countries with fragmented markets, it is essential to address these gaps by examining both the current implementation of these solutions and their potential to deliver environmental and economic benefits. This would contribute to literature by adding the point of view of more fragmented markets and to practice by providing managers with an actionable tool to verify the economic and environmental convenience of collaborative digital solutions.

3. Methodology

The methodology follows a multimethod approach, from qualitative interviews to a numerical economic and environmental assessment.

3.1. Methodology for RQ1

The first research question has been addressed through an analysis of extant literature, grey literature, and interviews to experts in the industry and industry participants. 10 interviews are conducted and analysed through a coding procedure.

The analysis of the extant literature allows to understand what has already been investigated by academics.

The analysis of the grey literature (mainly company reports, websites, interviews published by industry associations or consultants) allows to investigate practical applications of the main solutions found in literature and to highlight solutions that are studied but not applied (and may have barriers to application) or solutions that are applied but not studied (warranting further attention in academic research) [54,55].

Interviews serve several purposes, primarily to deepen understanding of the supply chain's structure, challenges, and possible solutions. Interviews are semi structured, to guide the interviewee but to leave her the space to express thoughts and ideas [56,57]. Respondents were selected to ensure a diverse sample, offering varied viewpoints. The 11 interviewees represent magazines, supermarkets, farms, agribusiness centres, wholesalers, start-ups, and other small businesses. The aim of interviews is not only answering RQ1 but also providing data for RQ2.

3.2. Methodology for RQ2

An economic and environmental assessment helps in answering the second research question. It is developed using Python and the Vehicle Routing Problem tool in ArcGIS software, which allows to optimize transport routes with various constraints, such as capacity, time windows, and distances. The model is informed by data from interviews and the systematic literature review, which help identify key parameters like transport saturation and delivery times.

The objective of the model is to show, through a simulation, how a collaborative digital platform can positively impact the economic and environmental sustainability of the fruit and vegetable chain. This platform would allow small producers and local retailers to work together to optimize logistics flows and reduce inefficiencies.

3.2.1. Description of the scenarios

The definition of two scenarios allows to analyse the differences between a model where collaborative digital platforms are not implemented and a model where they are.

The AS IS scenario does not include any form of cooperation between producers and retailers regarding transport, as shown in Fig. 1. As a result, this mode of transportation is organized only in the direct mode between the producer and the retailer. This allows for multi-drop practices to be performed by the single producer, but not for multi-pick. In the AS IS scenarios there are 25 producers and 75 retailers. Each producer may supply more than one retailer, but each retailer can be supplied only by one producer, as a single-product model is chosen. Since multi-pick is not considered, each producer delivers to the assigned retailers with at least one delivery route. The routes are therefore $\geq$ 25. Moreover, it is important to note that the deliveries (being the study focused on fresh products) must happen early morning, as quickly as possible. This leads to the necessity of having one van for each route

In contrast, the TO BE scenario involves cooperation between manufacturers and retailers to optimize logistics, as shown in Fig. 2. This is achieved through a multi-pick and multi-drop system. This system allows transporters to collect goods from several producers or deliver them to different retailers on the same trip. There are still 25 producers and 75 retailers, but this scenario allows also for the presence of an external logistics operator, that manages transportation. This operator works with a consolidation centre close to the delivery area. Moreover, producers are divided in different clusters to allow better routing in the collection phase. The phases are therefore:

1. Collection from different producers (with multi-pick)
2. Consolidation at the logistics' operator centre
3. Delivery trips to the retailers.

The number of routes is expected to be lower in the To BE model than in the AS IS one.

3.2.2. Analytical application

The stages of the analytical simulation were:

1. The preliminary stages of model development: generating operator locations, demand, and production data (carried out in Python).
2. Vehicle Routing Problem in ArcGIS. ArcGIS-based model allows to account for actual distances between nodes, eliminating the need to rely on average distance estimates. By utilizing the Vehicle Routing Problem (VRP) tool, the model accurately determines the optimal sequence for visiting operators, allowing for precise calculations of both travel distance and time. ArcGIS performs a minimization of km travelled therefore reducing also costs and emissions.
   a. In the AS IS scenario, only one VRP was carried out.
   b. In the TO BE scenario, two VRP were carried out.
      i. The first one is for collection of producers

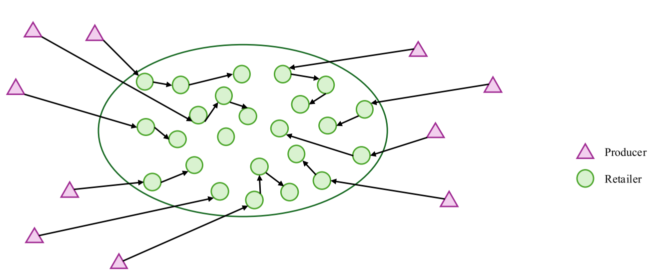

Fig. 1. Producers and retailers in the AS IS Scenario.

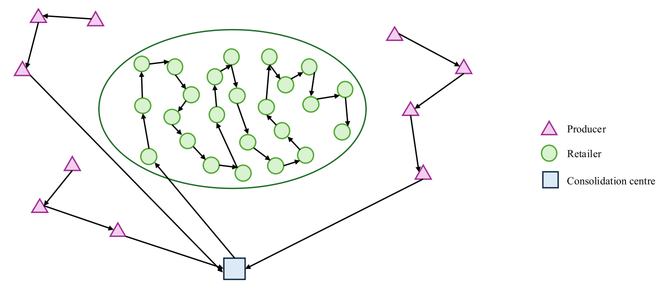

Fig. 2. Producers and retailers in the TO BE Scenario.

      ii. ii. The second one is for distribution to retailers

To ensure compatibility with the ArcGIS network analysis tool, it was necessary to pre-assign each retailer's demand to a specific manufacturer. This step was required because the tool does not support load balancing, meaning it cannot ensure the equality between the quantity loaded and the quantity delivered by each vehicle.

In the TO BE model, producers were grouped into clusters. The division into clusters was designed considering both theoretical principles and practical considerations. To determine the optimal number of clusters (K) for K-means clustering, the Elbow Method was applied [58]. The results revealed that the optimal number of clusters ranged between 3 and 4.

A sorting centre located at the centre of gravity of the cluster depots was considered. This centre receives products from all clusters of producers and then arranges distribution to retailers. The cost of operating this centre is an additional parameter in the TO BE model compared to the AS IS model and can also be interpreted as a cost of collaboration.

Analysis of performances, in terms of costs and environmental performances. The use of the eco-efficient approach [59] is particularly suited for our case study, that wants to tackle the worthiness of application of collaborative digital platforms from both points of view. The model provides a way to jointly analyse economic and environmental results of a specific practice, by converting emissions in an economic cost, as per Eq. (1).

$$\begin{aligned} \textit{Total cost} = {} & (\textit{economic cost per km x km travelled}) \\ & + (\textit{environmental cost per km x km travelled}) \\ & + (\textit{economic cost per hour x hours employed}) \\ & + \textit{economic cost of the distribution centre} \end{aligned} \tag{1}$$

The total cost is the sum of the economic cost of the transportation itself (obtained by multiplying cost per kilometre by number of kilometres), the environmental cost per kilometre, that is the translation in economic terms of the emissions released (obtained by multiplying cost per kilometre by number of kilometres), and the economic cost per hour, that is the time cost of the driver (obtained by multiplying cost per hour by number of hours employed by the driver). Additionally, in the TO BE model, the operational costs associated with the distribution centre are included.

Sensitivity analysis was conducted by modifying the values of specific parameters within the model input. The parameters that were varied are as follows: vehicle capacity, cost per kilometre, unit cost of collaboration, and the average and standard deviation of demand.

4. Results

4.1. Current implementation of digital and collaborative technologies

Among digital technologies, the IoT is the most frequently cited and analysed in grey literature. One of its most significant applications is related to monitoring the cold chain, therefore controlling temperature and humidity, improving food quality and safety. Additionally, IoT can be implemented in agricultural projects, in the "Agriculture 4.0″ paradigm. Furthermore, the application of AI has proven beneficial in optimizing resources, analysing data from sensors or satellite images, and automating decision-making processes. For supply chain traceability, several blockchain-based solutions are under development.

Grey literature also demonstrates that the fragmentation of the sector and its need of collaboration among parties. Aggregation of producers is considered pivotal for counterbalancing the growing consolidation of major retailers, rebalancing contractual power, and improving efficiency.

The results of the interviews also confirm the criticality of the different trends analysed, even though their application in practice is far from being complete. Starting from digitalization, for smaller companies, the technologies used are limited to very basic ICTs to ensure communication with suppliers and customers. Larger companies have more advanced technologies for communication and automation of processes such as order management. Logistics, however, does not benefit from the application of digitalization at the current state, and this highlights the need to further study its potential in the Italian landscape. Agrifood centres have highlighted the lack of visibility of supply and demand as a major inefficiency at the distribution stage, estimating that the saturation level of the vehicles used to supply local retailers usually does not exceed 40 %. The channel of large-scale distribution shows more sophisticated IT solutions that facilitate a cost-effective and environmentally conscious distribution process.

Collaboration is another critical area. Larger operators are vertically integrated, with centralized management systems ensuring coordination among producers, transporters, and other stakeholders. Smaller companies express interest in collaborative systems, including horizontal collaboration, but cultural barriers hinder widespread adoption. Cooperation among small producers could enhance distribution and complementary activities, such as packaging procurement.

4.2. Economic and environmental advantages of collaborative digital platforms

The results show a reduction in number of vehicles used and in kilometres travelled. Moreover, kilometres per tour decrease, indicating an increased efficiency in routing. These results are both linked to economic and environmental advantages. Additionally, kilograms of CO_2e emissions decreases. The total cost, that considers both economic and environmental inputs, is reduced by ~10 %. More specifically, the main components of total cost are environmental cost per kilometre, economic cost per kilometre, economic cost per hour (including drivers' cost), and the cost of collaboration, represented by the distribution centre present in the TO BE scenario. The main results are summarised in Table 2.

Table 2
Collaborative digital platforms: economic and environmental results.

	AS IS	TO BE
Number of vehicles (#)	**27**	**15**
Collection (#)		15
Last mile (#)		12
km tot (km)	**2631.19**	**1757.96**
km/tour (km)	**97.45**	**117.20**
Collection (km)		58.60
Last mile (km)		73.25
kgCO_2e	**526.24**	**351.59**
Tot cost (€)	**2027.78**	**1829.81**
Economic cost per km x km travelled (€)	789.36	527.39
Environmental cost per km x km travelled (€)	33.68	22.50
Economic cost per hour x hours employed (€)	1204.74	1199.29
Cost for collection (€)		*387.98*
Cost for last mile (€)		*357.96*
Cost for return (€)		*53.35*
Cost for service time (€)		*340.00*
Cost for cross docking time (€)		*60.00*
Economic cost for the distribution centre (€)		80.62
Cost for space (€)		*20.62*
Cost for people (€)		*60.00*

5. Discussion of results

5.1. Economic sustainability impact

In the collaborative model, there is a cost reduction, due to a decrease in total kilometres travelled. In the case of the AS IS scenario, the cost is directly proportional to the distance and the time travelled. In contrast, in the collaborative scenario, the total cost is not solely dependent on the distance and time travelled, but a collaborative cost is factored in, which is represented by the distribution centre. The economic performance of the collaborative model is superior, primarily due to a 33 % reduction in distance travelled (from 2631 km to 1758 km). Overall, the reduction in economic cost, excluding the emissions component, is 9 %.

The positive economic impacts extend beyond these savings and also encompass reduced vehicle downtime, improved relations with suppliers, and potential savings on operating costs, including vehicle maintenance.

5.2. Environment sustainability impact

Environmental benefits stem from the reduction in CO_2 emissions, which directly correlates with the decrease in total distance travelled. Emissions are reduced by 33 % in the collaborative scenario, reflecting the reduction in mileage. The positive environmental impact also includes the efficient use of resources, such as replacing fossil fuels with alternative green fuels.

5.3. Other effects

Other effects include increased saturation of vehicles, due to multi-pick and multi-drop practices that allow the consolidation of orders from different manufacturers and directed to multiple dealers. Moreover, the number of trips and vehicles are reduced from 27 to 15 vehicles utilized (assuming number of vehicles equal to number of trips). Higher saturation is the primary factor driving the decrease in the total kilometres travelled. Additionally, demand management improves, thanks to the increased visibility, which in turn improves forecasting capacity. The introduction of the distribution centre before the delivery phase to the retailers proves to be efficient: the results confirm the greater efficiency of cross-docking between the collection and delivery phases.

5.4. Sensitivity analysis

The sensitivity analyses are performed on the variables described below. The first sensitivity is related to vehicle capacity: by reducing the capacity from 1250 kg to 800 kg, the performance worsens. With 800 kg, the performance of the To Be scenario is 13 % worse of As-Is scenario, as smaller vehicles limit the potential for order consolidation and the cost of the distribution centre is not justified. With higher capacities, the performance differences between the two scenarios increase. Additionally, cost per kilometre is tested: an increase in the cost per kilometre raises total costs for both models. However, the AS IS model is more sensitive to increases in cost, given the lack of a collaborative effect. The

To Be increases by 33 % and the As Is by 42 % if we increase the cost by 75 %. Cost per emission and emissions per kilometre increase lead to a costs increase in both scenarios, but the increase is negligible. Regarding hourly wage and stopping time, the hourly cost (increased four times) increases the costs of the two models (the total cost doubles), but since the total time of the collaborative model is less than that of the AS IS scenario, the collaborative option remains the more cost-effective option, with a 4 % decrease in costs. The same considerations are applicable to stopping time, that increases the hours worked. Interestingly, as the mean value of demand increases, the convenience of the collaborative model decreases. When demand is high, multi-pick and multi-drop collaborative practices are no longer used because only direct delivery is processed. Therefore, with high demand, the To Be model leads to higher costs because the cost of the distribution centre is not justified (To Be +2 % with higher demand, with respect to −10 % with lower demand). The variability of demand does not have a significant impact on total cost. This is also true for the average saturation and the number of trips.

6. Conclusions

Sustainability is becoming increasingly crucial, and sectors such as food and agriculture receive greater attention for their impact on emissions released. In the food supply chain, transportation plays a key role and new green logistics practices are emerging to face this issue. Trends such as collaboration and digitalization help in the reduction of CO_2 emissions. The scope of this work focused therefore on the environmental sustainability of food products distribution, specifically the delivery of fruits and vegetables. The aim of the work was to identify the main opportunities and barriers in the implementation of collaborative strategies and digitalization.

Through a systematic literature review, an analysis of grey literature, and interviews with practitioners, the assessment of the current state of application of the mentioned strategies was conducted. These efforts led to the identification of a collaborative digital platform as a potential solution. By developing a mathematical model, the performance of this solution was assessed, and the findings showed an improvement in both economic and environmental terms.

According to the results of the interviews, a collaborative digital platform is a solution that is generally welcomed by small producers, who otherwise have difficulties in competing with large retailers. For large producers in the retail chain, the platform could serve as a supplementary distribution channel, complementing their existing operations. This argument also supports the platform's scalability for broader application. The model, on the other hand, highlights the convenience of the solution both from an economic and an environmental point of view.

The contribution of the research is both academic and managerial. On the one hand, academically, the analysis of a digital collaborative platform fits in the discussion of the sustainability of last mile delivery but adds to this discussion a real-world analysis. In particular, it clarifies what is the current application of collaborative digital platforms in logistics and what are the barriers and opportunities in the field. Moreover, it tests the economic and environmental effects, providing actual motivation to overcome the barriers identified. This work is done in a context that it is not currently studied in literature, i.e. a context with fragmented demand and lots of SMEs acting as retailers and producers. The context is relevant as it is typical in Italy, one of the main producers of fresh food in Europe. The region of Emilia Romagna is chosen as a representation of this context. Additionally, the research covers a solution that fosters horizontal collaboration, topic that deserves further attention in literature.

On the other hand, practically, the research can push managers in the direction of implementing collaborative and digital solutions and thus to improve the sustainability of food supply chains. The primary application of this model is to provide managerial figures, especially those involved in the transportation of fruit and vegetable products, with a useful tool to enhance logistics management. This would help achieve superior performance in both economic and environmental terms. Additionally, the findings of the systematic literature review suggest that digital solutions are more effective when integrated comprehensively. The proposed solution is particularly well-suited for integration with AI and blockchain technologies. Additionally, this study offers several policy implications. In the short term, policymakers could initiate pilot projects for collaborative digital platforms, launch awareness and training programs, and provide incentives to support the development of digital infrastructure. These measures would help establish a supportive mindset and facilitate the diffusion of this innovative solution. In the medium term, governments could focus on developing regulatory frameworks that promote horizontal collaboration among SMEs in logistics while introducing incentives or requirements for logistics operators to monitor and report CO_2 emissions. In the long term, regulators might consider creating certification systems for "collaborative green logistics" operators, acknowledging verified emission reductions and efficiency improvements to enhance market differentiation and foster consumer trust.

A key limitation of the study was the focus on single-product deliveries. A significant avenue for further research would be to explore multi-product deliveries, thereby enabling each retailer to be linked to multiple suppliers.

In conclusion, future research could expand on the model presented or apply it to other sectors. Moreover, future research could focus on the trade-offs between environmental and economic results, dropping the use of the eco-efficient approach and therefore exploring another perspective for the same green logistics solution.

With respect to previous studies, the results of this work focus on a specific region but can be generalized to similar areas. The authors believe indeed that the model has the potential to be applied to a broader range of products and geographical regions. The cross-panel data technique [60,61] could be used by collecting data from different regions across years to examine whether regional characteristics (fragmentation of demand, SME density, urban structure) affect the platform's effectiveness.

CRediT authorship contribution statement

Giulia Galli: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Chiara Siragusa:** Writing – review & editing, Validation, Supervision, Project administration, Methodology. **Davide Luzzini:** Writing – review & editing, Supervision. **Angela Tumino:** Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Giulia Galli reports financial support was provided by OnFoods. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors are unable or have chosen not to specify which data has been used.

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