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Implementing the circular economy paradigm in the agri-food supply chain: The role of food waste prevention technologies

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ABSTRACT

Food systems are plagued by the grand sustainability challenge of food waste, which represents a urging issue from economic, environmental and social point of view.

dThe Circular Economy paradigm can open up different actions which are framed within the so-called Food Waste Hierarchy (FWH). In these regards, scholars recommend to leverage on those practices that are able to prevent the generation of surplus food, preserving a higher share of the sustainable value. For these pre-harvest and post-harvest practices that go under the name of prevention or reuse strategies in different FWH, technology plays a crucial role. Through a set of 34 semi-structured interviews with technology providers as well as with companies in the agri-food supply chain, the present work investigates extensively the range of the available technologies and the detailed objectives of such technologies for food loss and waste prevention (i.e., forecasting, monitoring, grouping, shelf life extension, product quality and value upgrading). Moreover, different forms of collaboration enable to reach these objectives in different ways. Collaboration with technology providers can be based on continuous technical assistance and consulting for data elaboration and data analysis as well as on full data sharing and co-design, allowing to achieve a different impact on food loss and waste prevention.

Finally, our study reveals that the adoption of different technological options can represent the engine to establish vertical collaborations between the adopter of the technology and another stage in the agri-food supply chain, in order to fight food waste and loss with a coordinated supply chain effort.

1. Introduction

Food waste reduction is one of the sustainability grand challenges for food systems. Food waste derives from an ineffective management of food surplus (Papargyropoulou et al., 2014, Garrone et al., 2016).

To indicate the total amount of wastage generated within different stages of food supply chain, the terms “food losses” and “food wastes” are commonly used (Vilariño et al., 2017).

The common expression of food loss and waste (FLW) includes a share of total food production, that was originally intended for human consumption, but not consumed (Gustavsson et al., 2011). FLW is food that is produced, retailed or served but it is not consumed and not redistributed to feed people, animals or used for new edible products (Garrone et al., 2014).

Notably, food loss is generally associated with the quantity lost during the production, post-harvest and processing stage, whereas food waste refer to food that is fit for human consumption but that is discarded in retail, food service or consumption stage (Vilariño et al., 2017, FAO, 2019).

In the definitions of FLW, different stages of food production are considered, from the moment in which crops are ready for harvest until the consumption stage (Chaboud and Daviron, 2017). From field to fork, postharvest losses are estimated to be the 30–40% of all food production (Godfray et al., 2010), which amounts to 1.3 billion tons per year world-wide (Gustavsson et al., 2013) .

Surplus food can be managed in different stages of the food supply chain in such a way that it does not end up degrading into FLW, thus surplus food can be recovered for human consumption or it can be prevented at the source limiting the unnecessary use of natural resources (Garrone et al., 2014).

The Circular Economy (CE) paradigm appears to be paramount in this context as it opens up different solutions to tackle food waste that refer to practices and approaches that combine technological solutions, behavioral and cultural changes as well as policy recommendations

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(Vilariño et al., 2017).

In particular, Food Waste Hierarchy (FWH) frameworks suggest different available options for organizations to tackle food waste, identifying a set of priority actions (Redlingshöfer et al., 2020), which are ranked mostly from an environmental impact perspective, from the most sound environmental option to the least one (Cristóbal et al., 2018). Nevertheless, the actions and strategies connected with the layers in the upper part of the FWH, i.e., food waste prevention, are underrepresented in the current literature (Redlingshöfer et al., 2020). The gap in the understanding of the potential benefits of such solutions, leads to a lack of guidance to choose the most effective technologies for FLW prevention.

On the technological side, in the recent years the urging challenge of food waste has represented a fertile ground for technological innovations. All in all, different technologies can support the valorization of food waste at different levels of the FWH (Vandermeersch et al., 2014a,b), thus tackling the issue while opening up new business opportunities.

Notwithstanding the priority role assigned, the adoption of the innovative technological solutions for *food waste prevention*, can bring relevant challenges for the companies in the food supply chain. The key competences and technical expertise related to such infrastructures and technologies (e.g., innovative food packaging or innovative process technologies - Mourad, 2016), lie outside the agri-food supply chain, therefore immediate and potential performance are uncertain and difficult to be fully understood by agri-food players. These solutions might end up in becoming "weak" forms of prevention, if not properly supported by a shift in the business model (Mourad, 2016). This uncertain scenario does not clarify what are the extra efforts and costs that these technologies might represent for some actors within the chain and whether or not they would be compensated by extra benefits for one or more players along the agri-food supply chain.

Hence, these technologies are just partially explored in the literature and little is known about the implications connected to their adoption by the players in the food supply chain. The present paper, through a set of 34 semi-structured interviews explores i) the typologies of technological solutions proposed by different technology providers for FLW prevention; and ii) which factors stimulate or hinder their adoption under different forms and the application within the agri-food supply chain.

The paper develops as follows, Section 2 reports a synthetic overview on the literature background. Section 3 present the research questions and methodology, while Section 4, 5 and 6 are focused on the presentation of the results and their discussion and conclusions respectively.

2. Background

2.1. The sustainability challenges of food loss and waste

Food loss and waste (FLW) is a relevant issue from the social, environmental and economic standpoint.

As for the economic dimension, reducing FLW represents a saving for all the actors in the supply chain (Chaboud and Daviron, 2017). Notably, initiatives that tackle FLW at its roots are beneficial for food producers that aim to sell more, but also to consumers who could have access to available food which is more affordable (De Steur et al., 2016). Whether and to what extent managing surplus food to prevent FLW can outweigh the cost connected to the extra operations needed to handle this surplus food, is still subject to a debate in the literature (Chaboud and Daviron, 2017).

Regarding the environmental dimension, a significant amount of agricultural inputs such as fertilizers, energy, and water are used to produce, then process, transport, distribute, store, and make food available for human consumption. Consequently, FLW is also a waste of land, water, energy and inputs (Gustavsson et al., 2011). Yet, all the actions that aim not only at managing surplus food but preventing its generation, can decrease the pressure that is exerted on natural resources (Timmermans et al., 2014; Chaboud and Daviron, 2017).

In addition to the important implications for the environment, surplus food and food waste prevention can also have a considerable impact on the society.

A reduction in the FLW generates indeed higher food security that extends the benefits to households (Timmermans et al., 2014; Chaboud and Daviron, 2017). When surplus food is redistributed thanks to food aid organizations or food banks to people who normally struggle to have access to nutritional food, food waste from a social point of view is avoided (Garrone et al., 2014) and thus there is a direct impact on the social dimension. Moreover, the increasing awareness around the so-called "food paradox", i.e., having a large amount of food waste in a world which is still food insecure (FAO, 2018), represents a relevant social driver for the implementation of FLW reduction strategies. The food that is wasted every year could indeed feed the nearly one in nine people all over the world who suffers from hunger, especially in developing and under-developed countries (Godfray et al., 2010).

2.2. Circular economy and food waste management hierarchies

Circular Economy represents a compelling reference framework for the management of food waste (Teigiserova et al., 2020). Put differently, food waste valorization options, like reduction, reuse and recycling support the aims of the circular economy paradigm (Geueke et al., 2018). Food waste hierarchies, as waste hierarchies in general, represent a powerful guidance for practitioners and policy makers to understand possible practices to be adopted. As Table 1 exhibits, different priorities of actions and different policies to follow for food waste management are embedded into different hierarchical frameworks that have been developed after the Waste Framework Directive 2008/98/EC (European Commission, 2008). In the Food Waste Hierarchy (FWH) framework introduced by Papargyropoulou et al. (2014) for example, the strategies of avoiding surplus food generation as well as the strategy of reusing surplus food for human consumption are high priority strategies because they allow to reduce the depletion of natural resources and to limit the negative social and ethical implications of FLW. Garrone et al. (2014) is aligned with the view that prevention of FLW through different redistribution and reuse options still targets human consumption, thus minimizing the waste from a social perspective. Garrone et al. (2016) identifies different reuse options (e.g., remanufacturing and repacking, sales with promotions and discounts, sales in secondary channels as ad-hoc distributor for surplus food) as well as redistribution, both internal to the employees of a company and external, through the collaboration with food aid organizations. Rood et al. (2017) classify the different redistribution and reuse options, not implying reprocessing, as forms of *human food recovery*. In a distinct layer in the ladder they instead consider *converting into human food*, in those cases in which food products are transformed into new edible products, so they are not consumed in their original forms. Interestingly, while most of the frameworks are aligned in terms of available options in the lower parts of the waste hierarchy (ranging from recycling of food products into not-edible alternatives, food recovery for the generation of energy and then incineration and disposal) some differences can be found moving up the waste hierarchy. When referring to *prevention* policies Garrone et al. (2016) and Vandermeersch et al. (2014a,b) refer to the prevention of food waste and loss, and not the reduction or avoidance of surplus food. This approach focuses on avoiding the post harvest losses and thus considering the possible generation of *food waste* from the moment in which food products are ready to be harvested (Chaboud and Daviron, 2017). The Food Recovery Hierarchy (United States Environmental Protection Agency - EPA, 2012) esplicitly considers the reduction of the volume of surplus food generated as the strategy having highest priority. As a whole, extant food waste hierarchies focus primarily on priorities of actions to manage surplus food, considering harvesting losses as unavoidable, hence

Table 1
Different food waste hierarchies presented in the literature

Name of the framework	Levels in the hierarchy (from most preferable to least preferable)	References
Waste hierarchy Food waste hierarchy	a) Prevention b) Preparing for re-use c) Recycling d) Other recovery (e.g. energy recovery) e) Disposal	(European Commission, 2008) (Papargyropoulou et al., 2014)
Food waste management hierarchy	a) Avoid b) Reduce c) Reuse d) Recover e) Treat f) Dispose	(Kosseva, 2011)
Food recovery hierarchy	a) Source reduction b) Feed hungry people c) Feed animals d) Industrial uses e) Composting	(United States Environmental Protection Agency - EPA, 2012)
Availability-Surplus-Recoverability-Waste Model (ASRW)	a) Recover surplus food to feed humans b) Recover surplus food to feed animals c) Waste recovery d) Waste disposal	(Garrone et al., 2014)
Food waste management hierarchy	a) Prevention b) Conversion for human nutrition c) Use of animal feed d) Use as raw materials in industry e) Process into fertilizer f) Use as a renewable energy g) Incineration h) Landfill	(Vandermeersch et al., 2014)
Moerman's Ladder	a) Preventing food losses b) Human food c) Converted into human food (food processing) d) Used in animal feed e) Use as raw materials in industry f) Process into fertilizer through fermentation g) Process into fertilizer through composting h) Applied for sustainable energy i) Incineration	(Rood et al., 2017)

devoting less attention to non-yields or less productivity in the farming operations (Chaboud and Daviron, 2017).

Nevertheless, especially the upstream stages of the food supply chain have the greatest potentials to prevent the generation of food surplus through new infrastructures, skills as well as storage and transportation technologies (Papargyropoulou et al., 2014).

2.3. *The technologies for surplus food prevention and management in the agri-food industry*

Technology is a fundamental element in the CE framework, which claims for socially radical and technologically advanced solutions to create effective circular patterns (Ghisellini et al., 2019). This is true especially for translating the CE frameworks in the food industry into specific actions, which requires the support of the technology for any layers in the FWH. Notably, the role of technology to prevent and manage surplus food is recognized as pivotal in moving up the food waste hierarchy, thus offering innovative tools to support companies in the top and high-priority layers of the food waste hierarchy. Technology not only has a crucial role in the conversion of waste, but, most importantly, in the prevention of useless extraction of raw materials (Nilsen, 2019). For example, information technologies can facilitate food sharing and redistribution via web platforms or apps (Harvey et al., 2019). Instead, strategies for *effectively manage surplus food*, once surplus food is generated, are generally linked to transformation technologies, since they deal with processing the surplus food in order to obtain animal feeding, fertilizers or energy (Arshadi et al., 2016; ReFED, 2016, Laufenberg et al., 2003, Girotto et al., 2015).

Nevertheless, the implications deriving from the adoption of technologies for *surplus food prevention* are disregarded in literature. In fact, literature mostly focuses on tackling food waste from the moment agricultural products are ready for harvest (Chaboud and Daviron, 2017), while a limited body of contributions analyze more in depth the adoption of technologies to prevent the generation of surplus food in the pre-harvesting phase.

As a whole, the agri-food context represents a fertile ground for the development of technological solutions to prevent and manage surplus food, spanning all the layers in the food waste hierarchy.

The high perishability of food products indeed has led to the emergence of new technologies that allow to extend the shelf life of the products, both through packaging technologies to enhance and extend conservation (Parfitt et al., 2010) and through ad-hoc storage systems (Van Holsteijn and Kemna, 2018).

The high intrinsic recoverability of some food products in particular, as fruits and vegetables (Garrone et al., 2014), together with the high potential of their byproducts to be re-processed opens up to additional transformation technologies to obtain a new edible derivative product (Galanakis, 2012).

Interestingly, new technologies can also help prior to the harvesting phase, through precision agriculture solutions that can represent potentially innovative technologies not just considered from a system productivity point of view, but also to prevent surplus food pre-harvest as well as to fight food insecurity (Ambler-edwards et al., 2009) .

The picture of the available technological solutions is variegated. Different technological options are currently not analyzed in terms of their actual applicability in the food eco-system as well as in terms of impact on food waste and loss reduction as well as from an extended sustainability perspective. More in general, as technology is fast developing and the urgency of FLW prevention is recent, there is a need to further understand which role technology can play in moving up on the ladder of the food waste hierarchy.

2.4. Collaboration as a key aspect of technology adoption for FLW prevention

As for many other technological innovations in the supply chain, also food waste prevention technologies benefit in their implementation from the collaboration of actors along the value chain (Chen et al., 2017). Several technological innovations that aim to create an impact on different sustainability dimensions are enabled by collaboration with multiple stakeholders. Technological innovations considering management systems based on time–temperature measurement in the context of the cold chain (Mercier et al., 2017), traceability systems in agriculture (Chen and Yada, 2011) new technological infrastructure to support information exchange in the meat supply chain (Lehmann et al., 2012), for example, are all presented in the literature as challenged by the implementation of the proper collaborative environment. Closer collaborations among actors that perform different types of activities along the supply chain (e.g. processing, storage, transportation technologies and agriculture) are considered of pivotal importance to promote sustainable food supply chains and tackle grand challenges like the FLW (Alamar et al., 2018).

With reference to technological innovations tackling the specific issue of FLW, they need to confront with the complex ecosystem of actors represented by the food supply chain (Garrone et al., 2014).

This ecosystem includes both companies operating in the same supply chain stage, that are generally direct competitors, and companies operating in different stages (Gellynck and Kühne, 2010).

The food supply chain ecosystem has to face a considerable power unbalance between the different supply chain actors (Taylor and Fearne, 2006); there is a high risk of having a loss for a supply chain partner (generally the weakest in the chain) which is greater than the benefits for another supply chain partner (Rutten, 2013; Chaboud and Daviron, 2017). According to Mena et al. (2011) the root causes of FLW lie in the interfaces of different supply chain stages, with the downstream ones (i.e., the interface between food manufacturer and retailer) being particularly relevant because the food product carries a considerable added value from an environmental and an economic point of view at these stages (Mena et al., 2011). Good practices to solve the FLW issue need therefore to be sought in collaborative processes and through information sharing, but also reliable storage and shelf life management systems (e.g. sales through alternative channels, sales with discounted prices) (Mena et al., 2011).

Such complex set of dynamics is undoubtedly relevant to understand how to effectively move towards hands-on applications to effectively fight FLW. Most of the analyzed studies refer to root causes identification of FLW (e.g., Mena et al., 2011, Garrone et al, 2014), but remedies to such issues are rarely investigated in terms of technological applications. Moreover, when real case studies are presented (Warshawsky, 2016) or real companies are involved in the discussion, the technological aspect is often missing in favor of motivational and organizational analyses.

3. Materials and methods

3.1. Research questions

Through the present study we aim at contributing to a better understanding of the role of technological solutions in surplus food prevention and management, i.e in the application of circular economy principles to the agri-food ecosystem. Yet, the focus is on the higher priority layers of the food waste hierarchies, which allow to preserve both social and environmental value.

The context is represented by the fruits and vegetables segment. On a global level, these productions weight around one third of the overall purchases of fruit and vegetables from the downstream stages of the supply chain and in particular, households, food service and retail businesses (De Laurentiis et al., 2018). This segment, accounts for almost the 50% of the waste generated in households, food service and retail stages due to the rapid decay of these fresh food products that shorten their shelf-life (Blanke, 2014; De Laurentiis et al., 2018). FAO (2012) estimated that around 45% of the overall production of fruit and vegetables end up being wasted (world-wide average in quantity). In terms of economic value lost with the wastage of fruits and vegetables from the harvesting phase until the distribution (retail, food service and consumption excluded), this value is around 21% of the total amount of fruits and vegetable produced on a global scale (FAO, 2019). Instead, the amount of food loss and waste (considering the supply chain stages from harvesting until retail - included) is on average slightly more than 10% of the overall food loss and waste quantity (FAO, 2019).

In the Italian context, the quantity of fruit and vegetables wasted at the retail stage is the highest compared to other food product (i.e., a total of 24 tons of fruits and vegetables wasted per year) (Cicatiello et al., 2017). Moreover, at the households and transformation stage of the supply chain, fruits and vegetables are among the first three product categories per food waste generated (Giordano et al., 2016, Grosso and Falasconi, 2018).

Thus fruits and vegetables segments presents high potentials to prevent the generation of surplus food (Halloran et al., 2014), but this would require new infrastructural and technological solutions (Papargyropoulou et al., 2014).

The focus on “technology” is here intended to include not only digital and processing technologies, but also packaging and conservation technologies. The different types of solutions are adopted by different actors in the fruits and vegetables supply chain, which can be described as in Fig. 1.

In light of the above discussed challenges and the lack of an extensive understanding on the pre-harvest and post-harvest technological solutions to prevent and manage surplus food, our guiding research questions are the following:

RQ1: How does technology enable surplus food prevention along the fruit and vegetables supply chain?

In order to provide a rich taxonomy of such technologies, we focus not only on i) the type of technological solutions, but also on ii) the different objectives with respect to food waste prevention pursed by the technology; and iii) the supply chain stage that represents the main user of the technological solution.

RQ2: How does the collaboration with technology providers or between supply chain stages allow to address different objectives with respect to FLW prevention?

Hence, we observed and analyzed different ways in which companies along the food supply chain adopt the investigated technologies, thus focusing on the relationships in place between the technology providers and the food companies. The technological solutions analyzed can be adopted by different stages of the agri-food supply chain or, when adopted in a single stage, their benefit can expand in other stages as well. Therefore, they can create the proper ground to initiate dyadic vertical collaborations (i.e. collaboration between two stages of the agri-food supply chain), which are particularly effective when dealing with a supply chain-wide issue as food waste (Garrone et al., 2012). Therefore, technology is here investigated with a different value assigned to its role of antecedent, depending on the different forms of collaboration that it enables.

3.2. Methodology

3.2.1. Case selection

Given the nature of our research questions and in order to compare an extensive number of cases looking for both similarities and differences across them to reach an extensive taxonomy multiple semi-structured interviews have been adopted as a research method. Semi-

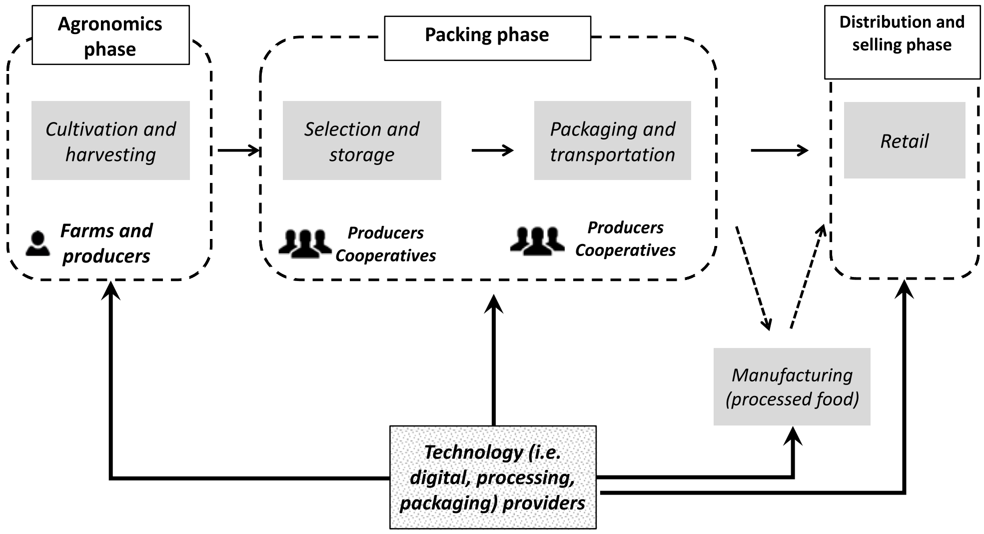

Fig. 1. Reference framework for the fruits and vegetables supply chain

structured interviews are based on a predetermined list of questions but they leave space to the participants to expose issues and comments (Segal et al., 1995; Longhurst, 2003). The unit of analysis is represented by dyad: technology supplier and its costumer, i.e. the adopter of the technology, which is represented by the company in the food supply chain (i.e. farms and producers, cooperatives of producers, manufacturers, retailers) targeting food waste reduction with the support of a technological solution and a corresponding technology provider. The target companies have been scouted thanks to the participation to two main events: a trade fair taking place in Italy in May 2018 (i.e., Macfrut 2018) and Seeds and Chips Summit. The former is an important trade fair that aimed at professionals operating in the fruit and vegetables sector, among which technology providers are prevailing. The latter, is an international event hosts yearly an interesting pool of young ventures in the agri-food supply chain. Additionally, companies have been scouted online by secondary sources and with a short preparatory interview to understand the suitability of a specific technology to address the goal of food waste reduction.

With the aim of achieving an extensive taxonomy a total of 34 structured interviews have been developed, with 13 interviews conducted with the twofold perspective of the supplier of the technology and the partner within the food supply chain, while 21 interviews have been conducted with the sole perspective of the technology supplier. We selected the companies applying a stratification purposeful sampling of the set of companies originally scouted, in order to capture a variety of technologies and detailed objectives connected to food waste prevention and thus to favor the comparison among subgroups (Miles and Huberman, 1994). We are aware of the rapid evolution and the variegated nature of such technological solutions, so our purpose is not to develop a taxonomy that aims to be exhaustive of all the possible technological solutions in the field, but a first satisfactory picture of the available options of technologies to prevent food waste and losses in the fruits and vegetables segment. The high number of interviews served this objective.

3.2.2. Data collection and data analysis

Data have been collected in 2018 through direct interviews conducted at least by two researchers. As reported in Appendix A, the interviewees are represented by Founders, Co-Founders and Managing Directors when dealing with start-ups or small sized companies (for instance Company R and S), Product Managers, R&D Managers, Account Managers and Sales Manager when dealing with larger firms (for instance Company B and O). Primary sources of information have been collected with a questionnaire addressing i) a description of the features of the technological solution and the supply chain stage the technology is conceived for; ii) relationship with the client companies: main features requested by the customers, main reason why the technology is chosen; iii) the relationship with food waste prevention objectives and therefore to what extent the impact in terms of FLW is actually perceived as one key performance by customers. Sections ii) and iii) were also present in the interview protocol with the main client company (i.e. the adopter of the technology within the agri-food supply chain). This twofold perspective allows us to validate the findings on the impact on food waste reduction and also on analysing different forms of collaboration.

Secondary sources have been adopted to complete the descriptive information collected from the technology providers. Coding have been performed by the members of the research team independently reaching convergence on doubtful aspects. Each researcher has shared his/her own results through a brainstorming session with the others, so to eliminate subjectivity and to ensure internal validity (Seuring and Gold 2012). Moreover, researchers relied on follow-up interviews in case of missing information which lead to struggle in reaching convergence. Interviews have been coded with an hybrid inductive/deductive approach (Skillman et al., 2019) deriving main topics of the research domain with a deductive approach, while set of codes have been derived inductively by collected data in order to expand the topics inductively defined (Skillman et al., 2019). The code book was developed both for descriptive purposes in order to build the taxonomy (i.e. to describe synthetically the analyzed technology and to assess the objective of the technology with respect to food waste) as well as for explanatory purpose and thus to differentiate different roles of antecedents for the collaborations that reinforce the impact on food waste reduction. When considering the antecedents of collaborations, the information collected have been triangulated and enriched with the point of view of the food company which is the main adopter of the technology. The coding process followed therefore the key dimensions in relation with RQ1 and RQ2, as reported in Appendix B.

4. Analysis of the results

4.1. A taxonomy of technologies to prevent and manage surplus food

With reference to **RQ1**, the technologies adopted by the companies (with reference to the subsample of 21 technology providers) have been classified according to the following dimensions: i) type of technologies; ii) objectives with respect to the reduction of FLW; iii) supply chain stage of the client company. Moreover, we integrated this classification with a more in-depth analysis of the technological solutions, differentiating them first of all in terms of **maturity of the technology in the market**. We distinguished between, i) consolidated technologies, namely technologies with more than 5 years of commercial applications of the specific or similar technologies in the industry, ii) cutting edge technological innovation (i.e., newly born technology or innovative applications in the food industry); iii) Limited market diffusion, for those technology which are not considered cutting-edge but have a limited application in the specific segment. Secondly, the **type of investment needed by the target user** in the food supply chain to adopt it (i.e., main capital and operational expenditures that the user would need to bear).

Table 2 and Table 3 summarizes the classification of the different technologies.

As regards the different types of technological solutions, we distinguish between: *information systems and analytics, chemical preservation, mechanical preservation* and *processing.*

Information systems and analytics are those technological solutions which rely on data collection systems to limit overproduction, identify causes of non-compliance and target products in the appropriate market, thus pursuing as objectives: forecasting, monitoring and grouping. For example, Company I develops a forecasting system based on machine learning algorithm application for the forecast of both offer and demand for fruits and vegetables. Moreover, Company M provides sensors that measure field and exogenous parameters (i.e. earth temperature, moisture, humidity, rain level, wind speed and direction) to help farmers in responding more precisely to the market demand in term of quantity and to avoid overproduction. *Chemical preservation* refers to chemical substances that, applied to fruits and vegetables directly and / or through active packaging, lengthen their shelf-life and improve their quality. An example is represented by Company E, which is able to slow down the ripening process and obtain a better quality of the fruits and an extended shelf life through the application of a specific molecule on climacteric fruits (i.e. fruits that continue the metabolic processes also after the harvesting). *Mechanical preservation* refers instead to conservation and transportation systems which are able to control specific parameters (e.g. temperature, O_2 level) with the aim of expanding the shelf life. Company Q offers storage technologies in controlled atmosphere with the aim of extending the shelf life of apples and pears.

Processing technology allows to develop *reuse* practices. These technologies are offered to manufacturers with the aim to transform fresh products, as fruits and vegetables, into other finished products like snacks, soups, fruits juices, etc.

The objective of the technology with respect to food waste looked at different set of actions that can be implemented to reduce FLW, namely: *forecasting, monitoring, grouping and sorting, better conservation for shelf life extension, product quality and value upgrading.* Type of technology and the objective of the technology with respect to food waste are strictly correlated, since information systems and analytics can be used for the forecasting, monitoring, grouping and flow managing activities, chemical and mechanical preservation can be used for shelf-life extension and quality upgrading. Finally, processing is used for product value upgrading (i.e., the outcome of the processing phase is a processed food product, different from the original fresh food).

The supply chain stages refer to the supply chain of fresh products (i.e., fruits and vegetables) and thus: *farming, conservation and packing, manufacturing, transportation and retail.*

As shown in Table 2, the farming stage is the one in which information system and analytics technologies are prevailing, to support precision agriculture methodologies. In the packing stage, information system and analytics are acquiring relevance, covering all the four objectives, with the prevailing attention for grouping and/or sorting. However, even if in a reduced way, this type of technology is present in all the supply chain stages with exception of the manufacturing one. In the post-harvesting stages mechanical preservation technologies are widespread in order to preserve the product as long as possible and avoiding to reach the "sell-by date" before reaching the retail stage and the final consumers. Retailers instead prefer chemical preservation options on the fresh products, in order to "*prolong the reduction of the ripening process also on the consumers' shelves*" (interviewee in Company E).

Processing technology is intuitively present only in the manufacturing stage and it has the potential to create value from commonly not-profitable products (i.e., fruits and vegetable products not compliant to market standards and requirements).

Finally, the analysis on the maturity of the technology and the investments needed by the adopter in the food supply chain, revealed that, in terms of the maturity of the technology, the picture is variegated for all the different types of technologies, while the investments needed by the food supply chain actors are different from one type of technology to the other. In the information systems and analytics category there are cutting-edge technology, which include data collection devices like drones and cameras, advanced predictive algorithms based on machine learning approach for data analysis and innovative alternatives to traditional mechanical sorting. Calibration and tracing systems are instead more consolidated, although some smart upgrades of such technology and just recently spreading. As for chemical preservation technologies, they are all more consolidated with more years of market applications (for bio-stimulants and active packaging),

Table 2
Taxonomy of technologies, objectives, supply chain stages that represent the main user of the technology

		Supply chain stage of the client company Cultivation and harvesting	Selection, storage, packing	Transportation	Manufacturing	Retail
Information systems and analytics	**Forecasting**	Comp. G Comp. M Comp. S				
	Monitoring	Comp. D Comp. T Comp. A Comp. C		Comp. N Comp. R		Comp. N
	Grouping / sorting		Comp. B Comp. P Comp. J			
Chemical preservation	**Shelf life extension**		Comp. E	Comp. E		Comp. K
	Quality upgrading	Comp. F Comp. L				
Mechanical preservation	**Shelf life extension**		Comp. H Comp. Q	Comp. O Comp. Q		
Processing	**Product value upgrading**				Comp. U	

Table 3
Details on the technological solutions, maturity of the technology in the market and investments needed by the adaptor

Cases	Type of technology	Details on the technological solution	Maturity of the technology in the market	Type of investment needed by the adaptor
Comp. A		Crop monitoring systems to monitor the condition of the soil for more effective decisions on the quality and quantity of nutrients to adopt	Consolidated	
Comp. B		Sorting machines based on advanced visual technology for performing the sorting based on internal and external features of the fruits	Consolidated	
Comp. C		Drones with remote sensors that allow to get information from the crops.	Cutting-edge	
Comp. D		Cameras to collect data and cloud-based software to analyse the conditions of the crops	Cutting-edge	
Comp. G		Data collected from a digital calibration system allow to forecast on average the diameters and the distribution in classes of fruit size.	Cutting-edge	
Comp. I	Information systems and analytics	Machine learning system aiming at forecasting the available supply capacity in the field as well as the demand for fruits.	Cutting-edge	Software licensing and hardware (e.g., sensors, cameras, drones, calibration systems) / machineries (i.e., sorting machines)
Comp. J		Managerial software for stock management and production planning.	Consolidated	
Comp. M		Sensors for collecting information on air and soil features.	Cutting-edge	
Comp. N		Sensors for tracking and monitoring food conditions (e.g., temperature, humidity) during transportation.	Consolidated	
Comp. P		Sorting machines based on advanced visual technology for performing the sorting based on internal and external features of the fruits	Consolidated	
Comp. R		Tracing system for food integrity based on IoT technology	Limited market diffusion	
Comp. S		Sensors for plant monitoring (hardware and software infrastructure)	Limited market diffusion	
Comp. T		Smart calibration system to analyse external and external conditions of the fruit.	Consolidated	
Comp. E	Chemical preservation	Molecule based on a chemical mutation of the natural processes of fruit breathing.	Cutting-edge	Additives / special cardboard material
Comp. F		Bio-stimulants: chemical molecules that alter the standard conditions of the plants.	Consolidated	
Comp. K		Active packaging made of cardboard impregnated with essential oils	Consolidated	
Comp. L		Bio-stimulants and "Intelligent fertilizers" that can gradually release the nutrients needed for organic culture	Consolidated	
Comp. H	Mechanical preservation	Mechanical system for the continuous and constant monitoring of the gaseous composition in controlled atmosphere.	Cutting edge	Devices for monitoring and modifying critical parameters
Comp. O		Reefer monitoring solutions in controlled atmosphere to reduce the production of ethylene	Limited market diffusion	
Comp. Q		Conservation systems with a technology that can modify the concentration of gases in the air	Limited market diffusion	
Comp. U	Processing	Machineries for processing fresh fruits and vegetables depending on their ripening conditions.	Consolidated	Machineries

whereas the technology proposed by company E is cutting edge and based on an additive to slow down the ripening process. Mechanical preservation solutions are instead mostly based on controlled atmosphere technology which still have a limited penetration in the market. For company U the processing technology is instead consolidated. As a whole, while information systems and analytics require investments in hardware and software, the other types of technology would instead require investments in additives and devices.

4.2. Different ways to address the different objectives with respect to food waste prevention

By performing a qualitative grouping based on i) the type of technology, ii) the objective of the technology with respect to surplus food and iii) the potential impact on food waste reduction, jointly, three main groups can be identified. The groups present some distinctive features with respect to the main levers adopted to tackle food waste but also with respect to other descriptive characteristics, as described in Table 4.

Within each group, companies are classified looking at the different levers they adopt to tackle food waste reduction, differentiating potential impact on food waste reduction from a more direct impact.

With a potential impact we mean that food waste can still be generated by several other root causes that the technology is not able to tackle, whereas a more direct impact means that the technology is able to address more than one cause determining food waste or that the specific cause of food waste is closed to the critical interface of the agri-food supply chain (i.e., between packing stage and distribution) (Mena et al., 2011).

Moreover, as a bridge for our second research intent, we also observed different ways in which companies along the food supply chain adopt the investigated technologies, with a focus on how different forms of collaborations can enable or reinforce the effectiveness of the technology in addressing the different objectives with respect to FLW prevention (reported in Table 2).

Collaborations between a company in the agri-food supply chain and the technology provider can contribute to the achievement of the different objectives with respect to food waste prevention in four different ways that are not mutually exclusive.

First of all, in the simplest scenario, the technology is just "adopted", meaning that the relationship in place is the traditional buyer-supplier relationship, with the technological solution that is sold "off-the shelf" and the technology provider supports only for operating the technology for the first time. In a second scenario, the establishment of a relationship with the technology provider is based on continuous technical assistance with the customer or assistance in case of any issue occurring during the life cycle of the technology. A third type of collaboration is represented by a more intense relationship based on full integration of data and/or co-design between the two parties. Finally, the fourth scenario, represents a dyadic vertical collaboration between the agri-food company adopting the technology and another agri-food company in another stage of the supply chain.

The three groups of companies and related technological solutions introduced in Table 3 can be discussed in light of both the impact on food waste reduction as well as in terms of the role of the collaboration to reinforce the impact.

In **group 1** there are information systems and analytics technologies adopted with the aim of *monitoring and forecasting* the productivity of the harvesting process, having real time information in order to act in a timely fashion for any issues that might deteriorate the product quality and also to match production with demand, thus avoiding overproduction in field, extra-stocks in warehouses or leftovers at the points of sale. As depicted in Fig. 2, these three different levers span from a more potential impact on food waste reduction (pre-harvesting intervention) to a more direct one, connected to an effective match between supply and demand.

In this group most of the companies in the agri-food supply chain rely on the technology providers for technical assistance to support the elaboration and interpretation of data. Only in one case (Company I) the relationship with the supplier is in the form of a full integration of information in order to design ad-hoc forecasting application based on artificial intelligence.

Moreover, as reported in Table 4, a common trait that these companies share is represented by the target of their offering, which is represented by farmers, packing houses and in by transportation companies. All the companies in this group have started to internationalize either through foreign direct investment or simply exporting their solutions without any clear trends in these regards.

In **group 2** there are information systems and analytics -based technologies which have *grouping* as the main objective. The three companies in this group rely either on an automated and intelligent sorting process that help, not only to estimate the overall processing time, thus allowing the fruit to reach the shelves sooner, but also to target the right market segment for fruits of different quality, thus

Table 4
Three groups of technological solutions with common leverages on food waste reduction

	Group 1	Group 2	Group 3
Companies (TPs)	A, C, D, M, N, R, S, T	B, J, P, U	E, F, H, K, L, Q, O
Type of technology	Information systems and analytics	Information systems and analytics	Chemical/Mechanical preservation/ Processing
Objective of the technology with respect to food waste prevention	Monitoring/Forecasting	Grouping	Shelf life extension/quality upgrading/ product value upgrading
Main levers to tackle food waste (from potential to more direct impact on food waste reduction)	• Prevent at the source (pre-harvest) controlling and forecasting potential factors causing quality deterioration • Help decision making to solve issues causing food waste in a timely fashion • Match production with demand along different stages of the agri-food supply chain through advanced forecasting systems	• Manage production planning in line with market demand • Speed up sorting, shortening the food product processing time • Address the proper market for the most suitable product thus diminishing rejections at the final stage of the supply chain)	• Pre-harvest intervention on the product quality (aesthetic features, e.g., size) • Improve organoleptic /aesthetics characteristics of the product post-harvest (diminishing rejections at the final stage of the supply chain) • Allow to better bear any transportation routes increasing the share of products that arrive with good quality on the retailer's shelves
Distinctive features of the companies in the group	• Addressing upstream stages of the fruit and vegetables supply chain and transportation • Operating in international market through Foreign Direct Investments and Exports	• Addressing manufacturers • Operating in international market through Foreign Direct Investments (need of technical assistance)	• Addressing upstream stages of the fruit and vegetables supply chain and retail • Operating in international market through Exports and Foreign Direct Investment when co-design is in place

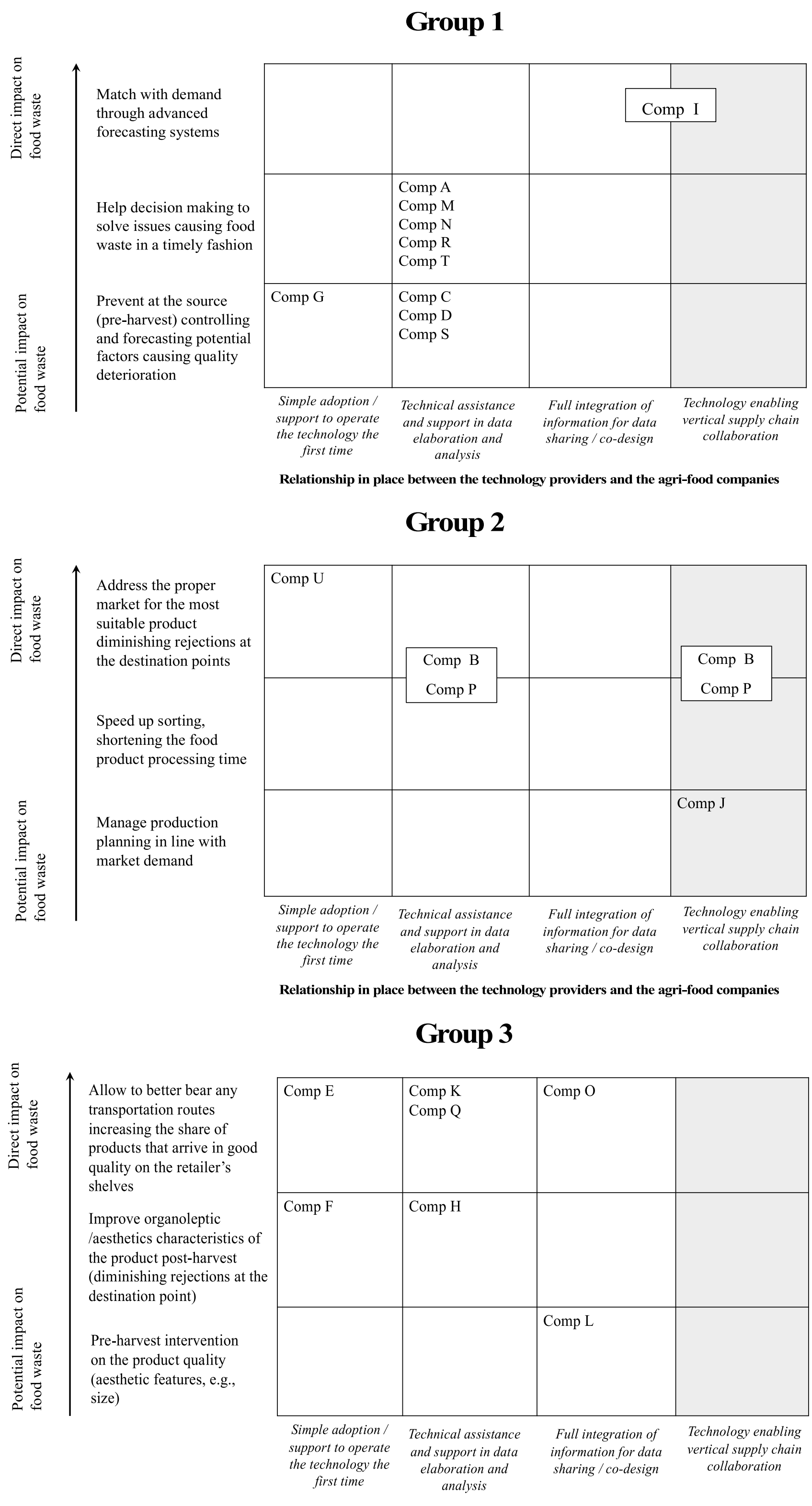

Fig. 2. Enriched taxonomy of technologies for food waste prevention

reducing the impact of rejections at the final stage of the supply chain. In terms of relationships with the customers, both company B and P base these relationships on a close technical assistance to their customers in order to operate the technology for the first time and to support them in case of any technical issues. Moreover, the technology enables a virtuous vertical collaboration along the agri-food supply chain. For company P for example, the innovative sorting technology enables a collaboration between a medium-size producer and an important exporter, in order to sort premium type of kiwis and thus reducing scraps for non-conformity with the standards imposed by the exporter.

Company J is a peculiar case in the group, with a technology to support the production planning process to reduce overproduction, with a highly customizable software for agri-food businesses. In this case the solution is co-designed with the customer in order to develop a tailor-made application.

Distinctive features of these groups of technology providers is represented by the fact that three out of the four companies in the group (i.e., company B, P, U) address food manufacturers and they all operate in international context by direct investments and not by simple export, because of the need to provide technical assistance close to their main international customers. Company J instead is young Italian venture addressing mostly packing houses and farmers that has not yet internationalized.

Finally, in **group 3**, we have chemical and mechanical preservation technologies which aim at extending the shelf life, upgrade the product quality and to assign a new (higher) value to a product. The quality upgrade is achieved both by acting on the pre-harvesting phase for example through specific nutrients and bio-stimulants which are able to modify a key aesthetic feature as the size or post-harvesting avoiding preservation disorders (i.e. skin browning). Moreover, thanks to transportation carried out in controlled atmosphere conditions, fruits and vegetables can bear longer transportation journeys or can be sold for a longer sales window. In this group most of the companies develop a relationship with the customer based on a technical support to implement the technology for the first time. Just in two cases (company O and company L) the solutions is co-designed with the customers and there is a continuous exchange of feedbacks even after the first operationalization of the technology. This is justified by the need to customize the parameters to establish the specific dosage of bio-stimulants or the need to regulate the controlled atmosphere conditions on the basis of specific customer/market requirements or on the basis of the technical considerations of the agronomist of the agri-food company.

Interestingly, for this group of companies, the prevailing orientation for what concerns internationalization is represented by export strategy, whereas only for companies O and L the internationalization is undergone through direct investment, thus supporting the co-design of the solutions, the trials in field by operating close to the main customers.

4.3. Implementing collaborations to reinforce the impact of technology for food waste prevention

The different types of collaborations in place are supported by different antecedents identified by technology providers and that have been validated and enriched by the actor in the agri-food supply chain stage adopting the technology, as outlined in Table 5.

Companies in the agri-food supply chain are pushed to adopt the different technological solutions because they lack of internal competences to develop such technological innovations and to exploit completely their potentials. Therefore, by adopting the technology, they gain access to ad hoc competences. Companies in the agri-food supply chain have understood the increasing importance of some technological trends within the industry and they perceive the importance to be exposed to state-of-the-art innovations to win the increasing competition as well as to receive an effective and continuous technical assistance and consulting on data elaboration and analysis, as well as further insights for the next directions of technological development.

Company Food1 for example, has identified in the adoption of the technology provided by Company B a way to *"fit with the quality/cost trade-off the market asks for, but having an important window to scout state-of-the art technologies in the sorting process"*.

On the other hand, technology providers do not have a specific knowledge for specific processes of the food supply chain and they need the participation of their customers to improve technological effectiveness. Company Food 4, which is a packing house managed by a cooperative of farmers and which is the main recipients for the technological solution proposed by Company C, emphasizes the importance of the technical external knowledge, not only as the main driver to adopt a new technology, but also as the key reason to establish a collaboration with the technology supplier based on data elaboration and analysis *"the lack of knowledge is the major barrier to spread the drone technology. For farmers is impossible to deal with this great amount of data alone. (…) collaboration with technology suppliers is fundamental to acquire the ability to read such data"* .

In some cases (i.e. cases I, J, K, L, O) the collaboration between the technology provider and the customer is based on full data sharing (as in case I) or on co-design of a tailor-made solution for a particular customer or food products.

Moreover, in our sample, a set of cases highlights how technology for surplus food prevention and management can represent the engine to initiate or develop further a collaboration between different supply chain actors. This is a desirable situation for a set of companies whereas is already actually implemented for another set of companies in the agri-food supply chain. Nevertheless, the unbalanced power in favor of downstream companies of the food supply chain does not favor a vertical collaboration among different agri-food supply chain players. For instance, downstream stages of the food supply chain could potentially exploit the greater benefits connected to the shelf life extension of fruits and vegetables as well as a better inventory planning to respond to the market demand.

Nevertheless, the perception of other players within the supply chain is that the sharing of these benefits through a better redistribution of the extra margin generated, is one of the main barriers preventing them from the collaboration with downstream players. As stated by Food 12: "*The price of fruits is equal to thirty year ago, but the advent of this technological innovations would require an additional investment for us which means higher costs and an even lower profit.*" (Office environmental sustainability and certification, Food 12).

5. Discussion

Reduction of FLW at each stage of the agri-food supply chain passes through the implementation of a CE approach (Vilariño et al., 2017). Technological solutions are one but fundamental piece of such approach. Our study proposes a taxonomy of possible technological solutions that clarifies the portfolio of technological options that are available for the different stages of the agri-food supply chain, with particular reference to the fruits and vegetables segment. The different technological solutions are linked to the different objectives to reach FLW reduction, then clarifying how different types of collaborations can reinforce the reaching of the different objectives pursued by the technological solutions. We have therefore enriched the discussion around the CE approach to tackle the challenge of FLW with some keys elements related to: i) an overview of the state-of-the art technologies available to move up the FWH and to translate the concept of "prevention" in hands-on applications that are currently on the market; ii) the potential role of such technologies in limiting the loss of sustainable value embedded in food products; iii) how collaborations with technology providers and vertical supply chain collaborations can facilitate the effectiveness of the technologies to reach FLW objectives.

It must be said that, in our overview of the possible solutions, we have excluded "redistribution" (i.e. distribution of edible food to people in need) as an option, although it is a high priority practice especially for the social impact that it generates. Technologies are available also for supporting the challenging operations and logistics activities connected with the execution of such strategy, but they are mostly in the form of apps or web-platforms facilitating the effective communication among actors involved in the redistribution cycle and they can hence be considered less state-of-the art technologies.

Moreover, moving down the ladder, despite the positive impact connected to the avoidance of the social impact of food waste, *processing* technologies can be considered lower priority for the

Table. 5
Types of collaboration and antecedents

Type of collaboration in place	Antecedent(s)	Cited as a driver by	(# of occurrences/tot number of cases for the specific type of collaboration) %
(no collaboration) Simple adoption of the technology by the single agri-food supply chain stage / the TP supports to operate the technology for the first time	Limited effort from the customer side to understand and operate the technology	E,F,G,U	75%
Collaboration between TP and a customer based on continuous technical assistance and support in data elaboration and analysis	Access to consulting and technical assistance deriving from the lack of knowledge of appropriate methods and skills to fully exploit the benefit of the technology (e.g. enriched data management)	A,B,C,D,H, M,N,P,R,S,T	84,6%
	Refinement of the technology collection of feedback from suppliers	Q, K	15,4%
Collaboration between TP and customer based on full data sharing/ co-design	Access expertise that could open up future opportunities for the research and development of state-of-the-art technologies	I,J,K	60%
	Access to a highly customized technology	L,O	40%
Technology to enable vertical collaborations between different supply chain stages	In order to take full advantage of the technology, the actors in the supply chain are encouraged to gain visibility on critical information (e.g. available / requested quantity and quality standards)	E, F, K, Q, R, S (desirable), B, P, J (already implemented)	100%

environmental impact. If indeed this technological solution and the set of supporting activities are implemented in supply chain stages that are progressively closer to the final market, they increase the negative environmental externalities generated by the management of surplus food.

Finally, we have gone in depth in exploring the ecosystem that represents the key locus of innovation to face the grand challenges connected to sustainability and CE in the agri-food industry, which is represented by the "extended" agri-food supply chain, in which technology providers are integral parts. We are contributing to extant debate in the literature connected to how to translate the CE paradigm in practice, with a specific focus on those actions incorporated in the higher layers of the FWH that allow to save most of the sustainable value. Hence, i) we confirm the importance of collaborations to effectively implement the CE paradigm (Dora, 2019) and ii) we shed lights on how the transition to a fully circular approach in the whole agri-food supply chain is far from straightforward, given the complex set of relationship in the agri-food ecosystem (Taylor and Fearne, 2006).

As for the first point, interestingly, some additional considerations emerge. The different types of relationships established with the technology providers do not present an option that revealed to be the most effective in terms of impact on FLW prevention. Nevertheless, as shown in Fig. 3, the different types of collaborations seem to be used to achieve different specific objectives within the higher-level objective of fostering an effective implementation of the technology and the CE paradigm.

On the one hand, establishing a relationship with the technology supplier that imply technical assistance is linked with the objective to bridge a gap in the competences and skills of the main adopter of the technology, which might lack of the competences to interpret and analyze the data collected by a specific technology in the category *information systems and analytics* or might need to be supported to fully understand the value of a cutting-edge technological solution related to *chemical preservation*. On the other hand, establishing a relationship with the technology provider oriented towards higher integration (i.e., the relationship based on full data sharing and co-design with the adopted) is justified by the need of some specific technologies to be "tailor-made" and to effectively target the goal connected to FLW reduction. Interestingly, when there is this specific need, geographic closeness appears to be paramount as well. The technology providers need to provide not only continuous technical assistance but need to get to know the peculiarities of the processes characterizing the adopter in deep details. This is witnessed e.g. by the choice of companies like O, L and I to pursue internationalization through direct investments, which are mostly justified by the need to have after-sales but also R&D divisions that are close to the clients.

As for the latter contribution to the debate around the shift of the food supply chain with an end-to-end perspective to effectively implement the CE paradigm, we have pointed out that vertical collaborations are necessary conditions to exploit the full potential of some cutting-hedge technology. The vertical collaborations that would be enabled by the technological solutions would allow to apply FLW prevention at its roots by favoring the match between supply and demand. Nevertheless, we also derived that the orchestration of resources to implement such transition in the food supply chain is far from straightforward.

We have indeed underlined how upstream companies in such supply chain are more prone to search for the possibility to create stable relationships with downstream actors, in order to assure profit and to invest in technological solutions having a more balanced distribution of cost and benefits. On the other hand, downstream stages should be aware of the importance to share benefits and risk with upstream companies and to shift to an "end to end" perspective to quantify productivity as well as impact on food waste.

6. Conclusion

From the theoretical point of view, our findings represent an initial answer to the call of Chaboud and Daviron (2017) to enlarge the scope of surplus food prevention and management distinguishing pre and post harvesting solutions. Moreover, we have enriched the hierarchical framework proposed in literature (e.g., Papargyropoulou et al. (2014); Rood et al. (2017)) to translate the CE paradigm into practices and approaches that develop around technological solutions, focused objectives and collaborations to serve the scope of the prevention and partially the reuse layers (i.e. the "highest layers" in all the analyzed hierarchies). Fig. 4 represents our proposal of and "Extended Food Waste Hierarchy". This extension is to interpret both in terms of a more detailed overview of the possible options for the *prevention* layer, but also in terms of different supply chain stages that the technologies can address. The technological solutions investigated cover well the agronomics and packing phases of the agri-food value chain, while manufacturing and distribution phases are covered to a minor extent. The same holds true for the consumption stage, which, although highly important to the overall amount of food waste generated (De Laurentiis et al., 2018; FAO, 2019) has not been included in the study, given that the study of consumer behaviours would have required a completely different research design.

As for managerial implications, this work, makes two main contributions for practitioners. First, through our taxonomy we derive a

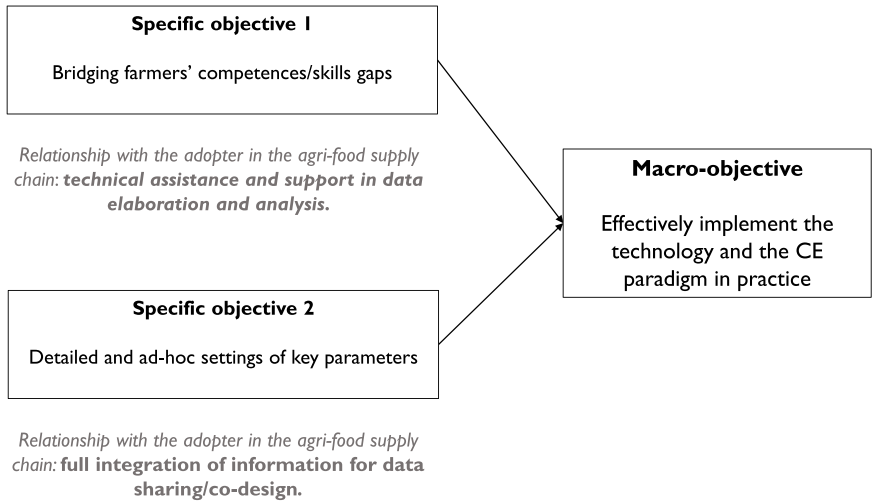

Fig. 3. Specific objectives connected to different relationships established with the adopter of the technology along the food supply chain

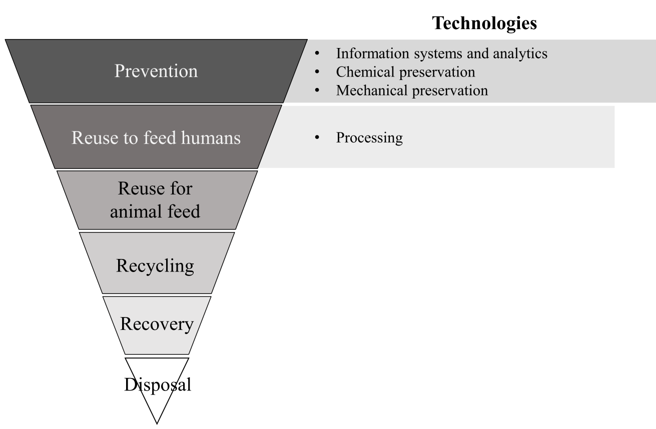

Fig. 4. Food Waste Hierarchy (adapted from Garrone et al. (2014) and Papargyropoulou et al. (2014) with indications of possible technologies to support the reaching of the objectives with respect to food waste

sort of compass to support companies in the adoption of new technologies for surplus food prevention and management. Secondly, we have enriched this tool with indications on the role of collaboration along among supply chain actors in order to unleash the full potentials of the technology and obtain an end-to-end impact on the agri-food supply chain.

Finally, although an extensive analysis is a preferred approach when the goal is to derive a taxonomy of possible solutions, there are some limitations to be pointed out. First and foremost, as remarked in the Section 3, our purpose was not to develop a taxonomy that aims to be exhaustive of all the possible technological solutions in the field, but a first satisfactory picture of the available options of technologies to prevent FLW in the fruits and vegetables segment. Most of the technology providers are Italian, whereas as small group is from United States and United Kingdom. Nevertheless, the geographical context didn't mark any significant difference/peculiarity in the taxonomy, not underlining any specific technological focus of a certain countries.

Moreover, some interesting dynamics regarding collaborations between technology providers and vertical collaborations along the agri-food supply chain deserve a more in-depth exploration.

Another main limitation of the study is represented by the fact that the extent of the impact on FLW prevention and the related sustainability impact are measured just qualitatively and in terms of potential and not actual measured impact on FLW prevention. This point would instead deserve a further quantitative assessment with an ex-post measurement of the impact of different food waste prevention technology to better support our considerations.

Finally, the twofold perspective of the technology provider and the main adopter of the technology could represent another interesting setting for future research avenues.

CRediT authorship contribution statement

Federica Ciccullo: Conceptualization, Investigation, Methodology, Writing - original draft. **Raffaella Cagliano:** Conceptualization, Writing - review & editing, Methodology, Supervision. **Giulia Bartezzaghi:** Conceptualization, Investigation, Supervision. **Alessandro Perego:** Conceptualization, Supervision, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. A. Information about the sample

Cases (Technology Provider – TP)	*Technology*	*Supply chain stage of the adopter*	*Name for the adopter*
Comp. A	Crop monitoring systems	Farmer	-
Comp. B	Sorting machines	Packing house	Food1
Comp B1		Packing house	Food2
Comp. B2		Packing house, Manuf.	Food3*
Comp. C	Drones	Packing house	Food4
Comp. D	Drones	Farmer	Food5
Comp. E	Molecule for shelf life extension	Packing house	
Comp. F	Bio-stimulants	Farmer	Food6
Comp. G	Forecasting system	Farmer	-

Comp. H	Conservation systems	Packing house	-
Comp. I	Forecasting system	Farmer, Packing house	Food7
Comp. I1		Packing house, Manuf.	Food3*
Comp. J	Managerial software	Retailer	-
Comp. K	Packaging	Retailer	-
Comp. L	Bio-stimulants	Farmer	-
Comp. M	Sensors	Farmer	-
Comp. N	Sensors	Transportation, Retailer	-
Comp. O	Reefer monitoring solutions	Transportation	Food 8
Comp. P	Sorting machines	Packing house	Food 9
Comp. P1		Packing house	Food 10
Comp. P2		Packing house	Food 11
Comp. P3		Packing house	Food 12
Comp. Q	Conservation systems	Packing house, Transportation	-
Comp. R	Sensors	Transportation	-
Comp. S	Sensors	Farmer	-
Comp. T	Sensors	Farmer	-
Comp. U	Processing lines	Manuf.	-

*= Company Food 3 adopts both CompB and CompI technologyAppendix B – Information about the interviewees, size and country of the technology provider.

Appendix. B. Information about the interviewees, size and country of the technology provider

Technology provider	*Interviewed role*	*Size of the company**	Country
Comp. A	Head of sales	Large	Italy
Comp. B	Sales director	Large	Italy
Comp. C	Founder	Small	Italy
Comp. D	CTO	Small	United States
Comp. E	R&D Manager Head of Sales	Large	United States
Comp. F	Sales manager	Large	Italy
Comp. G	CEO	Small	Italy
Comp. H	Owner	Medium	Italy
Comp. I	Business development Europe	Young venture **	United Kingdom
Comp. J	Product Manager	Young venture	Italy
Comp. K	Managing Director	Large	Italy
Comp. L	Head of sales	Large	Italy
Comp. M	Co-founder	Young venture	Italy
Comp. N	Account Manager Italy	Large	United States
Comp. O	Product manager	Large	Italy
Comp. P	Business development and HR	Large	Italy
Comp. Q	Owner	Medium	Italy
Comp. R	Growth Officer	Young venture	Italy
Comp. S	CEO and CFO	Young venture	Italy
Comp. T	Owner	Small	Italy
Comp. U	Founder	Small	Italy

*The classification of the company size refers to turnover and number of employees and refer to the classification from the European Union:
-Small enterprises: less than 50 employees or < than 10 million EUR of turnover
-Medium enterprises: less than 250 employees or < than 50 million EUR of turnover
-Large enterprises: more than 230 employees or > than 50 million EUR of turnover
** Young ventures refer to companies that were born in the last 5 years.

Appendix. C. Coding table

TP	Impact on food waste	Relationship with the customer	Drivers to adopt the technology	Drivers to adopt the technology with the type of relationship in place	Barriers	Involvement of others SC actors
A	Improvement of the quality of the product that can better bear transportation	Continuous assistance for support the elaboration and interpretation of data	Improve product quality in order to enhance opportunities for commercialization	Access to advanced technical expertise and consulting	Considerable investment in cutting-edge technology	No
B	Avoid useless scraps and store fruits of acceptable quality, packed in the correct way	Continuous assistance for support the elaboration and interpretation of data	Improve product quality in order to enhance opportunities for commercialization	Access to advanced technical expertise and consulting	Considerable investment in cutting-edge technology	Already implemented even if limited
C	Prevent the crops from illness	Continuous assistance for support the elaboration and interpretation of data	Increase productivity and solve an otherwise costly issue in timely fashion	Access to advanced technical expertise and consulting	Considerable investment in high-end technology	No
D	Prevent the crops from illness	Continuous assistance to support the elaboration and interpretation of data	Resource optimization	Rely on state of the art technology	Region-specific technology which makes customization complex	No
E	Improvement of the quality of the product reducing the impact of rejections	Technical assistance to operate the technology	Reduce the risk of food losses due to the strict standards imposed by exporters	Good results with limited effort from the customer side	Perception of chemical substances as harmful for the environment	Desirable

F	Improvement of the quality of the product reducing the impact of rejections	Technical assistance to operate the technology	Improvement of the quality of the product that can better reach commercialization	Rely on state of the art technology	Perception of chemical substances as harmful for the environment	Desirable
G	Real-time countermeasures to avoid the production of non-suitable fruits	Simple buyer-supplier	Improve product quality in order to enhance opportunities for commercialization	-	Investments in dedicate personnel	Desirable
H	Better preservation of fruits maintaining organoleptic characteristics	Technical assistance to operate the technology	Improve product quality in order to enhance opportunities for commercialization	Access to advanced technical expertise	Lack of skilled personnel to support the implementation of the technology	No
I	Rich information to farmers to adapt production to market demand	Tailor made solutions and full integration of information	Resource optimization, improve product quality in order to enhance opportunities for commercialization	Rely on state-of-the-art technologies	Difficulties in accessing information from multiple supply chain actors	Already in place
J	Rich information to farmers to adapt production to market demand	Tailor made solutions and full integration of information	Improve product quality in order to enhance opportunities for commercialization	Access to advanced technical expertise	Rapid evolution of the industry that calls for continuous adaptation of the technology	No
K	Improvement of the quality of the product reducing the impact of rejections	Collection of feedback from the customers for continuous improvement	Increase productivity	Rely on state of the art / patented technology	The actors who benefit the most from the application of the technology does not have to bear the cost of it	Desirable
L	Improvement of the quality of the product reducing the impact of rejections	Tailor made solutions and co-design of the technology	Improve product quality in order to enhance opportunities for commercialization and increase productivity	Access to a highly customize solution	Perception of chemical substances as harmful for the environment	No
M	Plants preserved from illnesses thanks to a real time monitoring	Continuous assistance to support the elaboration and interpretation of data	Increase productivity and cost reduction	Access to advanced technical expertise	Cultural barrier to technological innovation in the Italian agricultural system	No
N	Monitoring of location, temperature and exposure to light that allow to have a better-quality product, reducing the impact of rejections	Continuous assistance to support the elaboration and interpretation of data	Improve product quality in order to enhance opportunities for commercialization	Rely on state-of-the-art technology (competitive advantage)	Rapid evolution of the industry that calls for continuous adaptation of the technology	No
O	Shelf life extension with products maintaining an higher quality during transportation	Tailor made solutions and co-design of the technology for specific products	Resource optimization	Access to a convenient transportation option with an ad-hoc approach for different segments	An effective adoption of the technology would require to overcome the usual relationship with the transporter (no longer short-term but long-term)	No
P	Intelligence sorting to avoid scrapping edible fruits- Fast sorting process that can save time for long distance transportation	Continuous assistance for customization, visibility on the data gathered and planning of technical assistance in case of problems	Improve product quality in order to enhance opportunities for commercialization and resource optimization	Access to advanced technical expertise	Affordability for small farmers (low volume)	Already in place but limited
Q	Mitigation of the impact of overproduction, postponing the available window to sell fruits in the market	Collection of feedback from the customers for continuous improvement	Improve product quality in order to enhance opportunities for commercialization	Access to a highly customize solution	Considerable investment in cutting edge technology	Desirable
R	Real-time countermeasures to avoid problems causing waste	Continuous assistance to support the transition in the customer's processes	Strengthen real time decision making reduce the risk of food losses during transportation and storage	Combination of resource efficiency and sustainability	Difficulties to develop trust between members of the supply chain	Desirable
S	Rich information to farmers to adapt production to market demand and reducing the impact of rejections	Continuous assistance to support the elaboration and interpretation of data	Increase productivity and improve product quality in order to enhance opportunities for commercialization	Access to constant real time information on productivity	Cultural barrier to technological innovation in the Italian agricultural system and affordability for small farmers	Desirable
T	Creation of homogeneous batches in terms of ripening level thus limiting food waste during storage	Technical assistance to operate the technology and continuous assistance to support the elaboration and interpretation of data	Increase productivity and improve product quality in order to enhance opportunities for commercialization identifying right timing for harvesting and storage	Rely on state-of-the-art technology	Considerable investment in technology	No
U	Shelf life extension of the semi-finished products, better match between the market and the production	Simple buyer-supplier	Resource optimization: better management of overproduction	Rely on state of the art technology in continuous growth	Considerable investment in technology.	No

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