Food engineering systems in the next future: a compromise between sustainability and Industry 4.0

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Abstract: In the next years, Industrial Food Systems Engineering will face important changes. The 2030 Agenda established 17 Sustainable Development Goals to be reached until 2030, such as the fight against climate change, the greenhouse gas emissions reduction and oceans' protection. Therefore, food and packaging companies will not only have to consider the consumers' demand for healthy, organic, fresh and nutritious foods, but also they will be called to move from a linear economy to a circular economy, implementing solutions that can make their products and processes more sustainable from and economic, social and environmental point of view. In the meanwhile, the fourth industrial revolution is almost upon us: industries are becoming more and more automated, interconnected and intelligent, thanks to the use of new technologies, such as 3D printers, collaborative robots, virtual and augmented reality, big data analytics and cyber security. Consequently, food companies who want to be competitive on the market must reinvent themselves, implementing new methods and tools to make their plants efficient and productive. Based on these premises, this work aims to analyze how the food industrial sector will face changes related to the 2030 Agenda and Industry 4.0 issues. To achieve this goal, a literature analysis is carried out on a scientific database: recent studies are considered to describe innovative sustainable or 4.0 technological solutions, as well as the main benefits achievable with these improvements. Moreover, the article will focus on the combination of these issues in order to investigate a relationship between these changes. The final purpose is demonstrating if new 4.0 technologies can also reduce the environmental impacts of food products and machines, contributing to create a smarter, but sustainable, food industry.

Keywords: Life Cycle Assessment; Industry 4.0; Agenda 2030; sustainability; food engineering

1. Introduction and background

The agri-food industry is the second largest manufacturing sector in Italy (Ministero dello Sviluppo Economico, 2021). More and more companies today are changing their ways of producing, not only to reflect consumers' preferences, who give today more importance to healthy, organic, nutritious and low-processed foods (ANSA, 2018) (Eurostat, 2019), but also to face the enormous changes taking place of our period. In fact, the current and near future challenge in the Food & Beverage sector will mainly be played on two issues: the advent of the Fourth Industrial Revolution and the attention to a more sustainable production, in order to contribute to reach a sustainable development as signed by United Nations in the 2030 Agenda (United Nations, 2015).

In fact, from the environmental point of view, the food system is one of the biggest contributors to climate change because of high greenhouse gases emissions, mainly due to livestock (Baldini, et al., 2018), but also a big use of land which causes deforestation, land degradation and pollution (Takacs & Borrion, 2020).

In particular, dietary high in processed foods, oils, meat, dairy and animal products are associated with high environmental impacts, besides being linked with obesity and other chronic diseases (Grosso, et al., 2020). Foods consume vast amounts of resources when it is harvested, stored, processed, packed and transported (Jagtap, et al., 2021), and at the same time produces a lot of wastes: the Food and Agriculture Organisation (FAO) estimates that 1/3 of all food produced globally is lost or goes to waste, and this happens especially in developing countries (Food and Agriculture Organization, 2021).

As regards food packaging, today the largest part of them are made of plastic, thanks to its resistance, versatility, hygiene, durability and flexibility (Plastic Europe, 2021). However, their excessive production, causes pollution from extraction to landfill or incineration disposal, contributing to global warming and polluting soils and seas up to the formation of plastic islands in the oceans with irreparable damage to the fauna and flora (National Geographic, 2019). Added to this, industrial processes generate a large amount of waste and emissions which contribute to eutrophication and acidification (Our world in data, 2018).

In this scenario, the commitment of companies to adopt strategies aimed at following sustainable paths is necessary. Many companies have already invested several resources in the search for biodegradable, compostable or recycled materials, using Life Cycle Assessment to evaluate the environmental impacts of their products and processes (Stefanini, et al., 2020), but also the social and the economic ones with the Social Life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC) methodology respectively. Therefore, to remain competitive on the market, all companies, sooner or later, will have to update their systems and keep up with the ongoing evolution.

In the meantime, industries are facing an epochal evolution called "Industry 4.0": a new phase of automation that enables innovative and more efficient processes, products and services, and demands new professional skills requirements in the workforce (Dantas, et al., 2020). After the steam engine of the first Industrial Revolution, the assembly line and mass production of the second one, the advent of the Internet and telecommunications of the third one, Industry 4.0 will employ many sensors and digitized systems connected together. In the food sector, the use of virtual commissioning, augmented reality (Bottani, et al., 2021), IoT technologies through which the machines can improve themselves (Kodan, et al., 2020), Radio Frequency Identification (RFID) as product identification systems (Bottani, et al., 2014), 3D printers and robots collaborative (Jambrak, et al., 2021) are just some examples of evolutions that could take place to produce in a more automated, interconnected and intelligent way and to contribute to the reduction of the environmental impact of food products and processes.

In this contest, food and food machines producers are reinventing their industries trying to implement sustainable and 4.0 technology solutions. However, research demonstrate that also digital technologies themselves could be linked with the pursuing of environmental sustainability (Chen et al., 2020; Oláh et al., 2020). Therefore, the aim of this study is to examine the state of the art of the recent and next future environmentally sustainable technologies and 4.0 solutions adopted in food industries, but also investigate how Industry 4.0 applied in the food sector can contribute not only to the specific environmental sustainability, but also to the generic definition of "sustainability", which involves also the social and economic aspects. The article is structured as follows: the next section presents the methodology used for the literature review, such as the keywords analysis. Then, chapter 3 describes the found papers and presents results obtained about sustainable food systems, 4.0 food systems and sustainable 4.0 food systems. Finally, key findings are discussed and conclusions about potential future research are drawn.

2. Methods

The research methodology used is a systematic literature review, considering studies that focus on 4.0 and sustainable solutions in food systems engineering. Only recent research were included, published in 2020 and at the beginning of 2021, since the study is written in February. A computerized search was made using Scopus database (Elsevier, 2021) looking for terms in "title, abstract, keywords" which investigate the relation between food systems and Industry 4.0 and/or environmental sustainability. Since the work is mainly focused on the food sector, we establish some keywords that, according to us, can describe it. Therefore, keywords were used i.e. "food packaging", "food engineering", "food systems", "food industry", "food manufacturing" combined in turn with three topics i.e. "Industry 4,0", "Environmental sustainability" and "Sustainability" + "Industry 4.0". The methodology is illustrated and summarized in Figure 1. The following figure illustrates the 149 results obtained about food industry, manufacturing, packaging and systems, while no results were obtained with the keyword "food engineering" (Figure 2).

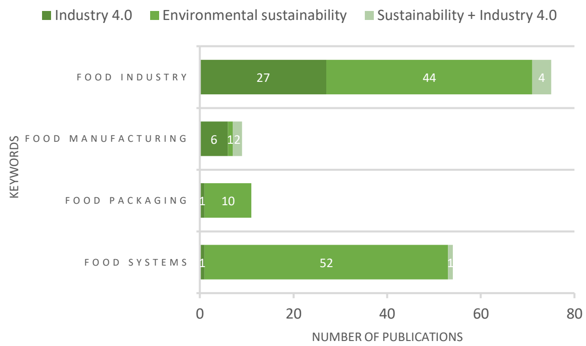

Figure 2: First literature analysis results about food systems

Moreover, in order to investigate their relation, also the general keywords "Sustainability" + "Industry 4.0" (without specific relation to food systems) were added, and other 27 works were found (Figure 1). Overall, the first search returned a total of 176 papers. Then, duplicates and papers which were not published as articles or reviews, such as conference papers or notes, were excluded. Moreover, studies were all examined individually, by checking the title,

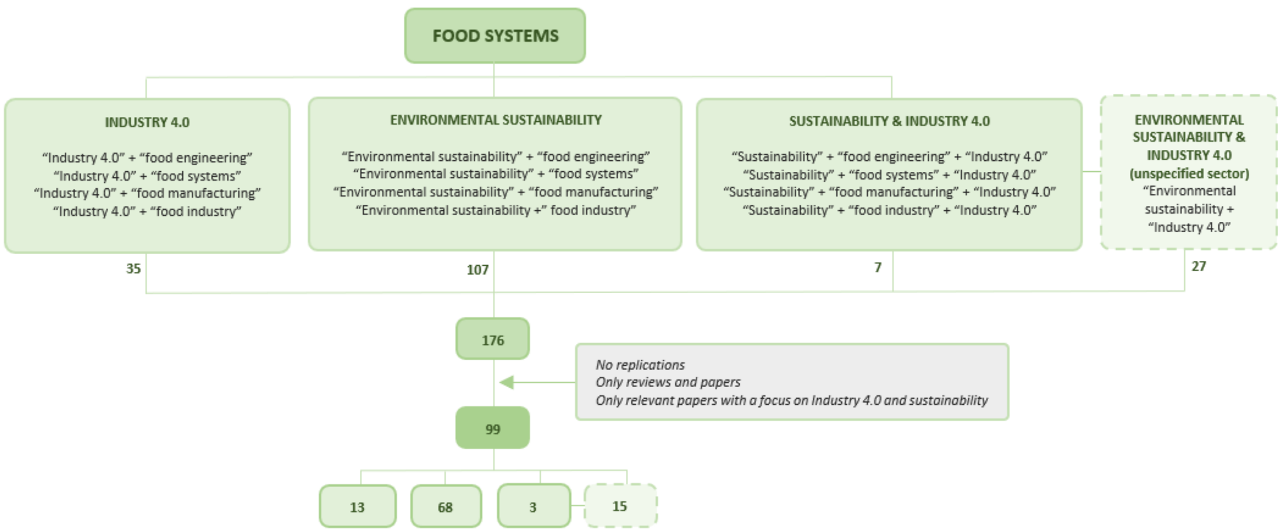

Figure 1: Structure of the literature analysis

abstract and mains contents: papers that did not target the food industry systems, but rather were carried out in the medical, agricultural, nutritional, construction contexts, were excluded from the analysis. Consequently, the number of relevant articles and reviews about Industry 4.0 and/or sustainability in food industries, published in 2020 and 2021, was reduced to 84 and distributed as illustrated in Figure 3. Finally, considering also 15 works that focused on the general relation between environmental sustainability and Industry 4.0 (Figure 4), the total number of found papers was 99 (Figure 1).

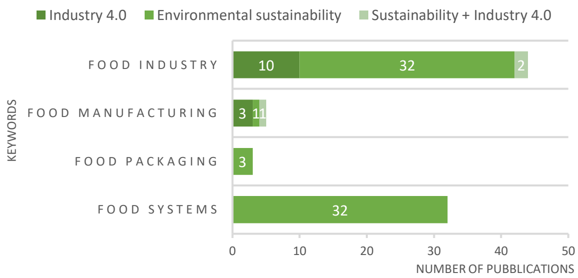

Figure 3: Final literature analysis results about food systems

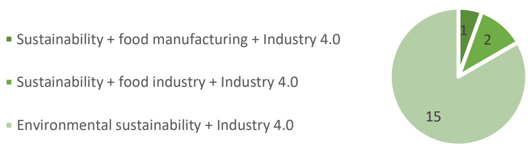

Figure 4: Works about Industry 4.0 and sustainability

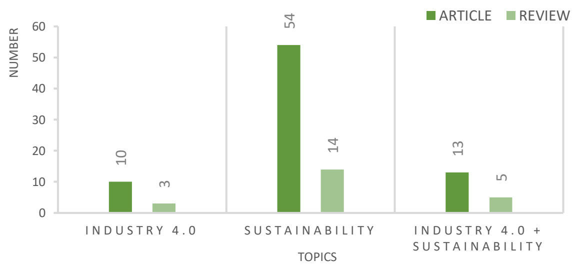

Figure 5: Articles and reviews about food systems Industry 4.0 or Sustainability and their relation

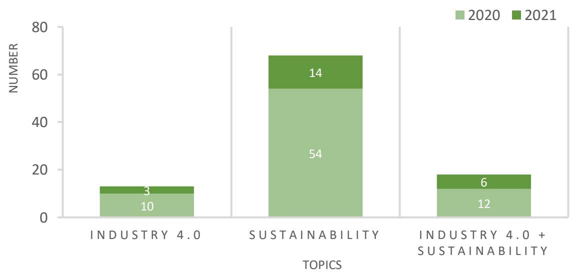

Figure 6: Publications in 2020 and 2021 about food systems Industry 4.0 or Sustainability and their relation

3. Results and discussion

Taking as a reference Figure 3, it can be stated that the most used keyword about food systems engineering is “food industry”, followed by “food systems”, “food manufacturing” and finally “food packaging”. Moreover, as illustrated in Figure 4, the number of works which investigate the relation between Industry 4.0 and sustainability in the food sector is very low (3 works), but broadening the horizon of this analysis to other works that do not include the keywords “food packaging/systems/industry”, it can be noticed that it is becoming a relevant issue (15 works). Consequently, for convenience, the topic “industry 4.0” + “sustainability” will consider both types of research, for a total of 18 studies.

Among the three topics, the sustainable one is the most studied in the food sector today, in fact, it has the highest number of articles and reviews (Figure 5). Moreover, 39% of articles are open access.

Even if this work is written in February, the number of publications in 2021 is high and we can suppose that at the end of the year the number will be higher than the one in the year 2020 in all the investigated topics, underlying their relevance and importance also in the food systems engineering (Figure 6).

3.1 Food systems engineering and industry 4.0

Starting the analysis from papers which apply the new technologies to the food systems engineering, some important results are now presented.

Food industry systems are developing in smart factories, based on intelligent manufacturing and intelligent production, which focus on advanced technologies that can be applied to the entire industrial process to create a highly flexible, personalized and networked food industrial chain (Clairand, et al., 2020). In particular, the concept of Internet of Things (IoT) is gaining popularity. All current developments and future prospects of this concept in food and agriculture sector are discussed in a review (Kodan, et al., 2020), and research investigate its application in case studies combined with other 4.0 technologies. For example, in a food manufacturing company which creates biscuits and water crackers, the implementation of IoT, big data analytics, machine learning and cyber-physical systems, allowed to improve productivity, efficiency, capacity, product consistency and savings in energy consumption across different production lines (Konur, et al., 2021). Another company, in the baking phase - where bread undergoes a series of transformations in its texture and colour - implemented a Computational Vision System (CVS) based on a Convolutional Neural Network (CNN) for the classification of browning degree of bread crust (Cotrim, et al., 2020). Traditionally, colour measurement are made by physical-chemical analysis, chromatographic and spectrophotometric techniques that have high implementation cost and long time to obtain the results. Instead, the new 4.0 technique resulted cheaper, based on objective and non-destructive measures, and can be applied on the processing line. Furthermore, research provide a IoT-based smart framework for evaluating the food-quality parameters in restaurants and food outlets (Bhatia & Ahanger, 2021).

Results demonstrated that also the application of Industrial Robots (IR) has many benefits such as cost savings, improved productivity and replace human operators in unsafe conditions: a recent study developed a methodology for the selection of appropriate robots to aid with largescale adoption of flexible automation within food manufacturing sector (Bader & Rahimifard, 2020). Moreover, smart warehousing in food industry, characterized by Automated Guided Vehicles (AGV), RFID and IoT, increased the overall service quality, productivity and efficiency while minimizing the costs and failures (van Geest, et al., 2021). In another paper, a system configuration in a dairy factory became simple introducing a five-level modularization design of an horizontal systems, which allowed managers to select the combination of modules according to their products, machine and human resources, saving 30-50% of cost compared with a traditional vertically integrated system (Matsumoto, et al., 2020). Furthermore, since a common denominator in the vast majority of processes in the food industry is refrigeration, it is important to report that, thanks to Industry 4.0, a new data-driven methodology improve refrigeration systems efficiency acting on the load side, reducing electrical consumptions, failures and downtimes (Cirera, et al., 2020).

Table 1: Papers about food systems and Industry 4.0

Authors	Nation	Focus/food product	Technologies
(Konur, et al., 2021)	UK	Biscuits, water crackers	IoT, big data, cyber security, artificial intelligence
(Bader & Rahimifard, 2020)	UK	Every food	Industrial robots
(Matsumoto, et al., 2020)	Japan	Dairy foods	Horizontal systems
(Bhatia & Ahanger, 2021)	India	Restaurants	Fog-Cloud computing IoT
(van Geest, et al., 2021)	Netherlands	Not specified	Smart warehouses (AGV, RFID, IoT)
(Cirera, et al., 2020)	Spain	Refrigeration systems	New data-driven methodology
(Kodan, et al., 2020)	Ireland	Not specified	IoT
(Cotrim, et al., 2020)	Brazil	Bread - backing phases	Computational Vision System (CVS)
(Khan, et al., 2020)	Korea	Meat	IoT , Blockchain
(Akyazi, et al., 2020)	Spain	All food industries	Skills requirement database - Food I4.0
(Kayikci, et al., 2020)	Turkey + India	Not specified	Blockchain (RFID, QR-code)
(Clairand, et al., 2020)	Ecuador/Italy	Energy efficiency in food industry	Industry 4.0 technologies review
(Sabrina, et al., 2020)	Spain	Fruit, vegetables, meat, fish	RFID, QR-code, NFC

In the 4.0 food industries the word "blockchain" is becoming usual and it refers to a system of recording information that are then impossible to be changed, hacked, or cheated. Its demand in food systems, combined with IoT, con be summarized about provenance (supply chain, traceability, information system), payments (cryptocurrency, digital transactions, financial services) and management (digital identity, data analytics, record keeping) (Khan, et al., 2020). In particular, food traceability is becoming more and more important, thanks to its ability to identify and localize foods along their supply chain, preventing food losses and ensuring products' quality to consumers. Data-capture technologies include for example RFID, Near Field Communication (NFC) and Quick Response (QR) Codes (Sabrina, et al., 2020), which make the blockchain transparent and help retailers to monitor information like delivery time, lot size, storage and transport conditions (Kayikci, et al., 2020).

Based on these premises, it is certain that the largest part of food industries in the next future will face important changes to remain competitive on the market. Therefore, it will be necessary to have a qualified workforce to overcome the big revolution challenge: training programs will be implemented to gain the required specific qualifications and reduce the skills gap between the workforce and the industry needs. To this purpose, research created an automated database for current and near-future requirements for the professional profiles related to the food industry, which can be used as a fundamental framework by the sector (Akyazi, et al., 2020).

To summarize the 13 papers about Food Industry 4.0, table 1 presents the main technologies tested in each of them, specifying the food product or machine where they have been applied. Finally, as illustrated, it can be stated that some nations, such as UK and Spain, published more works than others, however, we can suppose that the number of nations will be higher at the end of 2021.

3.2 Food systems engineering and environmental sustainability

In literature, we found 68 studies published in 2020 and at the beginning of 2021 which discuss how it is possible to improve environmental sustainability of foods systems and technologies. They demonstrated that the food service sector can accelerate the transition toward more sustainable and healthy food systems trying to resolve some hotspots, even if the relation between food systems and the environment is complex because environment changes are both a driver and an outcome of food systems (Fanzo, et al., 2021). Firstly, during the food production, benefits can be obtained by shifting food production from conventional to organic agriculture, reducing meat purchasing (Takacs & Borrion, 2020), improving dairy systems (Delaby, et al., 2020) and implementing anaerobic digestion of wet organic wastes which can make positive contributions to climate mitigation, energy security and nutrient cycling in agri-food systems (Nindhia, et al., 2021). In order to sustain the fishery's profitability, food security and employment possibilities, adaptive fisheries management are needed to anticipate ocean warming and acidification (Hänsel, et al., 2020). Also dietary choices can influence the environmental impact: for example the Mediterranean diet is associated with lower greenhouse gases (GHG) emissions, while Nordic diet with land and water use (Grosso, et al., 2020). Secondly, it is important to improve distribution switching to natural gas or electric vehicles and reducing food miles, eating local and seasonal ingredients, augmenting traceability and quality of the supply chain (Gallo et al., 2021; Gimenez-Escalante et al., 2020; Siddh et al., 2020). Thirdly, renewable energy should be used and water efficient appliances and cooking devices should be introduced also during the food storage and production (Fabiani, et al., 2020). New eco-friendly technology can be used, resulting in high-added-value products and reducing adverse impacts on the environment (Verde, et al., 2020). Finally it is absolutely necessary to optimize planning system to reduce over-production and subsequently food waste, in particular recycling inorganic waste and eliminating waste-to-landfill (Takacs & Borrion, 2020). In the meantime, since the majority of the food is packaged, it is necessary to motivate the transition of food industry toward the adoption of reusable packaging, developing an optimization model to design a closed-loop packaging network (Accorsi, et al., 2020).

In literature we found that many studies apply a Life Cycle Assessment (LCA) to quantify environmental sustainability of food systems (Gunnarsson, et al., 2020). This tool allows to find environmental problems associated to some products life cycle: for example, rice seed production, diesel fuel, urea and phosphate fertilizer are the major environmental hotspots in paddy rice production (Rezaei, et al., 2021), or the wheat cultivation presents the main environmental impacts of bread production, mainly due to the use of agrochemical and field emissions (Câmara-Salim, et al., 2020). Moreover, LCA is also applied to food packaging, and help to compare different materials in order to establish which is the most environmental friendly, i.e. plastics packaging impacts less than glass (Wohner, et al., 2020) or bio-based takeout food container composed by locally sourced sago starch and sugar palm fiber is better than a conventional material (Salwa, et al., 2020). However, some papers demonstrate that a consumer is not always willing to pay more for sustainability (De Daverio, et al., 2021), especially if it is not informed about this issue. Instead, consumers who received information on animal welfare and environmental sustainability show a preference for organic products and are willing to pay more for them, and this is important also for stakeholders strategies to promote sustainable products (Scozzafava, et al., 2020). Therefore, it is necessary to raise awareness among consumers, but also among students and children at school, in order to improve their understating of the complexity and expansive nature of sustainability, helping people during decisions that bring foods to their tables (Blodgett & Feld, 2021).

3.3 The relation between Industry 4.0 and Sustainability in food systems engineering

According to literature review, it can be stated that Industry 4.0 has great potential of growing the food industrial sustainability, not only from and environmental point of view, but also considering the social and economic pillars. New 4.0 food technologies are able to promote sustainable agriculture - i.e. using a smart fertigation pipelines which control with precision the dosing systems (Giannoccaro, et al., 2020) - clean and sanitize drinking water, ensure sustainable consumption and production, fight against climate change (Sahal, et al., 2021), contribute to reduce poverty and hunger thanks to more resources and services for people (Kunkel & Matthess, 2020) and respect life on land and below water (Yong et al., 2021; Sadiq et al., 2021). Consequently, among 17 Sustainable Development Goals (SDGs) signed by United Nations in 2015, Food Industry 4.0 can help to reach 8 of them strictly connected with foods (Jambrak, et al., 2021). For example, one of the SDGs is about clean energy, that can be integrated with food industry 4.0 during the goods production and transportation stages. Moreover, companies which invest in research bring more awareness of sustainable ways of enabling technology to be better reused, reduced, recycled and replaced, as SDGs suggest (Oláh, et al., 2020). Then, we discovered that additive manufacturing is more and more applied in the food sector, thanks to its ability to print edible ingredients. It not only has great advantages such as fast and simple production of complex customized food structures and geometries, but it has also environmental benefits. Firstly, it reduces the amount of raw material required in the supply chain and the amount of waste and pollution, since it create the final shape by adding materials with an efficiency of 97% compared to conventional subtractive production; also the carbon footprint result improved, thanks to a reduced weight of transported products and more efficient and flexible product design with better final performance (Jambrak, et al., 2021). Furthermore, the implementation of additive technology, smart sensors, artificial intelligence, big data, with non-thermal food stabilization methods, such as High Pressure Processing or Pulsed Electric Field, create smart factories with strong emphasis on sustainability, characterized by high quality and nutritive foods (Jambrak, et al., 2021). For example, the resource efficiency of food manufacturing can be improved through the design and implementation of a IoT-based tools for monitoring and reduce food waste as well as energy and water consumption (Jagtap et al., 2021; Corallo et al., 2020).

Despite Food Industry 4.0 has many strengths related to the economic, social, and environmental sustainability, it must be noticed that in some context its application still represents a challenge, due to the high initial investment for 4.0 technologies implementation and workers training. Consequently, its diffusion is often related to big companies that are able to invest in these improvements.

3.4 The relation between Industry 4.0 and environmental sustainability in generic fields

Extending our research, we investigated also articles not strictly related to food but which study the links between Industry 4.0 and sustainability (Li et al., 2020; Piwowar-Sulej, 2021): in literature, many papers found out that digitalization in manufacturing has many positive impacts on the environment. Firstly, at the design stage, IoT helps to achieve a green supply chain, minimizing wastage and reducing energy consumption and the carbon footprints (de VassT. et al., 2020; Ghosh et al., 2020). Secondly, great benefits are reached in the production phase, such as consumption and quality optimization, higher efficiency and reduced material wastes (Ghobakhloo & Fathi, 2020). Thirdly, during transportation, cyber physical systems and IoT promotes environmental sustainability by enhancing communication with customers, leading to a reduction of mistaken deliveries and waiting time. Moreover, at the use stage, they monitor and collect data, giving feedback to the design and manufacturing processes for further improvement along the supply chain (Esmaeilian, et al., 2020). Finally, at the end of life, digitalization contributes to environmental sustainability by extending the lifespan, proposing approaches to enable a disassembly-to-order system. Few studies highlight environmental limits of 4.0 technology in some context, for example assessing that additive manufacturing is not energy efficient due to the heating required in manufacturing process, and the customization of products obtained with Industry 4.0 increase transportations for smaller batches (Chen, et al., 2020). Even if the majority of the recent research suggest positive links between Industry 4.0 and sustainability, many companies – regardless their size, level of turnover and current digital level – are not fully aware of them (Chiarini, et al., 2020), because they focused more on other topics of digitalization such as errors' reduction, time savings, lower physical stress, flexible organisation work and costs reduction (Brozzi, et al., 2020). Therefore, more actions for knowledge transfer are needed in the future, and real industrial case studies which demonstrate the link between Industry 4.0 and sustainability should be shared and published.

4. Conclusions

This work investigated the changes that are occurring in the food industrial system today: the challenges in the next future will be played on the implementation of new smart, automated and intelligent "4.0 technologies" and on the reduction of the environmental impacts caused by food processes and products. A literature analysis that considered very recent papers and reviews about food systems and/or sustainability found 99 interesting works which demonstrate that those issues are becoming more and more relevant and discussed in the food packaging, food industries and food systems in general. In particular, we discovered that 4.0 and sustainability are often linked since the introduction of efficient and productive technologies can help to reduce not only the emissions in soils, water and air, but also wastes of energy and materials along the food supply chain. Besides these premises, it is clear that companies that want to be competitive in the future market should introduce these concepts in their industries, and students should study in deep their advantages and benefits. Therefore, campaigns to raise awareness among consumers, students and workers are necessary and can help them to make more informed choices as well as introduce sustainable products or processes in their lives. We believe that, as future development of this work, a complete review which include articles until the end of 2021 will be carried out, studying in deep all the three pillars of sustainability: environmental, social and economic one.

Appendix A.

For further information, a complete list of the 99 papers and their details is available in an Excel file.

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