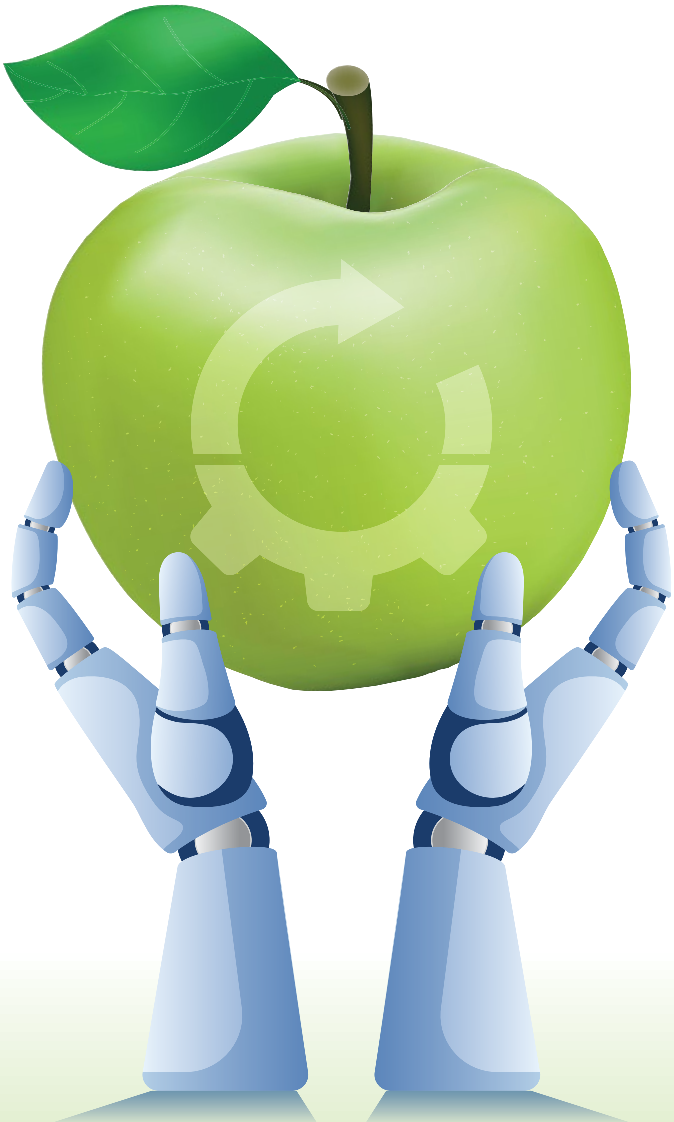
IND 4.0 against food wastage



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IND4.0 against food wastage

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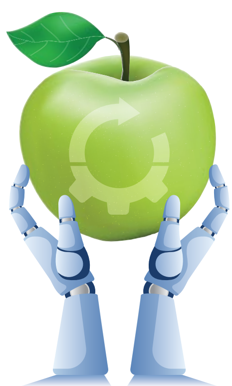
Contents

IND4.0 against food wastage



1. Introduction

Food loss (FL) and food waste (FW) have gained increasing public, academic and political attention, intensifying relevant research.[1–3] It has been estimated that about one third of the food produced is lost and wasted, such a high scale of waste involves also significant resource, energy, environmental and socio-economic impacts.[4] In the HoReCa (Hotel-Restaurant-Catering/Café) sector the FW constitutes a significant challenge, as this sector generates disproportionately large amounts of waste.[5] Thus, the quantity and causes of food wastage are to be comprehended in order to explore and establish innovative strategies, under governmental supervision and legislative guidance, which could lead to its reduction. The United Nations (UN) has set a target of halving per capita global food waste at the retail and consumer levels and reducing food losses along production and supply chains by 2030, in the Sustainable Development Goals (SDG) Target 12.3. The rise of Industry 4.0 offers a promising and safer approach in the food industry, providing solutions during each level of the food supply chain further supporting the reduction of food loss and waste (FLW). Finally, the inevitable FW could be sustainably managed by utilizing it in order to produce energy and value-added chemicals, aiming towards the reduction of waste disposal to landfills and promoting the circular economy.

2. Food loss and food waste

2.1. Definition of food loss and food waste

Food loss refers to the decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the Food Supply Chain (FSC), focusing on the losses that occur from production up to retail level (excluding retailers, food service providers and consumers). Food waste refers to the decrease in the quantity and quality of food resulting from decisions and actions by retailers, food service providers and consumers.

2.2. The issue of food loss and waste

The Food and Agriculture Organization (FAO) of the United Nations has reported that about one third of the food produced globally for human consumption is both lost and wasted.[6] The loss of resources results along the FSC, from the agricultural production to the end of life of the food (Table 1).[7] Food waste in the EU-28 was estimated to be around 88 million tonnes.[8] This estimation was for 2012 and equated to 173 kg of FW per person, with household and processing sectors contributing the most. According to the UNEP Food Waste Index 2021, around 931 million tonnes of food waste were generated globally in 2019, of which 61% came from households, 26% from food service and 13% from retail. Similarly, in EU the households generate more than half of the total food wasted, almost 47 million tonnes in a year,[8] highlighting the fact that an opportunity to feed the growing world population is missed. Yet, wasting food is not only an ethical issue but an economic also. Specifically, the cost associated with the food waste for EU-28 was estimated at around 143 billion €. Along with the negative economic impact of the FLW there are also environmental and social impacts (Table 2)[9–14]. Specifically, if FW was a country, it would be the 3rd largest country globally contributing to the greenhouse gasses emission (Figure 1).[15]

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Table 1. Causes of food loss and waste along the food supply chain

Food loss	
Production and harvest	Limitations on agricultural techniques Production surpluses Compliance with regulations and standards Climate and environmental factors
Storage and transportation	Limitations on storage infrastructure and transportation Compliance with regulations and standards
Food waste	
Industrial processing	Inadequate processing Technical limits on processing, production and infrastructure Overstocking Inadequate packaging
Distribution	Limits on the distribution system Errors in order forecasting and management of reserves Package failure Multiple handling of fresh production Marketing and sales strategies
HoReCa sector and domestic consumption	Excess purchases Excess portions prepared Confusion to understand the labelling Errors in food storage Inadequate food storage

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Table 2. Food loss and waste impacts.

Environment	Greenhouse gas emissions Soil degradation Waste of water resources Energy consumption Biodiversity and ecosystem services loss
Economic	Cost/Value of the food wasted Value of the negative externalities produced Opportunity-cost of farmland
Social	Food waste ⟷ Difficult food access Overeating ⟷ Malnutrition Waste of nutrients ⟷ Nutritional deficiencies

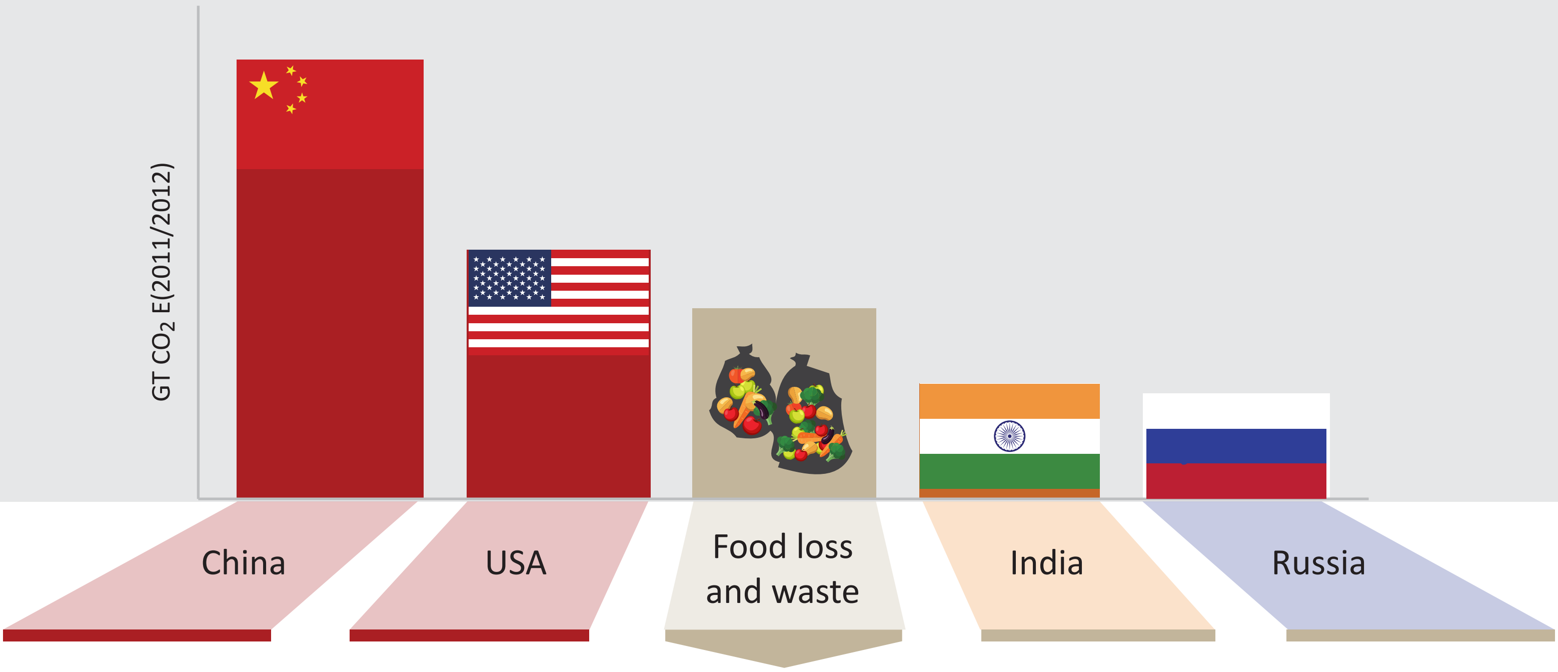


Figure 1. Green-house gasses (GHGs) emissions of 4 countries vs. Food wastage.

2.3. Where is food loss and waste occurring?

Any effort to reduce food loss and waste needs to start with a diagnosis of where it occurs. Analysing the FAO data provides some insights.[16] Regionally, about 56 percent of total food loss and waste occurs in the developed world- North America, Oceania, Europe, and the industrialized Asian nations of China, Japan, and South Korea- whereas the developing world accounts for 44 percent of the loss. On a per capita basis, however, North America and Oceania stand out from other regions, with about 1,500 kcal per person per day lost or wasted from farm to fork.

In terms of stages of the food value chain, 24 percent of global food loss and waste occurs at production, another 24 percent during handling and storage, and 35 percent at consumption. These three stages taken together account for more than 80 percent of global food loss and waste.

The distribution of this food loss and waste varies significantly between developed and developing regions with developed countries seeing more at consumption and developing countries seeing more during production and handling and storage (Figure 2).

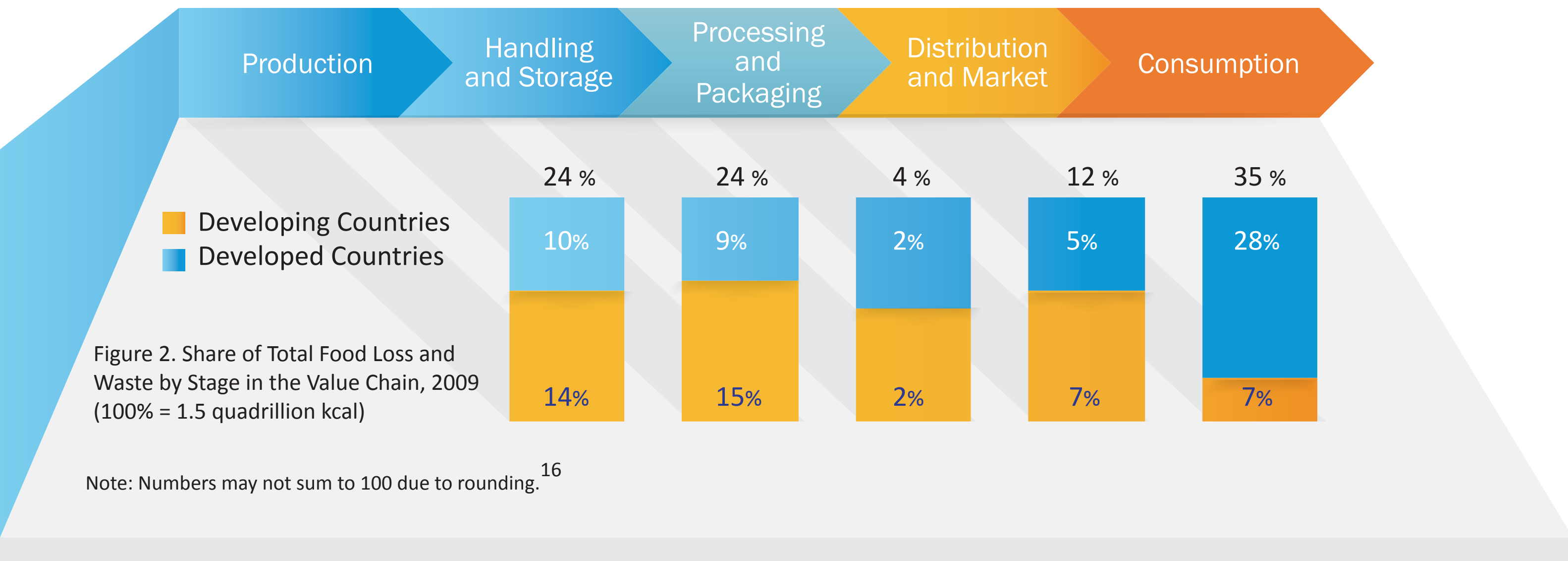


Figure 2. Share of Total Food Loss and Waste by Stage in the Value Chain, 2009 (100% = 1.5 quadrillion kcal)

Note: Numbers may not sum to 100 due to rounding.[16]

Figure 3 shows that more than half of the food loss and waste in North America and Oceania, and Europe occurs at the consumption stage. In contrast, the two stages closest to the farm-production and storage- account for two-thirds to three-quarters of food loss and waste, respectively, in South and Southeast Asia and in Sub-Saharan Africa. This distribution suggests that efforts to reduce food loss and waste should focus on stages "close to the farm" in most developing regions and focus on stages "close to the fork" in developed regions. However, it should be noted that almost all urban areas experience significant levels of food waste, regardless of whether they are in developed or developing countries. These levels of waste may even be higher in cities located in developing countries, which lack the infrastructure to address this problem.

The total share of food lost or wasted ranges from 15 percent to 25 percent across most regions (Figure 3). The one exception is North America and Oceania, where loss and waste is approximately 42 percent of all available food, suggesting the need for concentrated efforts to reduce the waste levels in those regions.

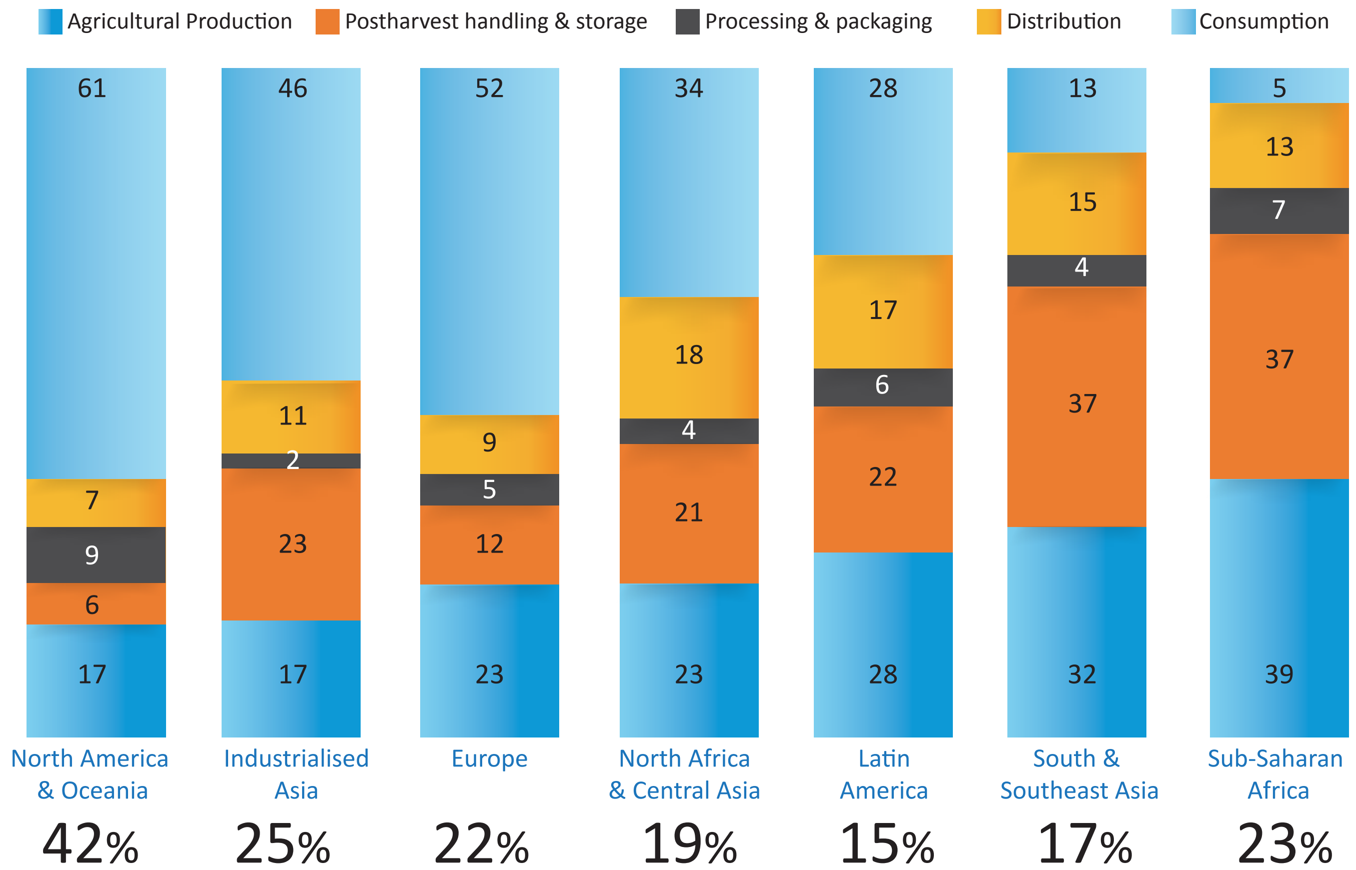


Figure 3. Food Lost or Wasted by Region and Stage in Value Chain, 2009 (% of kcal lost and wasted)[16]

2.4. The cost of food waste

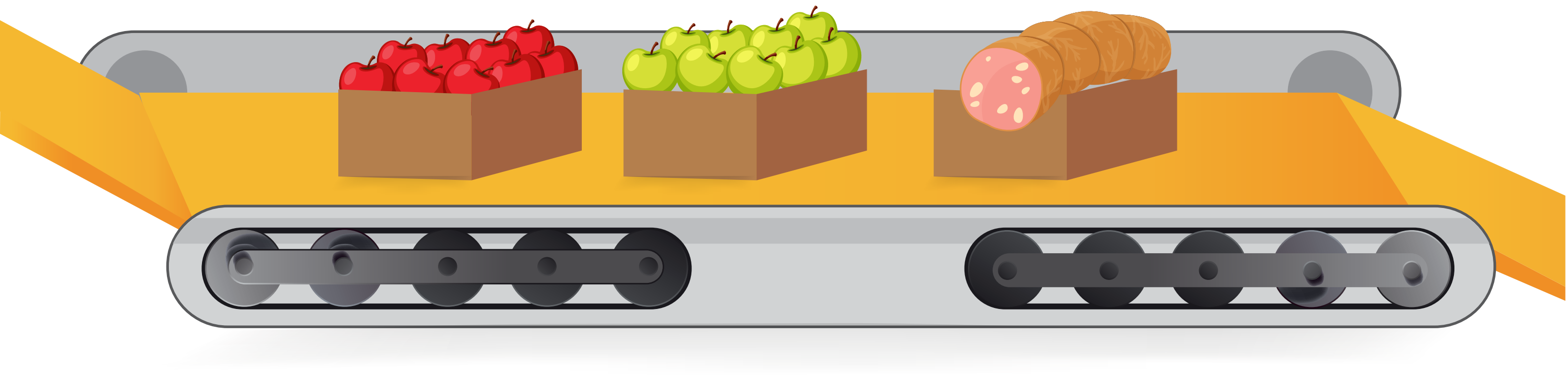
The cost associated with food waste is made up of at least two different types of costs: the economic and the environmental costs. The economic cost includes not only the cost linked to the value of the products themselves, but also the costs linked to the production, transport, and storage of the wasted products, as well as their treatment costs. From an environmental point of view, food waste represents a waste of the resources throughout the products' life cycle such as land, water, energy and other inputs, and the consequent increase in greenhouse gas emissions.

2.5. Data on Food Waste

Data on food waste varies significantly according to the source. Evidently, one of the reasons for this is the different interpretation of what constitutes food waste (i.e., the lack of an agreed definition) and the different methodologies used for measuring it. Different studies present divergent data for each of the sectors of the food supply chain.[8,16,17] Table 3 presents the results of a selection of those studies and shows that food waste occurs along the entire food chain, though care should be taken when comparing the results as the methodology and definition of food waste used are not homogeneous.

Table 3. Share of food waste at the different stages of the food supply chain (in %) according to different studies

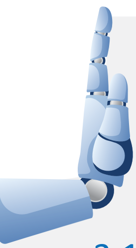
	FAO (Europe)	Foodspill (Finland)	FH Münster (Germany)	Bio Intelligence Service (EU)	Fusions (EU) *
Production sector	23	19-23	22	34.2	11
Processing sector	17	17-20	36	19.5	19
Retail sector	9	30-32	3	5.1	3
Consumers	52	28-31	40	41.2	40



* The study recognises that 'there is moderately high uncertainty around this estimate' (page 27). In particular, for the data related to the production sector, estimates are based on data from six countries only and 'the estimated uncertainties of ±17 % is probably underestimated' (page 21).

2.6. The challenge of addressing FLW

It is reported that every year 1.3 billion tonnes of food produced for human consumption is wasted, that is enough amount to fill about 8600 cruise ships.[18] The extent of FLW varies between countries, being influenced by level of income, urbanization, and economic growth.[19,20] As researched,[21] in less-developed countries, FLW occurred mainly in the post-harvest and processing stage, which accounted for approximately 44% of global FLW, due to poor practices, technical and technological limitations, labor and financial restrictions and lack of proper infrastructure for transportation and storage. Regarding the developed countries, a large portion of the food waste occurs after preparation, cooking, or serving, as well as from not consuming before the expiration date as a result of over-shopping, which might be associated with poor planning and bulk purchasing.[22] Recently, the FW crisis has been further impacted by the world-wide pandemic. With a study on COVID-19 and the food system suggesting that adopting circular practices hold the potential for a win-win solution, promoting the sustainable production and consumption of food while reducing its waste.[23]
Additionally, a study on FW along the global and European FSC indicated that the FW ranged between 194 kg/capita/year and 389 kg/capita/year on a global level and between 158 kg/capita/year and 298 kg/capita/year to the European scale.[10] The high variability of the results of this study highlighted the need of additional and join efforts to enhance the availability, reliability and level of detail in data provided on FW generation. As stated by the European Union ''Food waste takes place all along the value chain: during production and distribution, in shops, restaurants, catering facilities, and at home. This makes it particularly hard to quantify''.[24] Another study on knowledge and technology to reduce FW suggested that the accurate quantification of the FW at all stages of the FSC is essential in order to prevent the food wastetage.[25] A recent study on exploring methodological approaches in order to estimate FW in EU countries indicated that FW estimates obtained with the material flow analysis approach were higher than those obtained using the waste statistics approach, with the former presenting a better picture of the food system.[26] Finally, a study on forecasting the waste of the agro-food industry proposed a model that could estimate the waste material generated by the industrial and commercial sites.[27]



3. Legal framework in the EU

3.1. Environmental targets

Currently, EU law is trying to address the aforesaid issues related to FW. Regarding the environmental policy, Article 2 paragraph 1 of Paris Agreement[28] based on the UN Framework on Climate Change (UNFCC)[29] aims to keep the increase of global temperature below 2^{o}C, limiting the increase to 1.5^{o}C. The deposition of biodegradable waste at the landfills is responsible for an increased methane production due to their degradation. In 2009 2.6% of total greenhouse gas emission in the EU originated from bio-waste's decomposition in the landfills[30]. However, based on the European Environmental Agency's (EEA) air pollutant emission inventory guidebook,[31] EU has largely outlawed the practice of field burning agricultural residues, which leads to the mission of various atmospheric pollutants. In accordance to this, the Landfill Directive (Directive 2018/850/EC) aims to minimize biodegradable waste to landfills. Additionally, EU has launched a Biodiversity Strategy aiming to stop the biodiversity loss, with farmers playing an important role in preserving biodiversity by supporting the transition towards fully sustainable practices.[32] Moreover, EU Nitrates Directive[33] and EU Water Framework Directive[34] work together aiming to the prevention of pollution, caused from urban waste water and from agriculture. Finally, EU has reported on the Roadmap to a Resource Efficient Europe[35] that improving the recourse efficiency will ensure the safeguard of the environment, with food sector playing a crucial role.

3.2. Legislation and actions against food waste

Food waste is now subject to various legal acts of the European Union as it constitutes a major issue. As already discussed,[36,37] it is clear that FLW must become one of the main sectors to apply a new economic model. A study on the circular economy in food industry suggested that FW is not a waste in the true sense of the word but a raw material that could be included in other processes, satisfying the basic principles of circular economy.[38]

3.2.1. Sustainable Development Goals

Thus, UN has set a target for all member states to reduce food losses along the production and supply chain and halve per capital global food waste at the retail and consumer levels, by 2030 (Sustainable Development Goals).[39,40] Specifically, SDG Target 12.3 covers food and inedible parts that exit the supply chain and thus are lost or wasted, and is tracked through two indicators: Indicator 12.3.1(a), the Food Loss Index, and 12.3.1(b), the Food Waste Index. EU seeks to step up action towards the prevention of food wastage and the Food Waste Index has a three-level methodology:

- Level 1. Uses modelling to estimate food waste for member states
- Level 2. Is the approach for the countries, involving measurement of food waste the recommended?
- Level 3. Provides additional information to inform policy and other interventions designed to reduce food waste

In addition to this, another target which supports the FLW prevention and promotes a sustainable agriculture is SDG Target 2,[41] which aims to end hunger and malnutrition, by ensuring access to safe, nutritious and sufficient food to everyone. As an example, the Fund for European Aid to the Most Deprived (FEAD)[42] supports EU countries' actions to provide food and/or basic material assistance to the most deprived. Similarly, on a global scale UN has launched Zero Hunger Challenge[43] in order to reduce FW and address poverty, ensuring that all people have access to adequate food. Finally, Target 15 aims to protect, restore and promote the sustainable use of terrestrial ecosystems halting and even revering land degradation and preventing biodiversity loss.[41] This goal ensures that the health and functioning of ecosystems and the delivery of ecosystem services remain a priority, especially in the face of global trends such as population growth, accelerating urbanization and the increasing need for natural resources. Ecosystem services provided by terrestrial ecosystems offer many benefits to society, including recreation, natural resources, food and clean air and water.

3.2.2. Farm to Fork Strategy

Additionally, the Farm to Fork Strategy puts forward a series of actions to enable the transition to a sustainable EU food system that safeguards food security and ensures access to healthy diets sourced from a healthy planet.[44] Reducing FLW is an integral part of the strategy's Action Plan. The Commission will propose (a) legally binding targets to reduce food waste across the EU, by end 2023, defined against a baseline for EU food waste levels set following the first EU-wide monitoring of food waste levels and (b) a revision of EU rules on date marking ('use by' and 'best before' dates), by end 2022.[45]

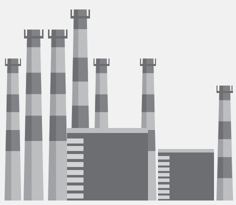
3.2.3. Circular Economy

The sustainable use of resources along with the reduction of FLW is also a targeted area of the EU Action Plan for the Circular Economy.[46] Specifically, the legislative proposals on waste, adopted together with this action plan, include long-term targets to reduce landfilling and to increase preparation for reuse and recycling of key waste streams. FLW takes place along the value chain making it particularly difficult to quantify, therefore addressing the measurement issue is an important step towards a better understanding of the problem. Within this framework EU has established the Platform of Food Losses and Food Waste.[47] This platform enables the communication between institutions and private sectors and provides support in defining measures to prevent food wastage, by evaluating the progress and sharing the best practices.

Circular economy
and sustainable manufacturing

Connecting food supply chain with

Charities,
food banks, etc.



Bio-refinery

Bio-fuels
Bio-packaging
Food additives
Bio-fertilizer
Animal food
Bio-chemicals

3.3. Concept of the food recovery hierarchy

A range of management options for food waste is available. The waste hierarchy, as set out in the Waste Framework Directive, ranks waste management options according to what is best for the environment. It gives priority to preventing waste. When waste is created, the hierarchy gives priority to preparing it for re-use, then recycling, then recovery, and last of all forms of disposal (e.g., landfill).

About 60% of biowaste disposed in landfills is food waste.[48] The Waste Framework Directive have established the waste hierarchy as the overarching principle guiding waste policies in the EU, with waste prevention being prioritised followed by recovery.[49] In addition to this, the European Commission (EC) developed the Food waste management hierarchy (Figure 4) to help the food system prioritise different methods for managing surplus food.[50] Practises at the top of the pyramid have the higher priority and the largest socioeconomic benefit, while practices at the bottom are less preferable. Various studies[25,51–58] have proposed multiple solutions in order to tackle the problem of food waste at each FSC level, from the primary production to the final disposal.[59,60,61] The Waste Framework Directive obliges EU Member States to monitor the generation of FW and develop specific waste prevention programmes.[49] The goal is to reduce the generation of food loss by preventing the surplus food and reduce food waste by preventing the disposal of avoidable food.[62] The resulting food recovery hierarchy takes into consideration the three factors of sustainability (environmental, economic and social) contributing to a holistic approach while addressing the FW issue.[63] However, there are several challenges towards FW prevention and management within the emerging circular economy.[64]

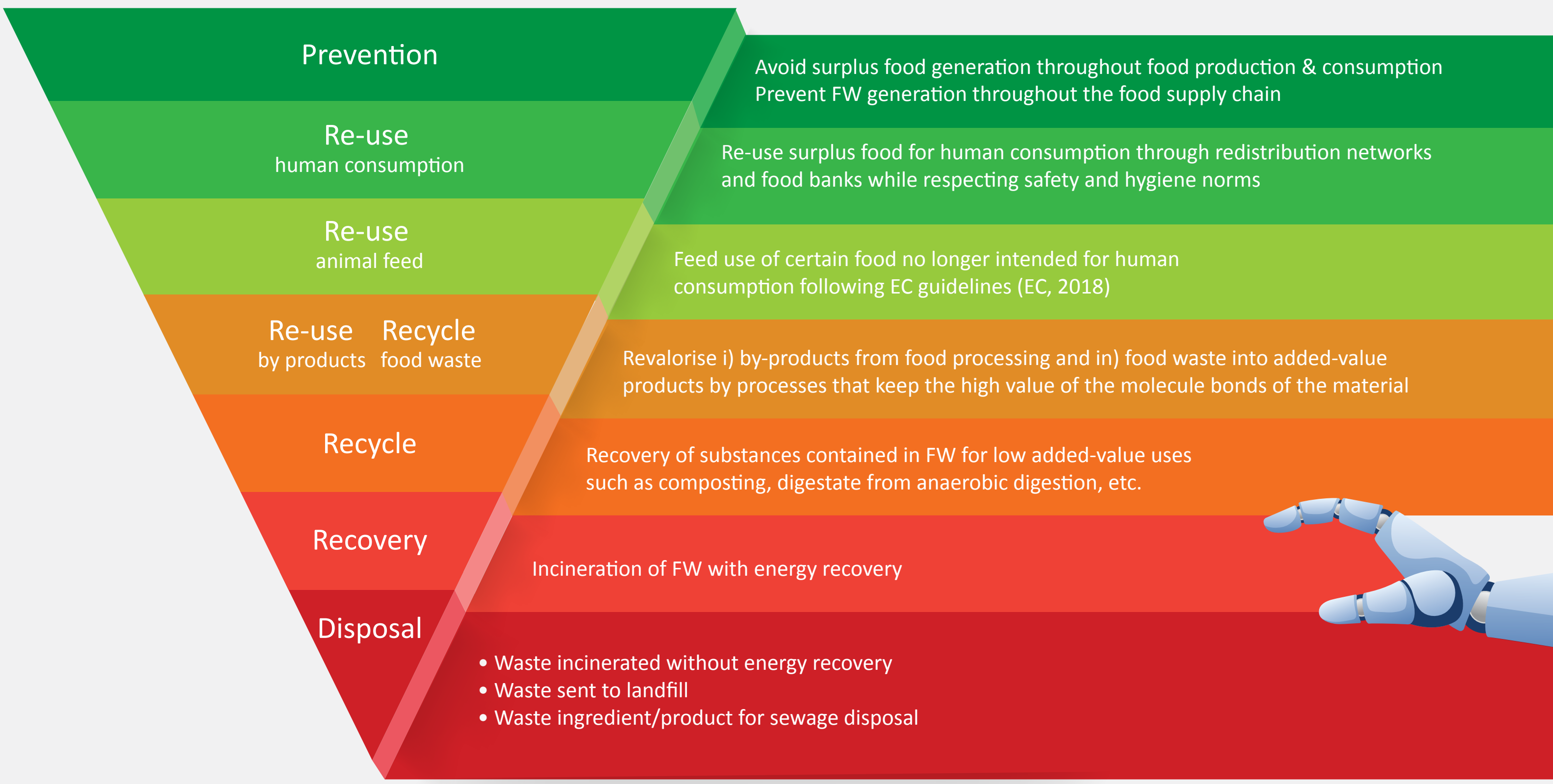


Figure 4. EU's Food waste management hierarchy[65]

4. Technologies and practises for tackling food waste

A study on Sustainability-Oriented Innovations (SOI) technological applications for food waste quantification suggested that such a method requires a multi-stakeholder approach to collaboration and business practices, with technology playing a central role in addressing the FW challenge.[66] In addition to this, EU commission establishes the European Green Deal[67] and presents the Farm to Fork Strategy,[45] launching a broad stakeholder debate covering all the levels of the FSC while paving the way to creating a more sustainable food policy. Additionally, advanced technologies and scientific innovations combined with public awareness and demand for sustainable food will benefit the stakeholders. Finally, the Farm to Fork Strategy will promote the circular economy, while reducing the environmental impact during food processing, food loss and food waste along the FSC.[45]

4.1. Production and harvest

Various studies have been exploring practises to advance food production.[68,69] Specifically, improved production has been observed while selecting crop varieties that have longer shelf life and/or higher disease resistance. Additionally, genetic editing technology shows promising results on reducing the vulnerability of the crop towards pests and diseases.[70] Regarding livestock, there are demonstrated techniques to select intelligently breeds with disease resistance, acquiring healthy animals.

4.2. Storage and transportation

The shelf life is associated with the conditions during storage and transportation. Thus, improved chilling technologies, rapid microbial detection techniques and remove temperature monitoring systems are applied, using a network of wireless sensors, in order to reduce the food waste.[71] Real-time cold chain management and monitoring could deal with the spoilage of the food along the storage and the transportation.

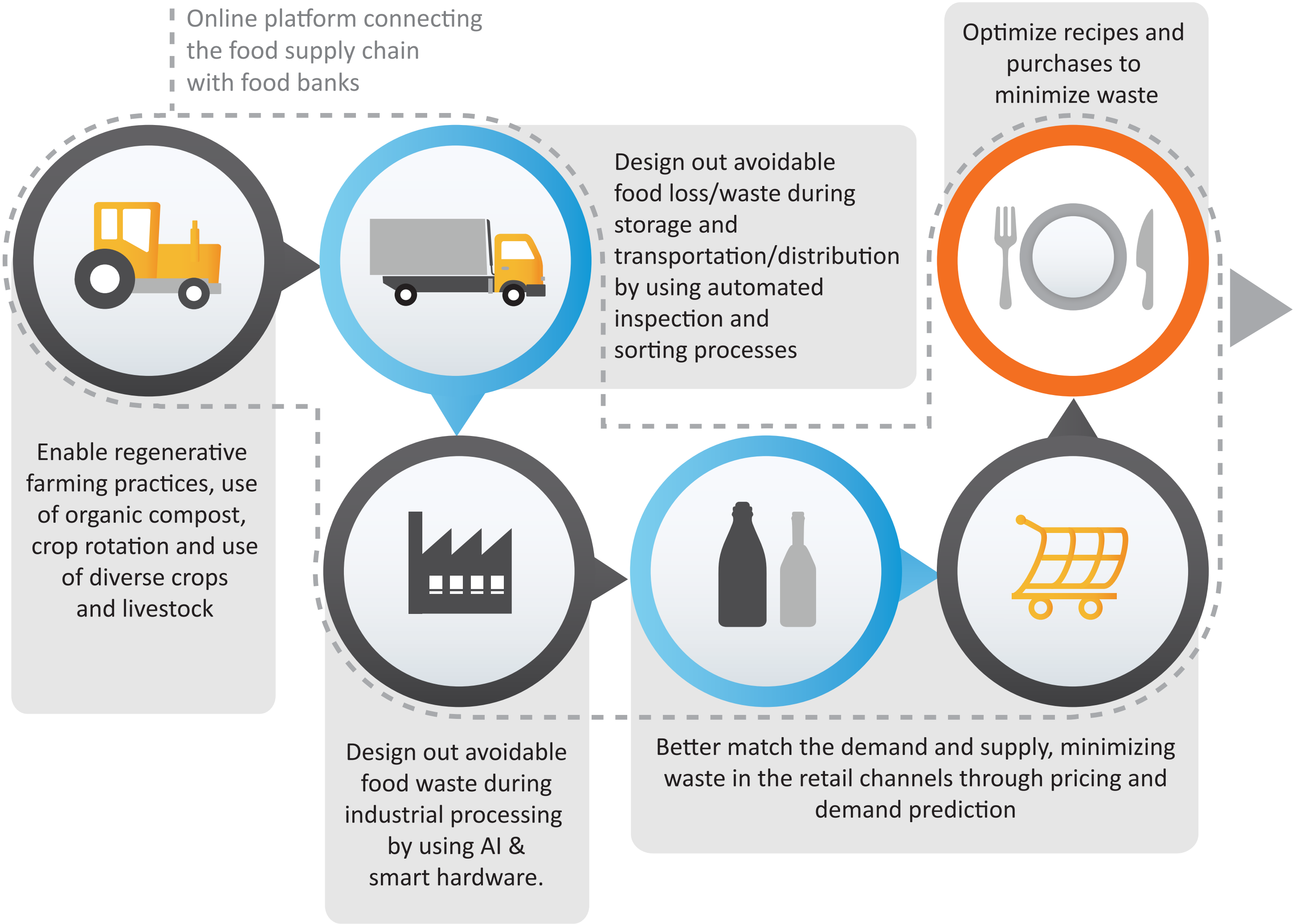
4.3. Industrial processing

Artificial Intelligence (AI) technologies and computer vision could be beneficial towards the reduction of food waste during the industrial processing of the food system[72]. As an example, AI combined with hyperspectral imaging could be used to analyse production line, predict quality, prevent decay and subsequently prolong shelf life. In addition to this, packaging plays an important role in whether food is wasted.[73] Therefore, the packaging design must ensure that the package contains the right amount of food, provides relevant information about the respective food product and is supportive of consumer practices through functionalities, such as being easy to use, resealable and empty.[74]

4.4. Distribution

Inconsistent distribution conditions throughout the FSC and the demand for cosmetically perfect supply pressures the food system so that could maintain the quality before reaching the consumer. Therefore, biotechnology start-ups are exploring on solutions that can be fitted into the current supply chain without extra effort. As an example, the use of edible coating made up of fruit and vegetables is examined to delay the degradation of food by slowing down the rate of water evaporation.[75,76]

A Circular Food Economy – Upstream solutions



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5. Food waste in HoReCa sector

The food waste in hospitality sector is becoming an important concern on various countries,[77] given that its contribution to total FW has been nearly 12% in the recent past.[78,79] Yet, the exact amount of waste generated in this sector has not got sufficient academic attention.[80,81] A study on the circular economy strategy in hospitality suggested that the HoReCa sector must play a significant role in delivering sustainable solutions towards the reduction of food waste.[82] Based on this, some hotels are already engaging Winnow system, which easily detects what and how food is thrown away in hotels, leading to the reduce of the FW at about 20% in these hotels. Winnow uses an AI-integrated waste disposal system, by employing food-identifying rubbish bins that can inform businesses regarding their food waste, assisting not only hotels but also restaurants.[83] However, a study on FW management innovations in the HoReCa sector indicated that not many businesses are actively innovating in the FW domain and suggesting that the food service industry is not leading the way when it comes to inovvaton.[84]

5.1. The issue of food waste in the HoReCa sector

Hospitality businesses generate a large amount of food waste, which is constantly increasing due to the rise in consumer disposable income and the growing frequency of food consumption out of home. In addition to this, both food distribution and retail have a major role in the FSC by connecting suppliers and consumers, with pre-store food waste being the biggest issue.[85] Moreover, poor consumer awareness and behaviour could also increase food wastage, yet costumer's choices could also be influenced to be more responsible in order to minimise waste in the hospitality enterprises.[86] However, there are insufficient information about the real magnitude of the FW generated in the hospitality sector and the accurate quantification and characterization in this sector are required. This action could be supported by the engagement of the hospitality managers who are responsible for the preparation of food, which can provide more thorough primary data regarding the FW in the HoReCa sector[84].

5.2. Preventing and managing food waste in the HoReCa sector

Food waste is a major concern for the HoReCa sector, with businesses gradually moving towards more of a preventative approach to FW which also results in the reduction of their total operational costs. The reduction of food waste in the hospitality businesses focuses on three operational stages (pre-kitchen, kitchen and post-kitchen).[87]

5.2.1. Pre-kitchen stage

For the pre-kitchen stage, a more accurate demand forecasting and stock management are required, in order to avoid ordering excessive amount of food and thus preventing it from spoilage. The systematic inventory management constitutes the first step towards the reduction of food waste. In various cases,[88] the use of technological innovations enhances the forecasting and capacity management to accurately predict the food supply and demand. In addition with the use of the First-In-First-Out technique which ensures the prevention of food ingredients spoilage.[89]

5.2.2. Kitchen stage

For the kitchen stage, the processes of handling, preparing, cooking and serving food need to be addressed. Menu planning can also contribute to the reduction of FW, by involving for instance the use of seasonal ingredients, along with offering costumers their preferred portion size.[90] Additionally, in order to minimize food wastage during food preparation training of the staff is needed, involving the prevention of over trimming and recycling food ingredients. While, in any case the monitoring and quantification of the FW is needed so that specific operational processes leading to increased waste could be eliminated.

5.2.3. Post-kitchen stage

For the post-kitchen stage, a pro-active work with costumers, the use of innovative methods for excess food redistribution and a more effective approach towards food disposal are needed. In this stage consumer's awareness is significant, with educative programmes which aims towards the reduction of FW. Additionally, the partnership between the hospitality sector and charities is crucial, so that unsold food could be redistributed to people in need. Finally, in this stage food-recycling techniques, such as composting, could further contribute not only to the reduction of FW but also to the reduction of food waste management cost.[91]

6. Integration of Industry 4.0 technologies with the food supply chain

The challenge to meet the incessantly growing global demand for capital and consumer goods while ensuring a sustainable manufacturing, have intensified relevant research towards the development of new technology.[92] Industry 4.0 refers to the fourth industrial revolution and provides a higher level of automatization within the manufacturing industry,[93] leading to a higher level of operational productivity and efficiency by connecting the physical world with the virtual world.[94] In accordance to this, European Commission is supporting the development of Industry 4.0 in order to increase the industrial activities and productivity levels.[95] Additionally, the European Technology Platforms (ETPs) which are forums of industry stakeholders, recognized by the European Commission, are formed to support the development of innovation agendas and technology roadmaps for several sectors, at national and EU levels.[96] Currently, technological advancements and digitisation are being applied on the industrial FSC, leading to the reduction of FLW while maximising profitability.[97] A study on the scope for Industry 4.0 in agri-food supply chain indicated that the recent supply chain makes an effort towards the utilization of digital technologies, predictive analytics and artificial intelligence, in order to reduce costs, food loss, food waste and other supply chain inefficiencies.[98] Various studies[97,99,100] have examined the potential impact of Industry 4.0 on the sustainability of the food industry, suggesting that the use of advanced technology could improve both the production and the processing of food with caution in environmental, economic and social impacts. However, there are still many areas along the FSC which need more improvement, in order to enhance the sustainability of the supply chain.[101]

6.1. Production

The first stage of the FSC is the primary production of crops and animals.[102] Conventional food production is less environmentally efficient and rises concerns regarding the extensive water and energy use, land degradation, air and soil pollution and reduced biodiversity.[103,104] Innovation has been the centre of the EU2020 strategy, with new technologies being adopted by EU farmers towards a sustainable agricultural development.[105] Nowadays, primary food production has been engaged with technology revolution, with the production processes using robotics and some forms of AI.[106] Farms are becoming smarter, more efficient, more environmentally sustainable and adapting autonomously in real-time changes, due to the incorporation of production technological devices, information and communication systems and data networks.[107]

6.1.1. FarmBot

Internet of Things (IoT) makes it possible to optimise the monitoring of farms. One of the leading examples is FarmBot, which is an open source automated farming machine, which utilises various smart sensors and assisting anyone with a small plot of land.[108] The robot moves around using tracks on the side of the box and it works in three dimensions. It has the ability to sow seed, water plants and get rid of weeds, using various attachments.

6.1.2. Ag EYE Technologies

Ag EYE technologies develops intelligent software and sensor solutions to improve the quality, predictability and profitability of agriculture. It combines machine vision (using drones), AI and machine learning to detect pathogens and contamination of the crops much faster and more accurate than humans can (https://ageyetech.com/). This way scouting the farm for diseases gets easier while preventing abnormalities which could lead to eventually to food loss.

6.1.3. HelioPas AI

HeliosPas AI develops technologies and solutions which can help farmers to deal with droughts in an informed manner. Specifically, they use field data by moisture monitor systems in order to inform the farmers regarding the moisture and dryness and run actual analytics forecasting the yield based on the measurements (https://heliopas.com/).

6.1.4. AppHarvest

AppHarvset has developed a controlled environment facility which helps farmers to sustainably grow more food. Specifically, it recycles rainwater and eliminates agricultural runoff, it utilises advanced technology (AI) to monitor the crop and precisely predict its yield and it is developing robotic harvesters to ensure the reduction of food loss (https://www.appharvest.com/).

6.1.5. Ida

Technology can also help to estimate the performance of farm animals, using monitors that can detect animal behaviour through motion and sound sensors.[109] Ida is one such example, using AI to monitor and learn the behaviour of cows in a her provides actionable insights for the farmers. For instance, Ida can detect the recovery of sick cows, therefore reduce the use of antibiotics (https://ida.io/).

6.1.6. Farm4Trade

Farm4Trade offers technological solutions to elevate productivity practices in the livestock sector. Specifically, the designed a farm management app suitable to capture and manage granular data for livestock and dairy farms, allowing farmers to manage more efficiently the farms while optimizing the production. It keeps animal records and provides information regarding their health and nutrition, increasing this way the productivity (https://www.farm4trade.com/farm-management/).

6.2. Storage

Following the harvesting, storage and handling methods are crucial so that food losses could be minimized. One of the most critical physiological factors is the moisture content of the crop.[110] High moisture content leads to storage problems as it enhances fungal and insect development. In addition to this, temperature is another factor that can affect spoilage.[110] Reducing the temperature during the storage stage could prevent germination and fungal development, consequently extending the storage life. However, increased heat and moisture are responsible for encouraging bacterial and inspects development, leading to food spoilage and therefore food loss. Thus, the development of effective storage management is necessary to maintain a high food quality and lower the operation costs while preventing food loss.

6.2.1. Centaur’s Internet-of-Crops

Centaur’s Internet-of-Crops uses smart sensors and AI offering unprecedented visibility and insights into store crop conditions, ensuring the best quality (https://centaur.ag/). Data from the sensors (moisture and temperature) are being combined with real-time weather data recommending appropriate conditions to ensure the crop’s highest quality. Additionally, it can predict ‘‘hotspots’’ events weeks or months ahead controlling then the fresh air supply in the storage unit. Currently, Centaur team is working with entomologists in order further develop technology that can identify infestation levels.

6.2.2. Agri Reach

Agri Reach is AI-driven focusing on the monitoring and micro-managing of storage environment remotely. Specifically, it is predicting storage conditions, suggesting preventive actions to avoid spoilage and predicting curative processes in case that storage conditions had deteriorated (https://www.sohanlal.in/about-us.html).

6.2.3. Refrigeration and Infrared spectroscopy

I addition to crop storage, meat storage is also important. As studied,[111,112] the spoilage of raw meat is mainly affected by the microbial development which occurs during the storage stage depending also on other various storage conditions. With low temperature playing an important role towards the soilage prevention of fresh meat, reducing the overall food loss. Maersk Line has developed a Remote Container Management software that monitors the ebb and flow of temperature in refrigerated containers in real-time.(https://www.maersk.com/supply-chain-logistics/captain-peter/services) For future food industries an automated food classification system could be applied, during meat storage and handlining, with the use of different sensors, such as FTIR, which could evaluate the freshness, microbial quality, food origin, etc. while decreasing the costs of quality monitoring.[113,114]

6.3. Industrial processing

Food processing is a complicated business, which involves various activities such as processing, grading, sorting, heating, milling and packaging. Thus, modern innovations in food industry paved the ways for novel food production and technical processing methods with their main priority the food safety. AI and machine learning solutions are therefore used in order to optimize and automate processes while reducing costs and human error in the food industry.

6.3.1. Gastrograph AI

Gastrograph AI based on data collection and classification methods aims to introduce a way to reliably measure flavor, while also could predict the preferences of costumers at the pre-production stage. It could comprehend the human perception of flavor and preferences, diving users into different demographic groups and modelling their preference behaviour or even predicting what they want.(https://www.gastrograph.com/)

6.3.2. Apeel

A large amount of fruits and vegetables get discarded due to their aesthetic defects, as markets and shops have strict rules regarding the appealing of food. Fresh food is particularly fragile and handling it roughly could impact their appearance and cause a quicker spoilage. Thus biotechnology is focusing on solutions that can be incorporated into the FSC without extra effort and cost. For example, Apeel has developed an invisible and edible coating for fruits and vegetables which slows down the rate of water evaporation and prevent the oxidation prolonging the storage life, leading eventually to less food loss. (https://www.apeel.com/)

6.3.3. SOCIP

Food safety management calls for clean and sanitized equipment in order to produce food free of physical, chemical, allergenic, and microbiological hazards. Many manufactures use a significant amount of various substances in order to clean their equipment, with this procedure demanding a lot of time and resources such as water. Thus, the University of Nottingham has developed a system called SOCIP (Self-Optimizing-Clean-In-Place) that is able to economize resources. It uses ultrasonic sensing and optical fluorescence imaging to assess food remains and microbial debris inside food processing equipment.(https://gtr.ukri.org/projects?ref=132205)

6.3.4. Food Sorters and Peelers

Manual sorting of large amounts of food (by size and shape) is time consuming and the human error could affect food safety. Yet, food sorting machines have the ability to solve these challenges. For instance, Food Sorters and Peelers developed by TORMA are used for food sorting increasing food quality and safety, by utilising core sensor technologies and a camera (which has an adaptive spectrum suited for optical food sorting) that recognizes material based on colour, biological characteristics and shape.(https://www.tomra.com/en/sorting/food)

6.3.5. Google's TensorFlow

Quality control is a major challenge for food processing industry as raw materials can vary dramatically, suggesting that inspecting and sorting the good ingredients from the bad ones is an important task for any food company. Google's TensorFlow machine learning can automatically detect anomalies on food ingredients.(https://www.tensorflow.org/) Such machines are important and especially used for baby food production where strict safety standards are imposed.

6.3.6. Hyperspectral imaging

Hyperspectral imaging combined with spectroscopy and digital photography could give a detailed imaging across the full range of visible and invisible light. ImpactVision (https://impactvi.com/our-story/), Specim (https://www.specim.fi/industry/), Stemmer (https://www.stemmer-imaging.com/), and Unispectral (https://www.unispectral.com/) have commercialized hyperspectral imaging for the food industry. Digital images and software are used to identify the chemical composition of food items providing information such as the ripeness and contamination without probing or piercing the skin. Additionally, it can be used to find foreign objects (such as plastic) obtained during the production, to measure product quality and to control the process. In case of meat production, it can further be used to distinguish fat, bone and gristle.

6.4. Transportation/Distribution

Following manufacturing, food is transported/distributed to retailers. Transportation conditions are significant as they could impact food safety and quality.[115] Therefore, companies frequently attach sensors for tracking and monitoring the ambient conditions (such as temperature and humidity) at which products are kept. Current monitoring approaches have proved to be capable of solving problems of food safety and quality during transportation stage.[116] Additionally, intelligent routing can calculate efficient paths for food trucks while tracking each vehicle as it moves.

6.4.1. Advantech and BT9 Xsense

Advantech (https://www.advantech.com/) and BT9 Xsense (http://www.bt9-tech.com/) provide a real-time cold chain management, monitoring and identifying potential problems with delicate food (such as fruits, vegetables and meat) along the transportation line. Specifically, their devices can record the temperature, the relative humidity and location and it is suitable for one-way shipments, return shipments and even fixed locations.

6.4.2. Sigfox

Sigfox (https://www.sigfox.com/en) uses IoT for cold chain tracking and monitoring food during transportation, following food safety guidelines. Additionally, it provides information regarding the weather and monitors track herds. While it can also notify retailers regarding the temperature fluctuations during food transportation.

6.4.3. Wakati

Wakati has developed a solar-powered, standalone hydration device that can preserve food in developing countries. It created a low-cost and low-energy alternative, instead of a cooling-system, using a small amount of water and mainly utilising solar energy. This system functions in warmer climates and can ensure the freshness of food, enabling farmers to efficiently store food on the farm and even in transit (https://www.digitalfoodlab.com/en/foodtech-database/wakati).

6.5. Retail

A digital supply chain network which is updated with real-time data, including current inventories, demand forecasting, storage space required, location tracking of food trucks and product perishability, is getting available for retailers. Blockchain is one of the most promising technological advancements, providing an efficient and robust mechanism for enhancing food traceability, safety, and efficiency, in food industry and therefore is getting a lot of attention[94–96]. Blockchain technology is being used in food industry connecting different contributors in the FSC, including farmers, exporters, shippers, importers, retailers, distributors and consumers[117].

6.5.1. IBM Food Trust

Post-harvest shelf-time and management solutions are important in the FSC. IBM Food Trust combines blockchain with AI and focuses on the reduction of food waste by connecting growers, processors, distributors and retailers (https://www.ibm.com/uk-en/blockchain?lnk=hm). IBM has invested in convening networks, establishing governance models and developing flexible technology.

6.5.2. Zest Labs

Zest Labs offers growers, producers, shippers and retailers autonomous and end-to-end cold chain visibility for proactive decision-making in order to enhance food freshness while avoiding spoilage. (https://www.zestlabs.com/challenges/fresh-food-supply-chain/). It provides the insights needed to suppliers and retailers so that they can manage the dynamic fresh FSC, utilizing real-time alerts to ensure sufficient food freshness.

6.5.3. AgShift

AgShift uses AI combined with IoT and machine learning (computer vision) and analyzes food for defects while performing quality assessments (https://www.agshift.com/). After photographing the food, the AgShift app informs retailers regarding the food freshness while also measures size and proportion bruising, handling quality control and monitoring trends and performances.

6.5.4. Symphony Retail AI

Symphony Retail AI is an AI-enabled platform which provides solutions and insights for driving profitable revenue growth for retailers. Specifically, it can estimate the demand for transportation and makes price and inventory management predictions to avoid getting an abundance of good that would potentially get wasted (https://www.symphonyretailai.com/).

6.5.5. Wasteless

Wasteless sets prices for fresh food via an AI-powered pricing engine and automatically lowers prices as the expiration date approaches (https://www.wasteless.com/). It uses small screens to display dynamically changing prices for each item on the shelf, with this machine learning to optimize the prizes. This way consumers can save cash while stores could sell food that would normally discarded.

6.5.6. Spoiler Alert

Technology is making it easier for retailers to track and monitor their inventory and help them to make smarter decisions. Spoiler Alert analyses waste levels and suggests reduction tactics intergrading also food donation in the workflow (https://www.spoileralert.com/). Specifically, it provides a mechanism to prevent spoilage by generating an accessible secondary market for at-risk food.

6.6. HoReCa sector and domestic consumption

A major amount of FW is generated from the HoReCa sector and households, with the behaviours causing this waste and the drivers of these behaviours already examined.[19,22] It cannot be defined through a single behaviour but rather through a combination of multiple behaviours, which could influence the probability of food being wasted.[118] Currently, various kinds of approaches are investigated in order to sustainably manage food and prevent its wastage.

6.6.1. NoWaste

NoWaste is an app that promotes healthy habits regarding food consumption and enables householders to create a digital inventory of their food stocks and plan meals in a way that minimise food waste (https://www.nowasteapp.com).

6.6.2. Olio

Olio is a platform that connects neighbours with each other to share surplus food (https://olioex.com). Users just upload a photo and a description and then people in the neighbourhood can claim the food before its wasted. It can also work with food service businesses, to reduce food waste through donation. Food items can be from homemade leftovers to wholesale amounts of pre-package ingredients.

6.6.3. FoodCloud

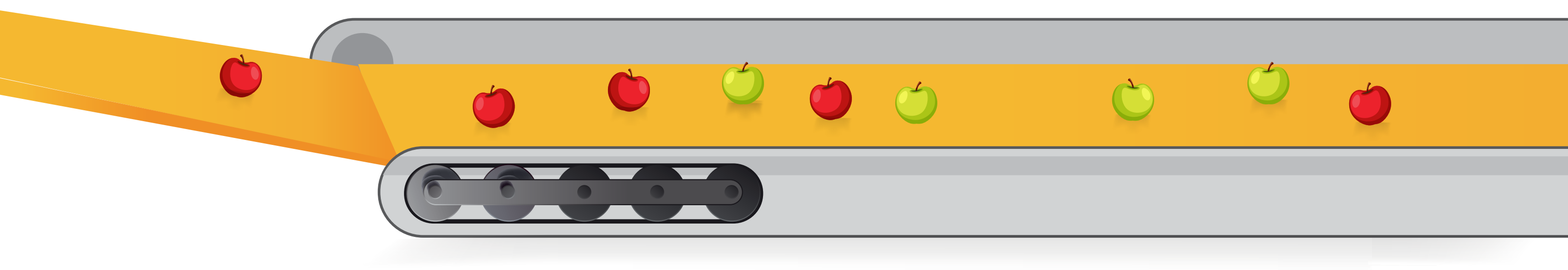
FoodCloud connects surplus food from food businesses (such as farms, manufacturers, distributors and retailers) to charitable groups (https://food.cloud/). Once food reaches FoodCloud it is counted and uploaded onto an IT warehousing system and then segregated into storage. Then the food is distributed to homeless hostels and support services, ensuring that no good food gests wastes.

6.6.4. Too Good To Go

Too Good To Go is an app that registered restaurants and catering businesses advertise their leftover food which can be purchased in lower prices (https://toogoodtogo.org/en).

6.6.5. Winnow

Winnow has developed a technological solution that provides an advanced approach to the food waste problem. Their AI-integrated waste disposal system, which utilizes computer vision and machine learning, supports food service businesses to facilitate wastage quantifications while also offering actionable measures, leading to a drastic waste reduction. Owners and staff can access the online dashboard which gives them insights into their food waste components, quantities, cost and sources of waste, adjusting then their food purchasing decisions accordingly (https://www.winnowsolutions.com/).

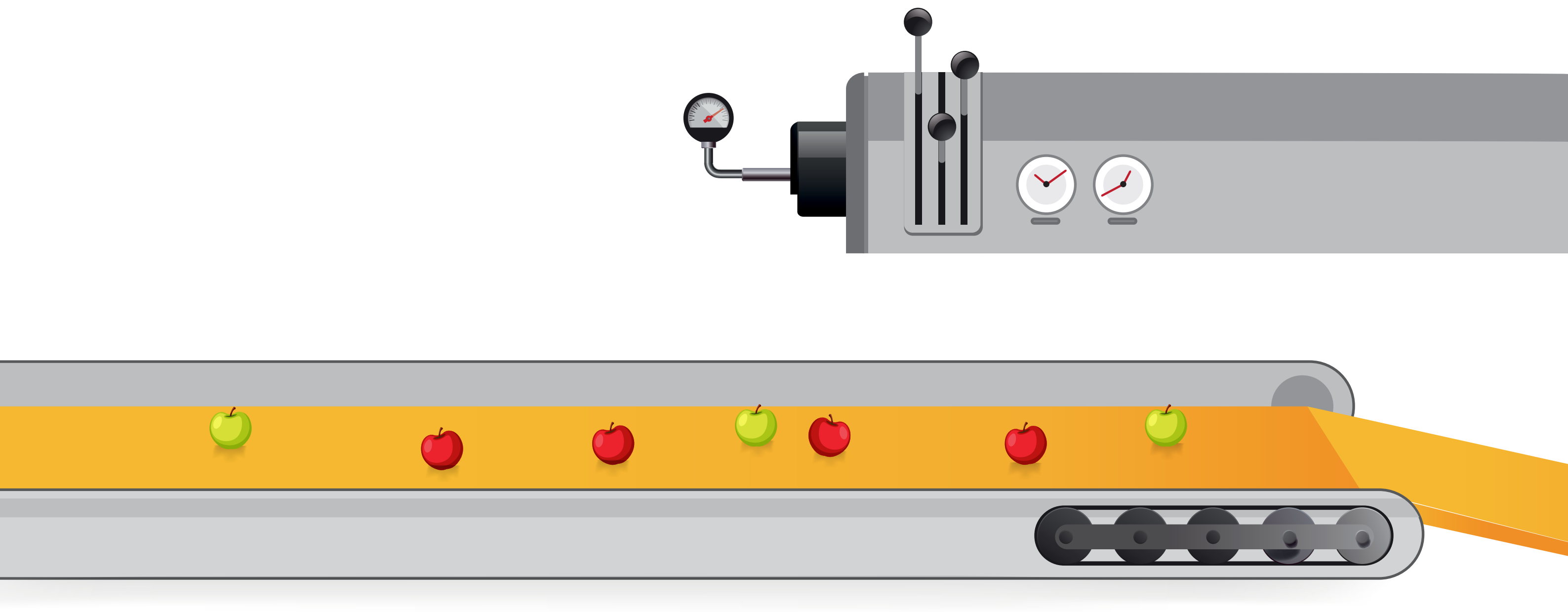


6.6.6. Kitro and Orbisk

Similar to Winnow, Kitro (https://www.kitro.ch/) and Orbisk (https://orbisk.com/en/) offer an automated food waste data collection and analysis solution while combining a hardware and a software system. The hardware consists of costumer's bin which is paced on a scale while above a camera is positioned and connected with the scale. Whenever new waste is disposed in the bin the recording is triggered by the scale and images are collected. The software then identifies both unavoidable waste (such as peeling) and avoidable food waste (such as dresses dishes). Their technology undertakes potential adjustments on the type of dishes prepared and served and the size of the portion.

6.6.7. TellSpec

TellSpec uses spectroscopy to determine the contents of food at a molecular level. It uses light photons which read chemical compounds. TellSpec claims to identify possibly harmful substances in food and determine freshness and even the calories of food (https://tellspec.com/).



7. Food waste conversion to fuel and value products

As previously discussed, one third of food produced for consumption is wasted along the FSC, contributing to environmental degradation and economic inequality. Today, food wastage, and particularly in the developing countries due to lack of technology and poor infrastructure, is disposed to a great extent in landfills.[119] However, a part of this food waste could be utilized as raw material for the production of fuel and value products, considering its physiochemical and biological nature.[120] Thus, the development of the food waste bio-refinery has been prompted from the need to increase circularity of industrial systems in order to address limited resources availability and environmental issues.[121] EU commission currently aims at ensuring sustainability production of renewable bio-based materials following the Bio-economy Strategy[122] and Action Plan[123], enhancing therefore the waste policy in support of waste prevention and circularity[124].

7.1. Bio-fuels

The present world energy demand is satisfied mostly from fossil fuel but the lack of the latter and the pollution problems, due to their extensive use, have attracted the attention of the governmental and industrial communities towards the search of alternative renewable fuels, intensifying relevant research[121,125]. EU has adopted the Towards Zero Pollution for Air, Water and Soil Action Plan[126], supporting research and relevant innovation which lead to zero pollution. Organic waste such as food waste, which predominantly constitutes of organic compounds like carbohydrates, proteins and lipids and is generally considered as non-hazardous and non-toxic waste[127], is a sustainable alternative to fossil-based resources. EU's Bin2Grid project encourages the segregated collection of FW, which could be utilized as an energy source towards the formation of biogas[128]. Various waste-to-energy technologies are utilized in order to convert food waste into bio-fuels, such as bio-methane, bio-hydrogen, bio-ethanol and bio-diesel[129].

7.1.1. Bio-Methane and Bio-Hydrogen

Bio-CH_4 and bio-H_2 production from food waste through anaerobic digestion (AD) has been widely investigated.[130,131] AD is a biochemical process carried out in a number of steps by several types of microorganisms which break down complex organic matter (proteins, fats, carbohydrates, sugars, amino acids and fatty acids). CH_4 and CO_2 are the gaseous products of the AD produced through hydrolysis, acidogenesis, acetogenesis and methanogenesis steps[132]. H_2 can also be a gaseous product through AD with its formation strongly related to the operational conditions during the acidogenesis step, where a pH between 5.5 and 6 is essential for the inhibition of the methanogenesis step.[133]

7.1.2. Bio-Ethanol

Another bio-fuel that can be produced from food waste is bio-ethanol, which could be produced through fermentation.[134,135] Fermentation is the biochemical breakdown of a substrate (such as carbohydrates) by bacteria or yeasts for the production of alcohols. The conversion of organic matter through fermentation for the production of ethanol (at an industrial scale) has been widely studied, as ethanol is considered to be a promising biofuel[136]. Specifically, the conversion of food waste to ethanol includes pre-treatment, hydrolysis, fermentation, and distillation steps.

7.1.3. Bio-Diesel

Food waste could also be used in order to produce bio-diesel, through the transesterification method[137,138]. Bio-diesel is a form of diesel fuel derived from plants or animals, consisting of long-chain fatty acid esters. It is typically made by chemically reacting lipids, such as animal fat, soybean oil and vegetable oils, with an alcohol. This chemical reaction is called transesterification, in which oil or fat reacts with alcohol (methanol or ethanol) in presence of a catalyst to form alkyl ester and glycerol. Unlike the vegetables and waste oils used to fuel converted diesel engines, bio-diesel is a drop-in bio-fuel, as it is compatible with existing diesel engines and distribution infrastructure.

7.2. Bio-fertilizers

The EU Fertilising Products Regulation creates a framework to encourage the use of organic fertilisers and soil improvers aiming to decrease the EU's dependency on imports of mineral fertilisers and therefore contributing to a circular economy for nutrients.[139] The production of organic fertilizer from food waste is an environmental-friendly and cheap method, which has been gaining a lot of attention[140,141]. Composting is the biological decomposition of wastes consisting of organic substances of plant or animal origin under controlled conditions, forming a useful soil amendment that can be used as a fertilizer. This treatment involves the placing of the organic material in a pile with sufficient water and air to stimulate microbial activity. The pile creates insulation which causes a rise in temperature increasing the biological activity. The temperature gradient within the pile stimulates air flow as the pile becomes a self-sustaining reactor.

7.3. Bio-Packaging

Packaging is an important element for the food industry, however conventional plastic packages used currently are damaging both the environment and the economy. Encouraged by the EU regulation regarding the Circular Economy,[46] researchers are developing an environmental friendly alternative to petrochemical-based packaging made out of food waste.[142,143] Bio-plastic products constitute an important innovation as they are manufactured to be biodegradable while have similar functionality to that of conventional petrochemical plastic.[144] Aligned with circular economy principles, the next generation of food packaging should significantly contribute to eventually reduced food and material waste, preventing this way the negative environmental and economic impacts.[145]

7.3.1. Vivo® Films

MonoSol (https://www.monosol.com/) has created Vivo® Films, that is an edible packaging composed of food grade ingredients. It is transparent and has no smell or taste when consumed. This type of packaging protects food products like traditional packaging, as it offers good oxygen barrier properties and presents robust mechanical properties, but dissolves in aqueous solutions (such as water, milk or juices).

7.4. Chemicals and food ingredients

Food waste provides an important source towards the production of value-added chemicals, due to its content with significant quantities of functionalised molecules (sugars, amino acids, starch, lipids, etc.).[146] The conversion of food waste to value-added chemicals favours the chemical industry as it allows the use of renewable raw material, supporting the food and chemical industry to form a mutually beneficial relationship. Physical and thermal extraction constitute the first step for obtaining specialty chemicals.[147] In other cases, further biochemical and fermentation processes are utilized in order to form more advanced chemicals, including food nutrients,[148] flavouring ingredients[149] and anti-inflammatory and antibacterial compounds used in pharmaceuticals, cosmetic and homecare products.[150] The prospect of the potential barriers and advantages are currently evaluating the viability of chemical production and the use of FW for the future circular economy[151].

7.5. Summary

The environmental and economic benefits of different management methods depend significantly on local conditions such as population density, infrastructure, and climate as well as on markets for associated products (i.e., energy and compost). To assess the sustainability of the different methods a life cycle analysis is required to provide a comprehensive picture of management options for food waste. When considering waste management options, it is important to consider the waste collection system jointly with the processing technology, since the collection regime will affect the food waste capture levels and the choice of processing method will be influenced by the composition of the input waste.

A brief overview of the main methods currently used to manage food waste, their costs and their impact on the environment and public health is presented in Table 4. These include landfilling, incineration, rendering and biodiesel production, biological treatments (anaerobic digestion, composting, and animal feed production, although use for the latter is currently very limited due to the restrictions. The different food waste streams and current management options are summarised in Figure 5 (Annex I). Most methods for treating food waste have a useful output, generating either energy or products that can be used for different purposes. The landfill sector can also generate biogas which is harnessed for energy production.

Table 4. Overview of treatment methods for food waste

Treatment	Environmental Sustainability	Health Impact	Climate Change* Kg eCO2/ tFW	Cost
Landfill	Generation of landfill gas and leachate	Risk of infestations	+948	€23-30**
Incineration	- Air pollutants emissions + Energy replacement	Emissions of fine particulates, of toxic	+325	€56-176
Donation	N/A	N/A	-281	N/A
Rendering and biodiesel production	Rendering potentially has a major role to play in a sustainable food chain and economy. The process itself leads to the safe recovery of animal by-products, thus avoiding the disposal of a substantial quantity of waste.	Risks of human exposure to biological hazards were found to be negligible when fallen stock and by-products were processed by rendering.	+36 (bioethanol)	€0.0458/litre
Composting	Compost is valued for its organic matter content and is typically used as a soil improver to enhance the chemical, physical and biological properties of soil. Compost also provides slow-release nutrients, containing nitrogen, phosphorus, and potassium, which complement traditional fertilisers and help to gradually build natural soil fertility	The use of compost in agricultural land could potentially have associated risks due, for example, to contamination of the waste with pesticides, pharmaceuticals, or other non-permitted substances. Compliance with quality assurance systems will minimise those risks.	+9	€32-78 (mixed food and garden waste) €32-72 (food waste)
Anaerobic Digestion (AD)	Generation of energy, which reduces emissions of climate change gases by offsetting emissions from fossil fuelled power stations. Digestate can be used as a soil improver	Air emissions are low due to the enclosed nature of the process. Combustion of the biogas will produce some nitrogen oxides. However, emissions from AD-CHP are generally lower than other forms of waste disposal.	-150	€23-72
Animal feed and pet food production	Data concerning costs, environmental and health impact of the different options for animal feed and pet food production are variable depending on methods, type of material, etc and they are currently insufficient.		Wet feed = -30 Dry feed = +2	€65-90

8. The Last Word

The staggering amount of food loss and waste currently generated along supply chain exacerbates global food system challenges. Specifically, food waste has a significant impact on the environment, the economy and even the society. There is a limited numbers of studies conducted at an EU or global level regarding the accurate FLW amount throughout each stage of the Food Supply Chain. As already examined, there are economic, political, cultural, and socio-demographic drivers leading to FLW globally. For instance, food loss is substantial in developing countries due to poor practices, technical and technological limitations, labour and financial restrictions, and lack of proper infrastructure for transportation and storage. Regarding the developed countries, the food waste occurs after preparation, cooking, or serving, as well as from not consuming before the expiration date as a result of over-shopping, which might be associated with poor planning and bulk purchasing. In addition to this, cosmetically perfect supply pressures the food system so that could maintain the quality before reaching the consumer, leading to increased waste. Currently, a significant share of waste originates from the HoReCa sector, requiring further organizational improvements which could lead to food waste prevention. Yet, the conventional food system enables the complexity of the food wastage issue. Current legislation encourages the prevention of waste and promotes circular economy, such as EU's commitment to the Sustainable Development Goals (SDG 12.3). In order to create an improved and safer food system a multi-sectoral approach is required, with governments developing and implementing policies which lead to a more sustainable food system. The technological revolution also known as Industry 4.0 could be applied on food industry, enhancing the food safety, and reducing the loss and waste along the Food Supply Chain. Finally, the development of the food waste bio-refinery has been triggered due to the need to enhance the circularity of food industrial system, to address the depletion of recourses and the environmental problems.

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ANNEX I: Food waste management options: relationships and outputs

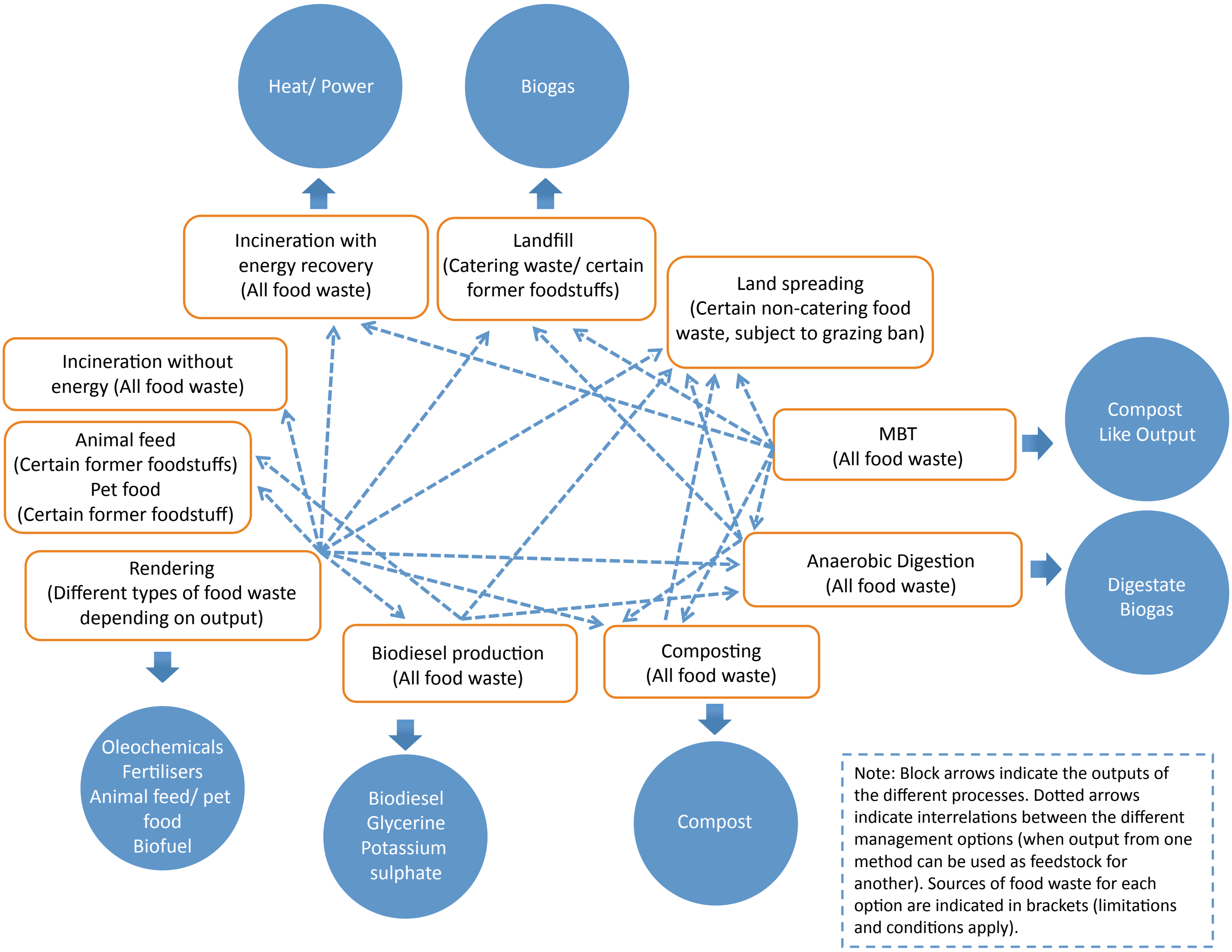

Figure 5. Food waste management options: relationships and outputs (adopted from DEFRA 2011) [159]

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