1 Introduction

Climate change, especially its consequences on several developing countries, together with the growing population trends expected over the coming years, make food production a crucial issue. In addition to the need for higher levels of energy and goods, a larger population also implies tremendous pressure on agriculture and farming systems. In this context, prevention and minimization of food waste is recognized as a key action. In addition, food waste is highly polluting as it leads to the squandering of the resources used in all stages of the food value chain, such as fresh water, soil, fertilizers, energy (FAO 2013; Lundqvist et al. 2008), and to significant greenhouse gas emission levels (Garnett 2011), in particular methane when food waste reaches landfill (Adhikari et al. 2006). Negative social impact, often associated with food security (see Stuart 2009; Kummu et al. 2012), has also been proven to be directly intertwined with food waste. Finally, food waste has a huge economic cost for consumers, producers and public bodies responsible for food waste management (see, among others, WRAP 2015; Buzby and Hyman 2012; Venkat 2011).

In this review paper we will try to frame the key issues associated with food waste into the emerging bio-economy and circular-economic mode, suggesting that these three concepts are intertwined, and considering them unitarily might provide win-win solutions able to minimize wastage, promote income growth and job creation, and prompt sustainable local development. However, in order to enable an effective transition to a circular bio-economy able to minimize the impact of food wastage, the economic, social, and environmental sustainability of this new model must be properly evaluated through appropriate tools, e.g. through an overall Life Cycle Sustainability Assessment (LCSA).

Keywords: food waste, food waste valorization practices, secondary biomass, bioeconomy

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management and bio-economy and circular-economic modes in detail. Section 5 concludes the article.

2 Framing the problem

Given the above-mentioned environmental and socio-economic negative and lasting impacts, food waste remains at the forefront of the global agenda. It has been estimated that, globally, 30-40% of food gets lost along the entire food supply chain (Godfray et al. 2010), i.e. from production to consumption. It is indeed a problem common to both developed and developing countries, even though a major pattern has been recognized; in low-income countries food is mainly wasted at early stages of the food supply chain, i.e. production, transport, storage and processing levels, mainly due to poor infrastructure and technology and economic limitations while in medium and high-income countries food is wasted at the final stages, i.e. at distribution and household level (Parfitt et al. 2010; Gustavsson et al. 2011).

Overall, the total amount of food waste production is almost the same between developing and developed countries\(^2\) (Gustavsson et al. 2011). However, as already mentioned, there is a significant amount of variation in the stages of the supply chain at which losses occur, depending on different levels of development. In addition, as emphasized by Parfitt et al. (2010), specific countries’ features (e.g. culture, climate, type of crops each country produces, market access and legislation) do play a role in determining wastage and in industrialized countries food waste has been found to be somehow correlated to income (e.g. Lyndhurst 2007; Secondi et al. 2015).\(^3\)

When possible (e.g. FAO 2013; FUSIONS 2016) food waste should be measured by taking into account its two main components, namely avoidable (edible) and unavoidable (inedible)\(^4\), as this distinction is also crucial in shaping strategies to reduce wastage (Papargyropoulou et al. 2014). The global volume of food wastage is estimated to be 1.6 Gtonnes of “primary product equivalent”, whereas the total wastage for the edible part of food is 1.3 Gtonnes (FAO 2013).

Although, as mentioned above, it is commonly recognized that in medium and high-income countries food losses mainly occur in the final stages of the supply chain, significant food losses have been found also in the early stages (Gustavsson et al. 2011). According to a study conducted on the EU-28 (FUSIONS 2016), the processing sector is the second contributor to food waste after households. However, households alone contribute to more than half of the total waste production. Indeed many studies, especially in western countries, have focussed on the household level. Several have been accounting for edible food waste, with particular attention to the consumer level both at national (e.g. Katajajouuri et al. 2014) and regional level (e.g. Vanham et al. 2015), while a number of studies have been specifically centred on major trends, motivations/behaviours related to food waste (e.g. Koivupuro et al. 2012; Graham-Rowe et al. 2014 Secondi et al. 2015).

Overall, despite efforts made by international organizations and scholars, outcomes on food waste are hardly comparable, mostly because they often utilize different methods of data collection (surveys, statistical estimations, combination of both) and there is still no common adopted definition of food waste (Bräutigam et al. 2014); other terms such as food loss and food wastage are commonly used. This obviously makes quantification and international comparisons difficult, with negative implications on strategies for tackling food waste (Falcone and Imbert 2017). International institutions and research centres, as well as several scholars, have been working on a common standard\(^5\). The EC has declared that a common and consistent methodology for monitoring food waste levels in member states will be adopted by the end of 2018.

3 Tackling Food Waste

As pointed out by the literature (see WRAP 2017; Papargyropoulou et al. 2014; Garnett 2011), food waste\(^6\)
can be tackled with a range of activities whose priority order is led by the broader waste hierarchy\textsuperscript{7}. The European Union has developed its own approach, which is defined as the most favourable option (see EPA 2014; Yolin 2015). In this respect, the establishment of a multi-stakeholder platform dedicated to food waste prevention was announced by the European Commission in 2015\textsuperscript{9}.

Secondly, re-use activities, through, for example, food banks and food sharing practices\textsuperscript{10}. Thirdly, recycle activities that include animal feed (see Salemdeeb et al. 2017) and composting (by aerobic process). Composting is a quite valuable practice from an environmental point of view, but it is still scarcely convenient from an economic point of view (Lin et al. 2013); this practice is encouraged by the European Union\textsuperscript{11} since, as mentioned above, composting, as well as the digestate (from anaerobic digestion) when used as a fertilizer, is included in recycle activities.\textsuperscript{12} However, this is not the case in countries such as the United States where composting is positioned at the fifth tier of Environmental Protection Agency hierarchy (i.e. penultimate)\textsuperscript{13}, after industrial uses and before landfill/incineration, namely the least preferred option.

At the European level, new guidelines on food donation and animal feed are going to be published by the end of 2017 as they represent two key priorities (EC 2017); this is because, according to waste hierarchy, re-use and recycle activities are preferable over energy recovery practices. A simplification of practices applied to food donation and animal feed falls within the broader European revised legislative proposals on waste. These include a proposal for a Directive of the European Parliament and of the Council amending Directive 2008/98/EC on waste (EC 2015), a Proposal for a Directive of the European Parliament and of the Council amending Directive 94/62/EC on packaging and packaging waste (EC 2015), and the Proposal for a Directive of the European Parliament and of the Council amending Directive 1999/31/EC on the landfill of waste (EC 2015).

It is worth noting that in recent years, together with prevention, re-use and recycle activities promoted by governments and international institutions, a number of citizens’ initiatives related to collaborative consumption have been put in place in industrialized countries. This type of initiatives included public refrigerators, food-sharing apps, and initiatives among students (see e.g. Falcone and Imbert 2017; Ferrari 2016). However, the relationship between food sharing and reduced food waste is not a foregone conclusion, as a number of barriers such as the absence of direct social relationships and, accordingly, of trust as well as the absence of domestic skills might affect negatively results on food prevention (Lazell 2016; Morone et al. 2016). Also on the production side, a number of alternative solutions, such as increasing shelf life of fruit and vegetables through innovative packaging, are being tested (see Gallagher and Mahajan 2011; Galgano et al. 2015).

Food waste prevention activities are the most preferred option as they have greater potential for improved environmental and socioeconomic outcomes, even though they are considered as the most challenging (Papargyropoulou et al. 2014). Also when comparing the European approach with other food waste management approaches at the global level, such as with the United States and Japan, prevention activities are always viewed as the most favourable option (see EPA 2014; Yolin 2015). This practice is encouraged through normative simplification (EC 2017).

\textbf{Figure 1:} The European waste hierarchy. Source: Adapted from EC, 2010 and http://ec.europa.eu/environment/waste/framework/

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{waste-hierarchy.png}
\caption{The European waste hierarchy. Source: Adapted from EC, 2010 and http://ec.europa.eu/environment/waste/framework/}
\end{figure}

\begin{itemize}
\item[7] Papargyropoulou et al. (2014) have applied this approach to the specific case of food waste based on environmental and social aspects. Therefore, the following statements are grounded also on this study.
\item[9] European Commission Communication 2015, Closing the loop – An EU action plan for the Circular Economy.
\item[10] Redistribution activities, especially food donation to people in need, are particularly encouraged by the European Union and will also be supported by overcoming some regulatory issues, in particular, through normative simplification (EC 2017).
\end{itemize}
When prevention, re-use and recycle activities (also known as “the 3-Rs”\textsuperscript{14} in descending order of preference, are not feasible, food waste can reach a number of potential destinations. These destinations are ranked in descending order from the most preferred to the least desirable choice (Figure 2)\textsuperscript{15} and can be grouped into two main categories: recovery/valorization practices, and disposal/non-valorization practices.

Recovery/valorization practices are aimed at increasing feedstock supply to produce energy and goods and represent the first three steps of Figure 2. Food waste can be either utilized as feedstock for anaerobic digestion and co-digestion\textsuperscript{16} to produce clean and renewable energy, such as biogas (Zhang et al. 2007; Zhang et al. 2014; Evangelisti et al. 2014), or utilized in biorefineries (Mirabella et al. 2014) to produce bio-based products\textsuperscript{17} such as biofuels, chemical intermediates and composite materials such as bioplastics. It is worth noting that the EU funded FUSIONS project does not include bio-material and biochemical processing as food waste\textsuperscript{18}. Also, incineration plants with high efficiency energy recovery are part of the valorization category (Grosso et al. 2010).

Despite the ranking of food waste end-of-life different destinations (Figure 2) offers a useful framework to establish an order of priority, policy decisions must be integrated also with technical assessments taking into account specific features at the national and local levels. From an environmental point of view, alternative food waste valorization practices can be evaluated with different assessment methods at different levels. While quoting a number of studies, Vandermeersch et al. (2014) outlined that the approach considered by many as the most valuable is cradle-to-grave through the Life Cycle Assessment (LCA) methodology, although other methods such as Exergetic Life Cycle Assessment (ELCA) should be taken into account. The importance of adopting life cycle-based methodologies within the overall food supply

\textsuperscript{14} Reduce, re-use and recycle.
\textsuperscript{15} This is based on the European waste hierarchy and the literature (Papargyropoulou et al. 2014; Hanson et al. 2016).
\textsuperscript{16} Co-digestion is when food waste is combined with other types of waste (also organic). Often this type of process has advantages both in terms of quality and reduced costs (see Lin et al. 2011).
\textsuperscript{17} Bio-based products are commonly defined as products that are wholly or partly derived from biomass.
\textsuperscript{18} On the other hand, it considers bio-energy production through co/anaerobic digestion as waste since it is not considered an efficient option. Specifically, food and inedible parts of food removed from the food supply chain, composted, crops ploughed in/not harvested, anaerobic digestion, bioenergy production, co-generation, incineration, disposal to sewer, landfill or discarded to sea is quantified as food waste by FUSIONS, whereas food recovered for material use such as bio-based products, animal feed, or sent for redistribution are not considered as food waste (see https://www.eu-fusions.org/index.php/publications/faq, FUSIONS 2014).
chain, together with the methodological challenges that it poses, has been pointed out by the literature (see Notarnicola et al. 2017). In particular, LCA represents an effective decision support tool for evaluating and comparing different end-of-life options for food waste, even though a harmonized modelling approach targeted for this field needs to be consolidated (Corrado et al. 2017). In particular, according to the European Commission19, the LCA allows the identification of selected cases, characterized by specific local conditions, in which it becomes more advantageous to deviate from the hierarchy ranking, giving priority to lower positioned activities. Moreover, it is worth noting that the waste hierarchy, as stressed by the European Union itself, has to be fulfilled with a degree of flexibility because socio-economic costs were not taken into account when designing the ranking order (see Rasmussen et al. 2005; BIS 2015).

According to Eurostat, thanks to the spreading of valorization destinations there has been a strong improvement in the reduction of the practice of landfilling municipal waste in the EU-27, despite increased levels of waste; the landfilling rate has dropped from 63.8% in 1995 to 25.3% in 2015. For example, “the recovery of organic material by composting has grown with an average annual rate of 5.4 % from 1995 to 2015”20.

4 Food waste management: challenges from the bioeconomy and the circular economy

Sustainable development has gained an increasingly central role in the global agenda and is now based on a circular economy model. The circular economy is grounded on resource efficiency, waste reduction, recycle and valorization21. “Food waste is a key area in the circular economy” (EC 2017), and is considered as an under-utilized resource that can be brought into use. The circular economy creates more employment with fewer resources (Mitchell and James 2015), and is strongly related to sustainable consumption and production, i.e. Goal n.12 of the UN 2030 Agenda for Sustainable Development22, which has also been identified as a fundamental requirement for sustainable development by the 2015 Paris Agreement23.

The bioeconomy is among the sectors most strongly linked to the circular economy. It includes a variety of production activities such as agriculture, forestry, fisheries and aquaculture, food, and pulp and paper production, parts of the chemical, biotechnological and energy industries, and manufacturing of bio-based textiles (Ronzon et al. 2015). The minor environmental impact of the bioeconomy is based on the use of renewable biological resources (biomass) from land and sea, instead of fossil fuel-derived feedstocks, to produce food, feed, energy and bio-based products.

The European bio-economy has a turnover of roughly €2 trillion and employs more than 22 million people (EC 2012). Many countries, both at the European and global level, have developed their own bioeconomy strategies since it is considered a strategic and highly innovative area. It is estimated that, by 2025, every euro invested by the EU in bioeconomy research and innovation could generate 10 euros of added value in the bioeconomy (EC 2012).

The “biorefinery”, as defined by IEA Bioenergy Task 42, “is the sustainable processing of biomass into a spectrum of marketable products and energy”; this means that it can be a facility, a process, a plant, or even a cluster of facilities (de Jong and Jungmeier 2015: 5). This is not a completely new concept, since biomass has always been used; however, advanced biorefineries employ innovative and green technologies to produce new types of products. At the same time, the adoption of these lower polluting technologies creates economic benefits such as new employment creation, as well as social benefits such as increased public health (see Bourguignon 2017). In recent years, attention has shifted to second generation biomass composed of secondary feedstock instead of dedicated crops, and includes a variety of waste streams such as food waste (see OECD 2014; BIS 2015) that can be used to produce high value chemical products (Pfaltzgraff et al. 2013; Lin et al., 2013. These types of raw materials do not compete with food production which has been one of the most debated and criticized issues related to the bioeconomy (Scarlat et al. 2015).

However, the production of energy and biomaterials from food waste is at an early stage of development. There is a strong need to reduce uncertainty and encourage...
investment by increasing transparency (Kretschmer et al. 2013), first, by providing precise information on the availability of food waste and by ensuring a lower environmental impact of bioenergy and biomaterials; this should not be taken for granted. Indeed, comparability of bio-based products versus fossil-based alternatives is a key issue. Sustainability assessment needs to be further investigated through Life Cycle Assessment (LCA), complemented by Life Cycle Costing (LCC), and Social Life Assessment (S-LCA) since also economic and social aspects should be taken into consideration.

In Figure 3, we report findings from a SWOT analysis conducted by Kretschmer et al. (2013), summarizing the most relevant critical issues, as well as the advantages associated with the development of this sector. Indeed, the implementation on a larger scale of biorefining from food waste will depend, as stressed by the literature (Lin et al. 2011; Kretschmer et al. 2013), on overcoming the following factors:

1. **Too high variety of quality and volume of food waste.** This strongly depends on a separate food waste collection that, albeit increasing, still needs significant improvements in quality as well as quantity;

2. **Low coordination of the different sources of food waste (such as distributors, retailers, cafes, restaurants, schools, hospitals and households);**

3. **Infrastructural and storage limitations, also because food waste decomposes rapidly;**

4. **Market demand of bio-based products, which strongly depends on policy actions such as a more adequate legislative support and higher public awareness;**

5. **Economic viability of the plants and technological limitations.**

These points show that one of the central factors is public awareness as a basis for increased demand of bio-based products (see de Besi and McCormick 2015) since they are still more expensive compared to traditional ones. The assessment through the life cycle approach will make clear the benefits of bio-based products to policymakers as well as to citizens as the transition to more sustainable circular models will not be possible without a strong public consensus.

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**Figure 3:** Main Strengths, Weaknesses, Opportunities and Threats facing the use of food waste and crop and forestry residues for material and energy substitution in Europe. *Source: Kretschmer et al. 2013*
5 Conclusions

An increased population needs higher levels of energy, food and goods; however, natural resources are limited and the current production system is highly polluting. In such a complex context, the loss or waste of about one-third (1.3 billion tonnes a year) of all food produced for human consumption (Gustavsson et al. 2011) is no longer acceptable, not only for social reasons, considering the implications on food security, but also for the costs associated with its economic and environmental impact (Falcione and Imbert 2017). According to the EPA (2016), food waste is the second largest contributor, after paper and cardboard, of municipal solid waste (MSW) in the United States24.

Efforts to reach the UN’s target of halving avoidable food waste by 2030 are needed on the part of both the consumption and production side (e.g. by implementing innovative solutions to extend product lifespans) as food waste needs to be tackled at all stages of the food supply chain. The circular economy package, adopted by the European Commission in 2015, supports European countries in a more efficient and lasting use of resources, which can also create new job opportunities. It devotes an important part to more effective waste management through revised legislative proposals on waste in order to achieve more ambitious results.

The waste hierarchy, and in particular the food waste hierarchy analysed in this paper, offers a framework on which countries’ food waste management strategies should be based. Although attention has been given to the ranking of food waste tackling practices with particular regard to end-of-life valorization destinations of food waste, the priority order cannot be ex ante strictly defined. Firstly, this is because local environmental and social impacts depend on a number of conditions related to country-specific features25, and therefore vary significantly across the geographic dimension (see Manfredi et al. 2015). Moreover, economic costs need to be more systematically taken into account in future analysis (see Papargyropoulou et al. 2014), and the assessment of alternative waste treatment activities (even when taking into account only environmental aspects) should become more consistent and comparable, considering also those cases where waste products are treated as individual streams (Vandermeersch et al. 2014; Eriksson et al. 2015).

Overall, the bio-economy and the circular economic model represent a great opportunity for tackling the food waste issue, especially in medium-high income countries where the bulk of the problem is associated with miss-consumption behaviours occurring at the end of the food supply chain. However, this transition needs to be accompanied by public policies. Demand and supply side polices are crucial for pushing out emerging sectors such as the bioeconomy. It is worth noting that two of the European countries where the bioeconomy has surged ahead - i.e. Germany and Italy - have developed somehow alternative approaches. Indeed, Germany has experimented supply-side policies through R&D investments, whereas Italy has mostly encourage market uptake policies for several bio-based products - such as bioplastics and second generation biofuels (Imbert et al. 2017). However, there is no one-size-fits-all policy tailored to meet countries’ regional and local needs. Indeed, in recent years there has been an increased interest in the policy mix (see Veugelers 2012; Quitzow 2015) for promoting sustainability transitions. This type of approach can provide effective guidance to policy makers ensuring the basis for a further development of the sector.

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