Food waste recovery pathways: challenges and opportunities for an emerging bio-based circular economy. A systematic review and an assessment.

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Abstract

The transition to a Circular Economy in the agri-food supply chain will require appropriate support mechanisms. Globally, 1/3 of food is wasted, generating by-products which could be treated and processed. In a bioeconomy perspective, qualitatively and quantitatively assessing the availability of secondary raw materials and classifying the different conversion systems is crucial for the transition to happen. For this reason, a literature review of food waste conversion pathways, and related trade-offs and opportunities, has been carried out. Ecological performances of EU28 food waste treatment processes have been assessed through Life Cycle Assessment and Emergy Accounting methods, providing information from a donor and a consumer side perspectives for supporting policies. The added value of this work is the commixture of the analysis of food waste recovery and recycle pathways, their environmental assessment and the indication of opportunities and constraints. A conversion pathways database has been generated and classified. A major interest towards recovery of mixed food waste and biological type of conversion processes is highlighted. The main identified opportunities are the reduced environmental pressure and better management of resources, the avoided loss of economic value and the generation of work opportunities, as well as conditioning stakeholders' behaviors. On the other hand, it is highlighted that bad management of food waste can pose a threat on human health. The planning of these processes must carefully acknowledge local characteristics.

Keywords

Food waste, Circular economy, Bioeconomy, LCA, Emergy accounting

1. Introduction

Different definitions of Food Waste (FW) have been adopted in recent times. The Food and Agriculture Organisation (FAO) differentiates among *food loss*, i.e. unintended loss of food during harvesting, post-harvest handling, processing, and distribution, and *food waste*, i.e. the food that gets lost at retail and consumption stages (FAO, 2011). *Food loss* and *food waste* are respectively acknowledged as "the unintended result of an agricultural process or technical limitation in storage, infrastructure, packaging, or marketing" and as "food that is of good quality and fit for human consumption but that does not get consumed because it is discarded" by the World Resources Institute (Lipinski et al., 2013). The European Union (EU) defines *food waste* as "fractions of food and inedible parts of food removed from the food supply chain to be recovered or disposed (including - composted, crops ploughed in/not harvested, anaerobic digestion, bioenergy production, co-generation, incineration, disposal to sewer, landfill or discarded to sea)" (Stenmarck et al., 2016).

In the last decades, food production rate increased faster than human population growth rate, producing nowadays enough food to feed 10 billion people (the projection of global population for 2050) (Holt-Giménez et al., 2012), but an estimated one third of the food is lost or wasted as flowing through supply chains (FAO, 2011). This represents a major drawback from an environmental, social and economic viewpoint: food losses are responsible for estimated almost one trillion USD of economic losses, a quarter of the water required by agriculture and an equivalent crop area as big as the entire China; FW also contributes to food insecurity and might add greenhouse gases deriving by their decomposition if landfilled (Hanson et al., 2016).

The fundamental action to be implemented in order to stop this huge depletion of valuable assets is reducing food waste and losses at every level of the food supply chain, including production, processing, storage, handling and transportation by final consumers. Nevertheless, a fraction of food is inevitably wasted (e.g. some agricultural residues, food production scraps, inedible parts of vegetable and animals). Recovering and using this unavoidable organic waste fraction could be considered a new way of mining resources, capable of reducing the depletion of non-renewable stocks. In doing so, conversion of vegetal biomass into chemicals and fuels (Chang and Venkata Mohan, 2016), as for example the generation of bioethanol from lignogellulosic biomass (Fiorentino et al., 2019), chemicals from different types of agricultural feedstock (Fiorentino et al., 2017), the conversion of *Brassica Carinata* biowaste to chemical and energy (Fiorentino et al., 2014), the biomethane generation from biogenic waste (Florio et al., 2019) and the generation of biofuel from waste cooking oil (Ripa et al., 2014), and conversion of animal by-products into commodities, fuel and electricity (Santagata et al., 2017 and 2019) would represent innovative valorisation patterns for more appropriate resource use and the achievement of increased environmental integrity.
FW is also addressed in the EU Circular Economy Package, introducing a FW reduction target under the forthcoming Farm-to-Fork Strategy. within the European Green Deal (EC, 2020). The EU Action Plan comprises a timetable for proposed actions and proposes regulations on waste. In 2018 a Revised EU Waste Legislation has been endorsed, prompting the reduction and monitoring of food waste throughout the food supply chain in EU countries, communicating the possible achieved progresses. EU countries committed to halve food waste generated per capita at the retail and consumer level by 2030 and to lower food losses across the whole supply chain (EC, 2018).

Circular Economy (CE) is a paradigm aimed at overcoming the linear "take-make-dispose" model, endorsing a more responsible and appropriate exploitation of resources and reutilisation of resource-rich by-products. As pointed out both by practitioners (Ellen MacArthur Foundation, 2012) and academics (Ghisellini et al., 2016) CE aims at reducing the environmental load and improve the wellbeing of humans. However, the dominant interpretation of CE is mainly promoting a reductionist perspective, mainly linked to improved waste management practices, advocating "enhanced" recycling, recovering and reusing patterns (Ghisellini et al., 2016). This might lead the transition towards a CE to be unsuccessful, given that some of the identified waste management pathways could be appropriate in certain conditions but fail in other situations. CE aims at: (i) implementing better waste management systems through preventive design, reuse and recycle; (ii) reducing the use of fossil resources by increasing the use or renewable resources; (iii) reducing the production of unnecessary goods and at implementing a "circular" governance with increased participatory strategies. Within this context, the unavoidable fraction of FW represents a huge opportunity for the bio-conversion in useful materials (i.e. chemicals) and energy (i.e. biofuels and electricity) (Dahiya et al., 2018), going a step further than CE towards bioeconomy.

Bioeconomy is proposed as a different approach for the sustainable exploitation of biological resources, leading to less environmental impacts and reducing the addition to fossil fuels, with the result of mitigating climate change and leading toward a post-petroleum society (EC, 2012). In order to achieve this, there is the need to go beyond the mere use of alternative raw materials and technologies, and to introduce innovations at all level of the various supply-chains affecting the entire network of systems (i.e. economical, technological, political and environmental, among others), so that the bioeconomy framework would be a component of the great transformation referred to as "worldwide remodeling of economy and society towards sustainability" (Urmetzer et al., 2020). Of course, bioeconomy systems will need proper environmental and socio-economic assessments to ensure their feasibility (Zabaniotou, 2018).

The aim of the present study is twofold. First of all, the review of current waste treatment patterns and strategies can serve as the starting point to identify still unexplored challenges, innovative options and perhaps constraining trade-offs. Secondly, new options need to be clearly assessed across a wide set of dimensions, in order to avoid the risk of investing resources and efforts without a reasonable certainty of environmental and social wellbeing improvement.
Indeed, it must be highlighted, that the implementation of some conversion pathways may be beneficial within a context and may not be feasible in others. Often, in the past, some conversion pathways were claimed to be *one-size-fits-all solutions* without any sufficient check of their broader consequences, resulting into burden shifts or even worsened impacts (biofuels from food crops have been a clear example of such issue). Environmental feasibility does not come for free, and different strategies are characterised by different performances and carry different burdens. The modelling and assessment of recycle and recovery strategies might be difficult, due to complex accounting procedures (Brown, 2015). From this point of view, the integration of different modeling and assessment methods (Santagata et al., 2020) represents a very promising tool towards holistic understanding of performances and burdens.
In order to achieve the above-mentioned objectives, after carefully reviewing the presently available disposal and conversion options for food waste, we perform in this paper an assessment of selected options based on LCA (Life Cycle Assessment) and EMA (EMergy Accounting). The aim is to provide examples of multi-dimension process and biosphere oriented tools for a deeper understanding of environmental costs and benefits of waste conversion processes and to support the decision making, towards the implementation of a circular bioeconomy. The present article is structured as follows. Section 1.1 provides an overview of the current food waste in EU28. Section 2 presents the methodological approaches used to carry on the review and the environmental assessments. Section 3 presents the main findings of the review and the quantitative results obtained by applying LCA and EMA to FW conversion options in EU28, discussed in Section 4. Section 5 summarizes the main opportunities and challenges to be taken into account for an effective implementation of food recovery strategies. Finally, some conclusions are drawn.

1.1. Food waste in the EU: an overview

Food and FW has been identified as a major hotspot of the bioeconomy development, including future and already implemented business models, that though still show very little participation from larger, multinational companies intended to maintain the status quo (Kristinsson, 2019). From this perspective, FW management and recovery becomes of maximum relevance.

FW has gained proper recognition in recent years, also within the scientific community. Figure 1 highlights the number of resulting scientific works obtained when inserting the key word "FOOD WASTE" in the Scopus and Web Of Science citation databases. It is clear how the interest towards FW continued to grow in recent years, in particular from 2014, when the publication of scientific works related to food waste outnumbered the previous years. The Scopus database was chosen for the retrieval of scientific articles within the present work because of its monitoring of a wider number of scientific journals.

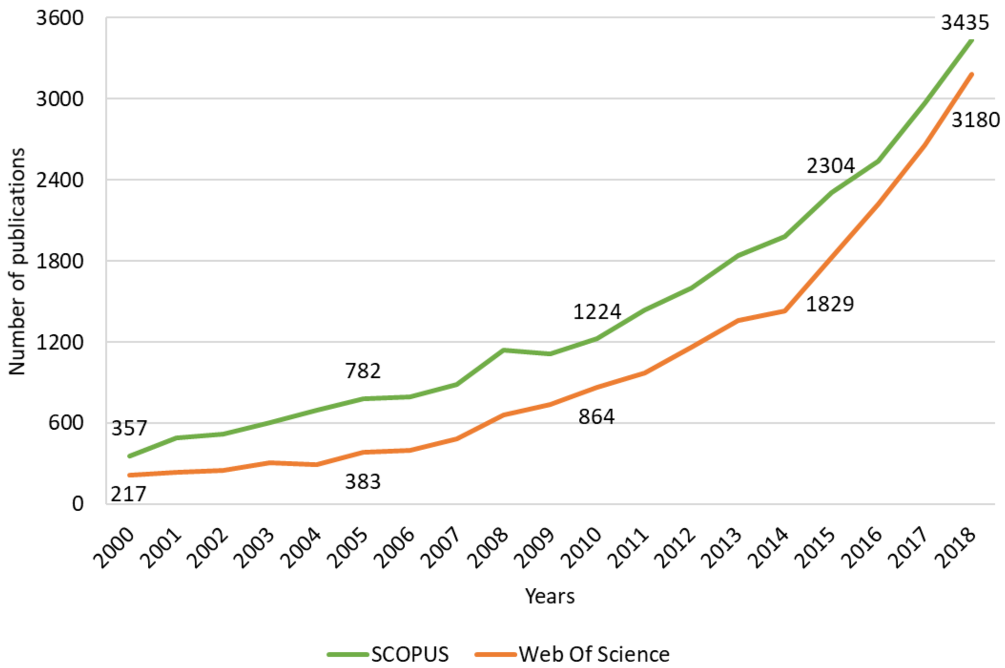

Figure 1 – Number of results from the search of the keyword "Food Waste" within Scopus and Web Of Science indexing databases in the time-frame 2000-2018.

Table 1 and Figure 2 list respectively the share in terms of tonnes generated and in terms of percentages of the different waste components, identified using EWC-Stat 4 codes (EC, 2010), generated by EU-28 countries in 2016, as presented by Eurostat data (Eurostat, 2019). Food-related waste represents a significant part (≈ 4%) of total waste production in the year 2016.

Table 1 – Waste generated within EU28 in 2016

EWC-Stat 4 codes	t (E+07)	Category
W01-05	5.4	Chemical and medical waste (subtotal)
W061+W062+W063	9.9	Metal waste
W071	1.9	Glass waste
W072	5.1	Paper and cardboard waste
W073+W074	2.1	Rubber & Plastic waste
W075+W076	5.7	Wood + Textile waste
W077_08	1.8	Equipment (subtotal, W077+W08A+W081+W0841)
W09	9.5	Animal and vegetal waste (subtotal, W091+W092+W093)
W10	30.7	Mixed ordinary waste (subtotal, W101+W102+W103)
W11	20.7	Common sludges

W121	34.5	Mineral waste from construction and demolition
W12B	70.4	Other mineral waste (W122+W123+W125)
W124	11.8	Combustion waste
W126	49.4	Soils
W127	90.3	Dredging spoils
W128	46.0	Mineral waste from waste treatment and stabilised waste

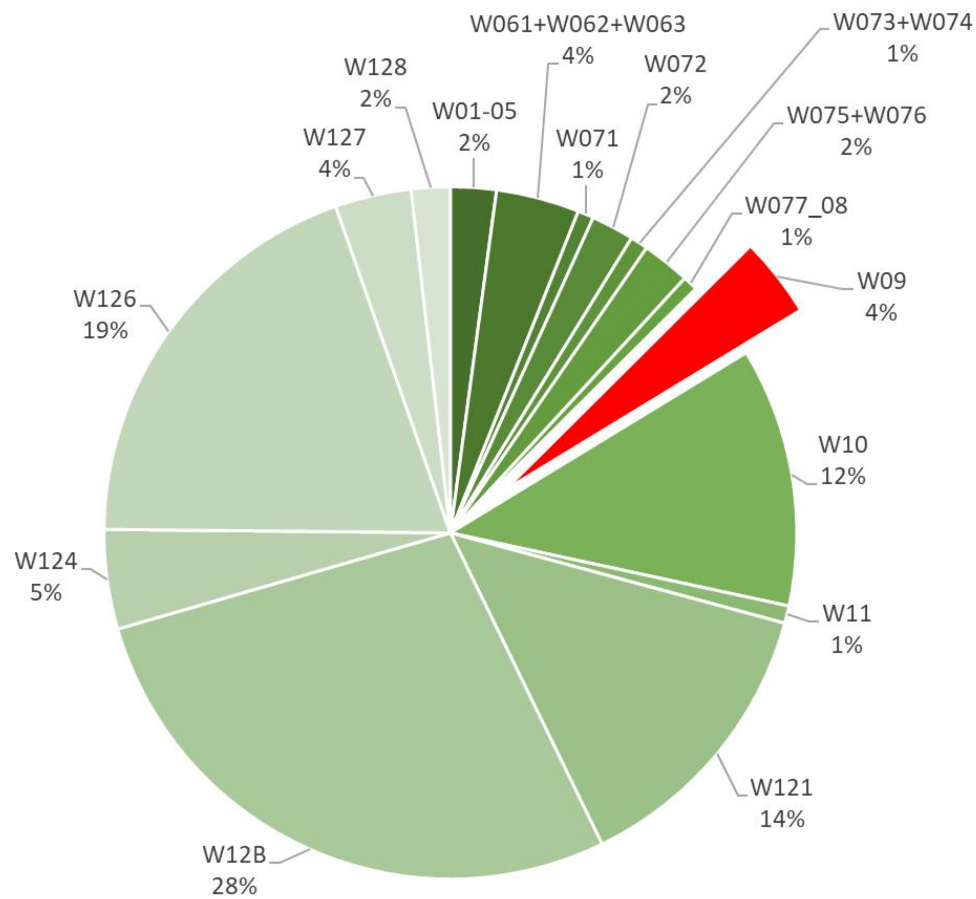

Figure 2 – Percentage of each waste category on total waste production in 2016. W09 (Animal and vegetal waste: W091+W092+W093) highlighted in red.

W09, as specified in EU (2010), represents the subtotal of W091 (Animal and mixed food waste), W092 (Vegetal waste) and W093 (Animal faeces, urine and manure). Production trends of each category in the 2010-2016 time span are reported in Figure 3.

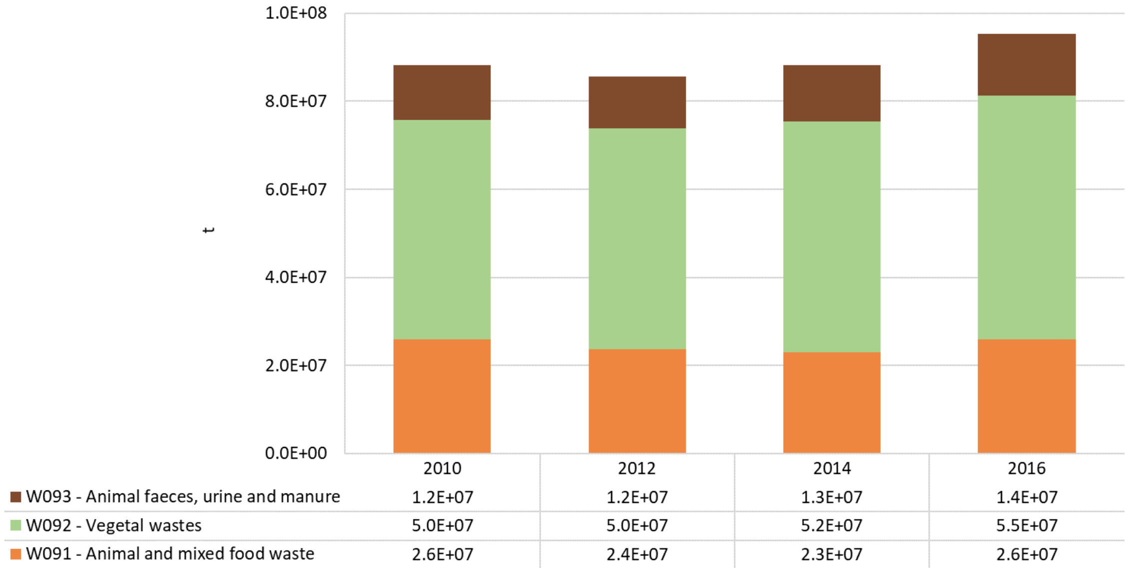

Figure 3 – Production of food-related waste in EU28 in the 2010-2016 timespan.

The previous figures state the growing relevance of the FW issue in both academic literature and practical terms. As stated in the introduction, the present work aims at performing a systematic review of scientific works related to FW, identifying conversion pathways and consequent bio-products (i.e. bio-materials, bio-fuels, bio-energy), challenges and opportunities of the highlighted FW treatments. The next section provides an overview of the employed review framework.

2. Methodology

2.1. Review framework

The review performed in this work takes into account scientific works published in scientific journals and books and indexed within the Scopus database in a timespan between 2014 and the time when the data retrieval has been completed (i.e. May 2019). Given the larger number of entries, the Scopus database has been chosen for paper retrieval. The boolean search has been performed using the operators "Food AND Supply Chain AND Waste AND Recovery", with a result of 58 scientific works. A first selection has been performed, removing one duplicate article and two non-pertinent manuscripts. The 55 scientific works chosen has been classified into:

- Reviews: 9 published works
- Articles: 33 published works
- Book chapters: 8 published works
- Conference papers: 4 published works
- Conference reviews: 1 published work

The classified works have been screened a second time in order to assess the presence of possible conversion processes of FW. This second screening resulted in:

- 9 "Review" items including FW conversion processes
- 10 "Article" items including FW conversion processes
- 2 "Book chapter" items including FW conversion processes
- 2 "Conference paper" items including FW conversion processes
- 4 works from the "Conference review" item above, including FW conversion processes

The described general framework applied to perform the literature review is represented in Figure 4.

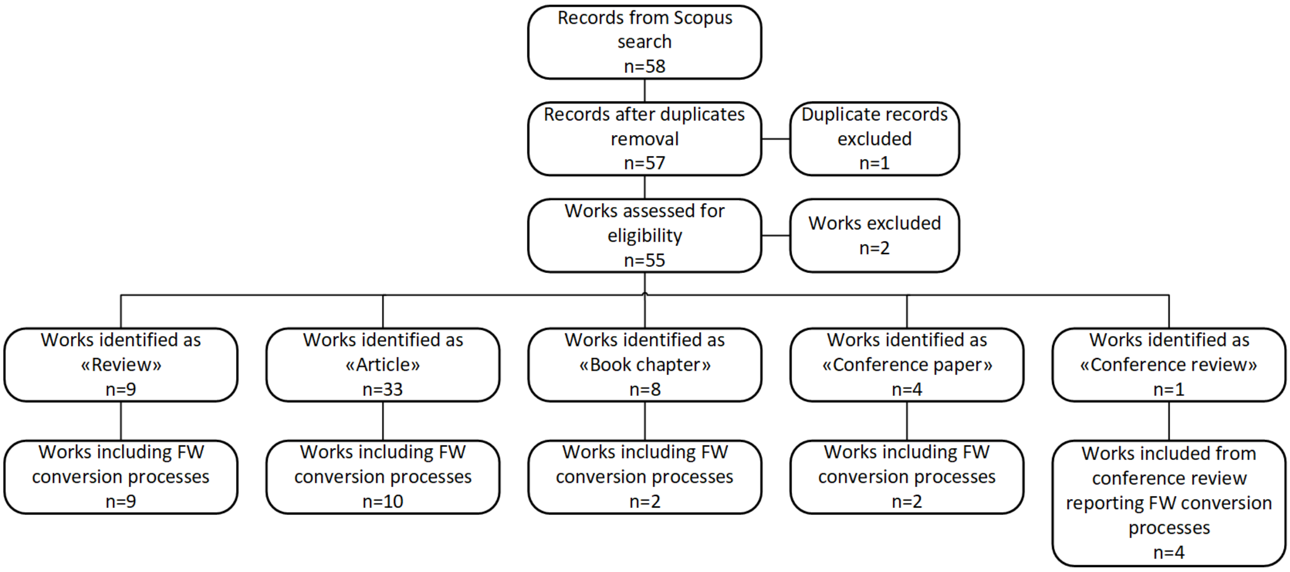

Figure 4 – Framework developed for the screening of scientific works.

The identified conversion pathways have been used to build a database identifying:

- The scientific works presenting the listed conversion processes
- The type of food-related waste, classified in two steps; the first step cataloging FW as i) Agricultural biomass (waste generated within the agricultural crop processing), ii) Animal biomass (waste generated during livestock rearing), iii) Biomass from vegetables, fruits and seeds (waste generated by the use and processing of plant products), iv) Herbaceous and woody biomass (energy crops, waste wood), v) Food waste (mixed waste generated by food consumption), vi) Waste water (organic fraction of wastewater)
- The specific FW material analysed
- The type of pretreatment classification: i) Biological (e.g. aerobic fermentation), ii) Chemical (e.g. hydrolysis), iii) Physical (e.g. grinding), iv) Physico-chemical (e.g. ultrasonic with acid), v) Physico-thermal (e.g. grinding/steaming), vi) Thermal (e.g. drying), vii) Thermo-chemical (e.g. organosolvation), viii) Thermo-physico-chemical (e.g. drying/grinding/hydrolysis), N/A (when pretreatment processes are not present or not indicated)
- The specific pre-treatment process considered
- The type of conversion process: i) Biological (e.g. anaerobic digestion), ii) Chemical (e.g. transesterification), iii) Physical (e.g. ultrasound-assisted extraction), iv) Thermal (e.g. incineration), v) Thermo-chemical (e.g. liquefaction), vi) Physico-chemical (e.g. upgrading)
- The specific conversion process considered
- The bio-product classification, as: i) Bio-fuel, ii) Bio-polymers, iii) Chemical, iv) Electricity, v) Food and feed ingredients, vi) Materials
- The specific final bio-product from conversion

Furthermore, the database connects the assessed pathways not only to the proper articles, but it also identifies, by means of NACE codes (Eurostat, 2008), the activities generating the considered FW and the activities whose products are eventually avoided by substitution with the bio-products generated by conversion of FW.

2.2. Assessment approaches

As previously mentioned, costs and benefits of proposed alternatives need to be carefully assessed to prevent failure risks and burden shifts. The literature about assessment methods is very rich. It is beyond the goal of the present study to review all of them nor to claim that some are more telling than others. As explained in the next two subsections, the two methods to be used in this study have been selected due to their multidimensional design as well as their broad perspective (LCA being process chain oriented and EMA being biosphere space and time scale oriented). The two methods have been applied to selected disposal and/or recovery pathways of W091, W092 and W093 FW generated within EU28 countries. Other methods may certainly provide additional insights and understanding if integrated properly.

2.2.1. Life Cycle Assessment

This work uses the LCA method, standardised by ISO standards (ISO, 2006a, 2006b) and ILCD Handbook guidelines (JRC, 2010) as a four steps procedure (definition of goal and scope, inventory analysis, impact assessment and interpretation), to evaluate potential burdens and depletion of resources throughout a product's life cycle. LCA results are presented as a set of environmental impact categories, including, among others, climate change, stratospheric ozone depletion, depletion of resources, toxicological effects (Pennington et al., 2004). The study has been performed utilising the SimaPro software version 9.0.0.30 (https://simapro.com/), the Ecoinvent database version 3.6 (Wernet et al., 2016), and the ReCiPe method (Goedkoop et al., 2009) for impacts assessment. ReCiPe Midpoint (H) v.1.03 method has been chosen. The ReCiPe method incorporates characterisation factors to evaluate the potential contributions to each impact category and normalisation factors to allow a comparison across categories (Europe ReCiPe Midpoint (H), 2000, revised 2010). Characterised results cannot be compared, due to different physical units; therefore a normalisation procedure is applied. Normalisation is a life cycle impact assessment tool used to express characterised impact indicators in a way that they can be compared, with reference to average impact values calculated for a given area in a given year. The impact categories explored in this study are listed in Table 2.

Table 2 – Impact Categories considered within the ReCiPe Midpoint (H) v.1.03 impact method.

Impact category	Unit	Abbreviation
Climate change potential	kg CO_2 eq	CCP
Stratospheric ozone depletion potential	kg CFC11 eq	SODP
Ionising radiation potential	kBq Co-60 eq	IRP
Ozone formation, Human health potential	kg NO_x eq	OFHP
Fine particulate matter formation potential	kg PM2.5 eq	PMFP
Ozone formation, Terrestrial ecosystems potential	kg NO_x eq	OFEP
Terrestrial acidification potential	kg SO_2 eq	TAP
Freshwater eutrophication potential	kg P eq	FEP
Marine eutrophication potential	kg N eq	MEP
Terrestrial ecotoxicity potential	kg 1,4-DCB	TETP
Freshwater ecotoxicity potential	kg 1,4-DCB	FETP
Marine ecotoxicity potential	kg 1,4-DCB	METP
Human carcinogenic toxicity potential	kg 1,4-DCB	HCTP
Human non-carcinogenic toxicity potential	kg 1,4-DCB	HNCTP
Land use potential	m^2a crop eq	LUP
Mineral resource scarcity potential	kg Cu eq	MRSP
Fossil resource scarcity potential	kg oil eq	FRSP
Water consumption potential	m^3	WCP

2.2.2. Emergy Accounting

Originally formulated by Odum (1996), EMA accounts for the energy directly or indirectly available for transformations in a system, to obtain a product or a service (Brown and Ulgiati, 2004). The different emergy contributions to a system, in the form of material, energy and information resources, are classified as local renewable (R) and nonrenewable (N) and imported resources (F), including labour and services (L&S). The unit used is the solar emjoule (sej), expressing the amount of energy of one kind (solar) needed for a product or a service. The resulting total emergy (U) is the total contribution from the environment to products and services, calculated as the addition of all inflow amounts multiplied by the related emergy conversion factor, called Unit Emergy Value (UEV, measured as sej/unit-of-inflow). The UEV is calculated by dividing U by the yield of related product or service. A UEV defined as sej/J is called 'transformity'. UEVs are calculated with relation to a Global Emergy Baseline (GEB), accounting for the annual total emergy driving the biosphere. In this work, the 12E+24 seJ/yr GEB (Brown et al., 2016) is adopted. All UEVs related to previous GEBs are converted accordingly.

3. Results

The Results section will present the findings from the classification of the reviewed scientific works and then will discuss some explanatory assessment of treatments of EU28 generated food-related waste. The added value of the present work is the commixture between the analysis of specific FW conversion pathways and the comprehensive assessment of opportunities and constraints associated with FW strategies, still quite lacking and much needed.

3.1. Review of scientific works

Table 3 lists the 9 "Review" items, reporting also the number of citations at the date of retrieval (May 2019). Item A (Breitenmoser et al., 2019) focuses on the anaerobic digestion of different kinds of waste and agri-food waste in order to generate bio-gas, accounting for different digestion systems. Item B (Facchini et al., 2018) takes into account FW throughout UK food supply chain and redistribution of surplus food still edible. Item C (Koller et al., 2017) reviews the biological synthesis of polymers from different microbial strains applied to different food-related waste. Item D (Verstraete et al., 2016) is about recovery of nutrient from municipal, industrial and manure wastewater streams. Item E (Uçkun Kiran et al., 2015) is a review about the state of the art of the recovery of platform chemicals from various kinds of food waste through fermentation technologies. Enzyme production from conversion processes of food-related, mainly agricultural, waste is assessed in Item F (Uçkun Kiran et al., 2014a). Item G (Uçkun Kiran et al., 2014b) reviews the possibilities of useful biofuels production from fermentation of food waste. Items H (Reijnders, 2014) is about phosphorus resources pathways and their possible conservation and recovery, including phosphorus contained in food waste and in food losses at different levels. The last review item, Item R (Girotto et al., 2015), assesses possible uses of FW within the industry sector. Item R was erroneously identified by Scopus as an "Article" item, thus in this work it has been classified within "Review" items.

Table 3 – Outline of "Review" items on conversion pathways of food-related waste

Item	Authors	Pathway	Source	Citations
A	Breitenmoser et al., 2019	Anaerobic digestion	Journal of Environmental Management	0
B	Facchini et al., 2018	Food redistribution	Journal of the Air and Waste Management Association	1
C	Koller et al., 2017	Biopolyesters production	New Biotechnology	102
D	Verstraete et al., 2016	Water and nutrient recovery	Bioresource Technology	23

E	Uçkun Kiran et al., 2015	Platform chemical production	Journal of Chemical Technology and Biotechnology	31
F	Uçkun Kiran et al., 2014a	Enzyme production	Waste and Biomass Valorisation	20
G	Uçkun Kiran et al., 2014b	Energy generation	Fuel	179
H	Reijnders, 2014	Phosphorus conservation and recovery	Resources, Conservation and Recycling	81
R	Girotto et al., 2015	FW use within industry	Waste Management	58

The other scientific works (i.e. articles, book chapters, conference papers and conference reviews), included in the construction of the FW conversion pathways are listed in Table 4. The majority of items in both Table 3 and Table 4 present alternative, novel or specific physical, chemical or biological processing and/or conversion treatments of selected FW materials, far-looking into not yet explored perspectives.

Table 4 – Scientific works providing a FW conversion pathway included in the database.

Item	Authors	Title	Source	Type
I	Piccolella et al., 2019	Recovering *Cucurbita pepo* cv. 'Lungo Fiorentino' Wastes: UHPLC-HRMS/MS metabolic profile, the basis for establishing their nutra- and cosmeceutical valorisation	Molecules	Article
J	Ghosh et al., 2019	Towards waste meat biorefinery: Extraction of proteins from waste chicken meat with non-thermal pulsed electric fields and mechanical pressing	Journal of Cleaner Production	Article
K	Carraresi et al., 2018	Emerging value chains within the bioeconomy: Structural changes in the case of phosphate recovery	Journal of Cleaner Production	Article
L	Hu et al., 2018	A Supply Chain Framework for the Analysis of the Recovery of Biogas and Fatty Acids from Organic Waste	ACS Sustainable Chemistry and Engineering	Article
M	Ohnishi et al., 2018	Efficient energy recovery through a combination of waste-to-energy systems for a low-carbon city	Resources, Conservation and Recycling	Article
N	Tanguy et al., 2017	Service area size assessment for evaluating the spatial scale of solid	Waste Management	Article

		waste recovery chains: A territorial perspective		
O	Sgarbossa and Russo, 2017	A proactive model in sustainable food supply chain: Insight from a case study	International Journal of Production Economics	Article
P	Eriksson et al., 2017	Take-back agreements in the perspective of food waste generation at the supplier-retailer interface	Resources, Conservation and Recycling	Article
Q	Safar et al., 2016	Energy recovery from organic fractions of municipal solid waste: A case study of Hyderabad city, Pakistan	Waste Management and Research	Article
S	Tamis et al., 2015	Lipid recovery from a vegetable oil emulsion using microbial enrichment cultures	Biotechnology for Biofuels	Article
T	Wang et al., 2017	Waste-Energy-Water systems in sustainable city development using the resilience.io platform	Computer Aided Chemical Engineering	Book Chapter
U	Prasad, 2016	Recovery of Resources From Biowaste for Pollution Prevention	Environmental Materials and Waste: Resource Recovery and Pollution Prevention	Book Chapter
V	Slorach et al., 2019	Energy demand and carbon footprint of treating household food waste compared to its prevention	Energy Procedia	Conference paper
W	Kirby et al., 2017	The role of thermo-catalytic reforming for energy recovery from food and drink supply chain wastes	Energy Procedia	Conference paper
X	Inayati et al., 2018	Extraction of pectin from passion fruit rind (Passiflora edulis var. flavicarpa Degener) for edible coating	AIP Conference Proceedings	Conference review
Y	Distantina et al., 2018	Carboxymethyl Konjac Glucomannan from Konjac Flour: The Effect of Media and Temperature on Carboxymethylation Rate	AIP Conference Proceedings	Conference review
Z	Fadilah et al., 2018	Study on the Carboxymethylation of Glucomannan from Porang	AIP Conference Proceedings	Conference review

AA	Sembodo et al., 2018	Effect of Sodium Carbonate Catalyst Weight on Production of Bio-Oil via Thermochemical Liquefaction of Corncobs in Ethanol-Water Solution	AIP Conference Proceedings	Conference review

The generated database, provided as Supplementary Material, connects the cited scientific works to a set of conversion pathways composed by 189 combinations of different pre-treatment and conversion processes leading to several types of bio-products, grouped for the sake of simplicity into bio-materials, bio-fuels, bio-energy, bio-chemicals, starting from very diverse categories of food-related waste, identified from the analysis of the included scientific works. The identification of these bio-products is essential to identify alternative circular pathways in a bioeconomy perspective. According to Fiorentino et al. (2017), classification methods can be categorised according to feedstocks, processes or products. Accordingly, the diagram in Figure 5 highlights the variety of identified conversion pathways. In this work, the starting FW related material has been classified into six different categories, (agricultural biomass; animal biomass; biomass from vegetables, fruits and seeds; herbaceous & woody biomass; food waste; waste water) according to the characteristics in section 3.1, as the pre-treatment and conversion processes. The different shaped lines indicate the pathways for each one of these categories going through the pre-treatment and conversion processes and eventually delivering the final bio-product. Each pathway from the database is identified according to Table 3 and Table 4. For the sake of clarity, Item G (banana peel, categorised within "Biomass from vegetables, fruits and seeds") can be considered: it is first dried (thermal pre-treatment), and then fermented (biological conversion) to produce ethanol (bio-fuel product); instead, Item A (agricultural residues, categorised within "Agricultural Biomass"), can be grinded (physical pre-treatment) and anaerobically digested (biological conversion) in order to obtain bio-gas (biofuel product); finally, Item E shows how Food Waste can be ground (physical pretreatment) and then fermented (biological conversion), in order to yield lactic acid (chemical).

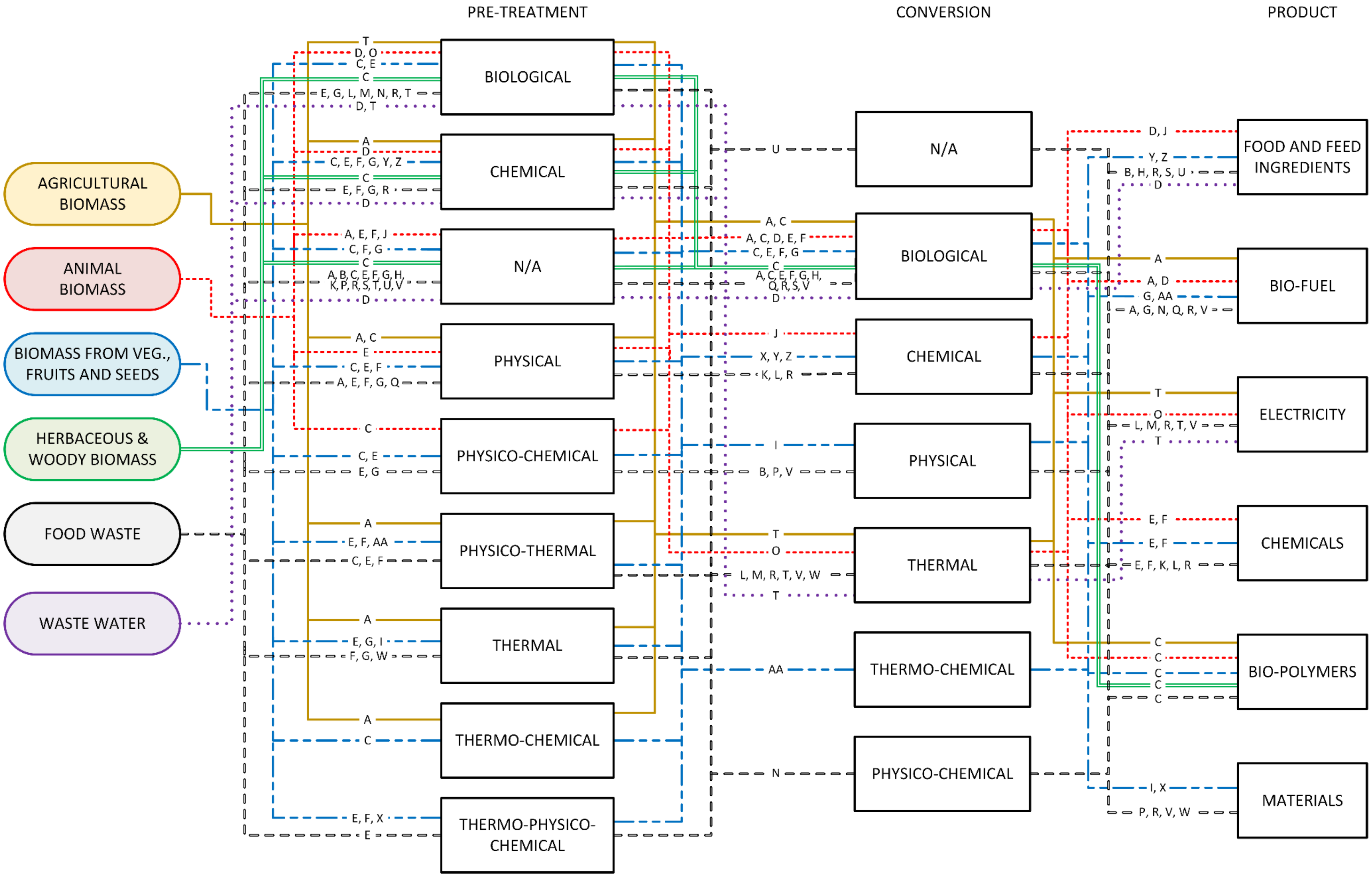

Figure 5 – Identified pathways for the conversion of FW, classifying the starting material, pre-treatment processes, conversion processes and final outputs (N/A implies non present or not specified processes).

Half of the generated database (≈ 52%) includes recovery pathways of mixed end use materials (i.e. food waste, waste waters), 33% includes by-product biomass from the processing of vegetables, fruits and seeds, about 4% is agricultural biomass and 9% animal biomass. The remaining part (≈ 2%) is represented by food surplus or inadequate food and by-products of other agricultural processes (i.e. energy crops). Considering pre-treatment processes, about 7% are of biological or biochemical nature (anaerobic fermentation or digestion), 8% of chemical nature, 30% are of physical or physico-related mixed nature (physico-chemical, physico-thermal, etc.), 29% of the reviewed literature does not present or does not specify any pre-treatment of food materials, the remaining ≈13% are of thermal, or thermal-related mixed nature (i.e. thermo-physico-chemical). When taking into consideration the main conversion pathways, almost all the FW elements within the database (≈ 85%) are processed through biological treatments, such fermentation, anaerobic digestion or polymer biosynthesis; 8% of the assessed conversion pathways are classified as thermal, 4% as chemical and 3% as physical. Finally, 6% of the obtained bio-products are identified as feed or food ingredients, 7% as bio-energy (i.e. biopower), 22% as biofuel, 13% as bio-materials, including biomass, and about 50% as chemicals and enzymes. These numbers clearly indicate the direction taken by bioeconomy research in the last years.

The generated outputs are expected to decrease the burdens related to extraction, production and perhaps use of virgin resources and energy, which have been the foundation of the traditional "linear economy". This means that the production of goods, fuels and energy (and then, the extraction of needed raw materials and the use of needed energy) may be partially replaced by bio-products coming from valuable sources that normally would be wasted and disposed of. The added value of these conversion processes resides in reestablishing the right worth (economic, social and environmental) to the so-called "waste materials" and exploiting their still present potential, instead of disposing them in useless and less environmentally feasible ways (i.e. landfills or incinerator).

In Figure 6, the NACE Statistical Classification of Economic Activities adopted within European Community is used to show how different kinds of systems, falling into different NACE categories, can influence one another through the conversion of food-related waste, allowing to avoid the common generation of materials and energy using raw materials. All categories in the left column generate food-related waste, to be treated in order to achieve one of the materials/energy in the central column. The generated goods will impact on the global economy by providing an alternative production process in substitution of the common ones classified in the activities in the right column (e.g. a NACE C 10.3 activity generating apple pomace waste that is treated in order to obtain lactic acid, an organic chemical, avoiding its fossil-based equivalent production, classified as a NACE C 20.14 activity).

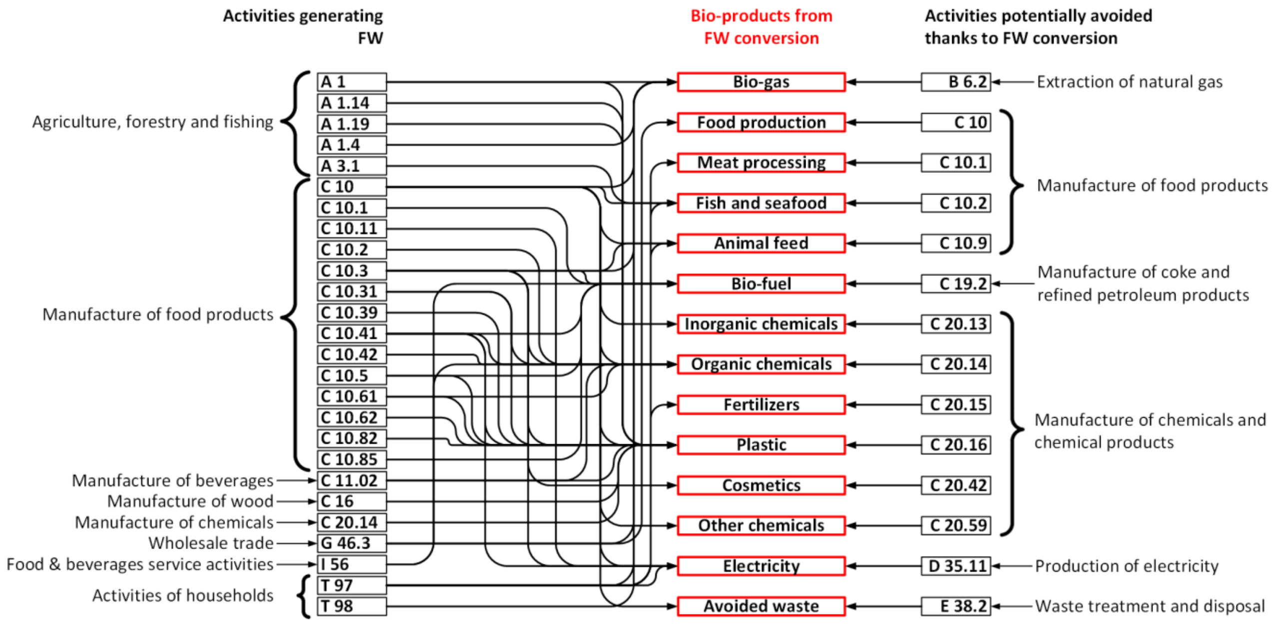

Figure 6 – NACE activities generating the identified classes of FW (on the left), treated in order to obtain bio-products (in the center), in so replacing previous business-as-usual NACE activities generating analogous products (on the right).

3.2. Review of scientific works not included in the conversion pathways database

Of the selected 55 scientific works, 24 do provide FW conversion processes, this number included one scientific work identified as "Conference review" providing items X, Y, Z, and AA, that made possible to build a database of almost 200 pathways. The remaining 31 scientific works, listed in Table S2 in Supplementary material, do not include a FW conversion process; however, they tackle the food wastage problem from other perspectives and their analysis is provided as Supplementary Materials.

3.3. LCA and EMA analysis of EU28 generated FW conversion options.

Food-related waste represents a not negligible fraction (4%) of EU28 waste generation (Figure 2), contributing with a total of 9.5E+7 t in 2016 (Table 1), categorised into Animal and mixed food waste (W091), Vegetal waste (W092) and Animal faeces, urine and manure (W093). The production of these three waste categories is more or less constant during the years, as showed in Figure 3. In 2016 EU28 countries produced a total of 2.6E+7 t of W091, 5.5E+07 t of W092 and 1.4E+07 t of W093. These materials could be disposed or reutilised in different ways, then causing different environmental impacts.

The presented review work highlights how a wide part of scientific articles about FW conversion processes focus on the chemical analysis of obtained bio-products, in order to understand their viability from a public health and environmental perspective. Others point attention to the supply chain management for retrieving bio-products and/or bio-energy. However, very few details are provided about environmental burdens and environmental feasibility of the conversion processes. Most often, FW conversion processes are reported at laboratory or pilot scale and their implementation at a real, industrial scale level, is not even mentioned. Yet, environmental performances of FW conversion processes should not to be ignored, since solutions that could be beneficial in certain contexts may not represent a feasible option in others (Fiorentino et al., 2017). Preventing and recovering of FW is a multi-dimensional issue that requires a multi-dimensional approach, achieved through a multi-method assessment. The following LCA and EMA analyses are not proposed here to identify the optimal or more innovative conversion pathways, but simply to highlight the importance of adopting a holistic perspective for more comprehensive understanding.

According to the most common disposal processes dealing with food waste from the Ecoinvent database (Wernet et al., 2016), biowaste can undergo incineration, anaerobic digestion (AD) or industrial composting (IC), while manure can be used for the production of biogas through anaerobic digestion (AD), or it can be used directly as fertiliser.

Table 5 and Figure 7 respectively show the LCA characterised and normalised burdens generated by using generic biowaste (i.e. W091+W092) as starting material for incineration, AD or IC (LCA Impact Categories are listed according to Table 2). This comparison shows how AD seems to be the overall most impacting system, with lower impacts within IRP, PMFP, TAP and LUP, where the highest values are related to IC system. However, the overall impact of IC seems to be the lowest, with Incineration standing in between IC and AD systems.

Table 5 – Recipe Midpoint (H) characterised impacts for the incineration, anaerobic digestion and industrial composting of the EU28 generated biowaste (Acronyms according to Table 2).

Impact category	Unit	Incineration	AD	IC
CCP	kg CO_2 eq	3.27E+09	9.82E+09	5.49E+09
SODP	kg CFC11 eq	4.73E+04	7.90E+04	2.34E+04
IRP	kBq Co-60 eq	3.93E+07	7.98E+07	1.39E+08
OFHP	kg NO_x eq	2.05E+07	2.27E+07	6.78E+06
PMFP	kg PM2.5 eq	4.50E+06	9.22E+06	1.75E+07
OFEP	kg NO_x eq	2.06E+07	2.30E+07	6.92E+06
TAP	kg SO_2 eq	1.13E+07	2.44E+07	1.19E+08
FEP	kg P eq	3.96E+06	2.06E+07	6.95E+05
MEP	kg N eq	9.47E+05	1.13E+06	1.50E+05
TETP	kg 1,4-DCB	6.08E+09	1.09E+10	5.19E+09
FETP	kg 1,4-DCB	5.29E+08	1.92E+09	6.86E+07
METP	kg 1,4-DCB	7.06E+08	2.53E+09	9.30E+07
HCTP	kg 1,4-DCB	6.95E+08	1.36E+09	2.41E+08
HNCTP	kg 1,4-DCB	1.15E+10	4.14E+10	1.33E+09
LUP	m^2a crop eq	5.81E+07	1.32E+08	2.55E+08
MRSP	kg Cu eq	1.42E+07	1.49E+07	8.75E+06
FRSP	kg oil eq	4.79E+08	1.14E+09	6.95E+08
WCP	m^3	4.58E+07	1.79E+07	1.85E+06

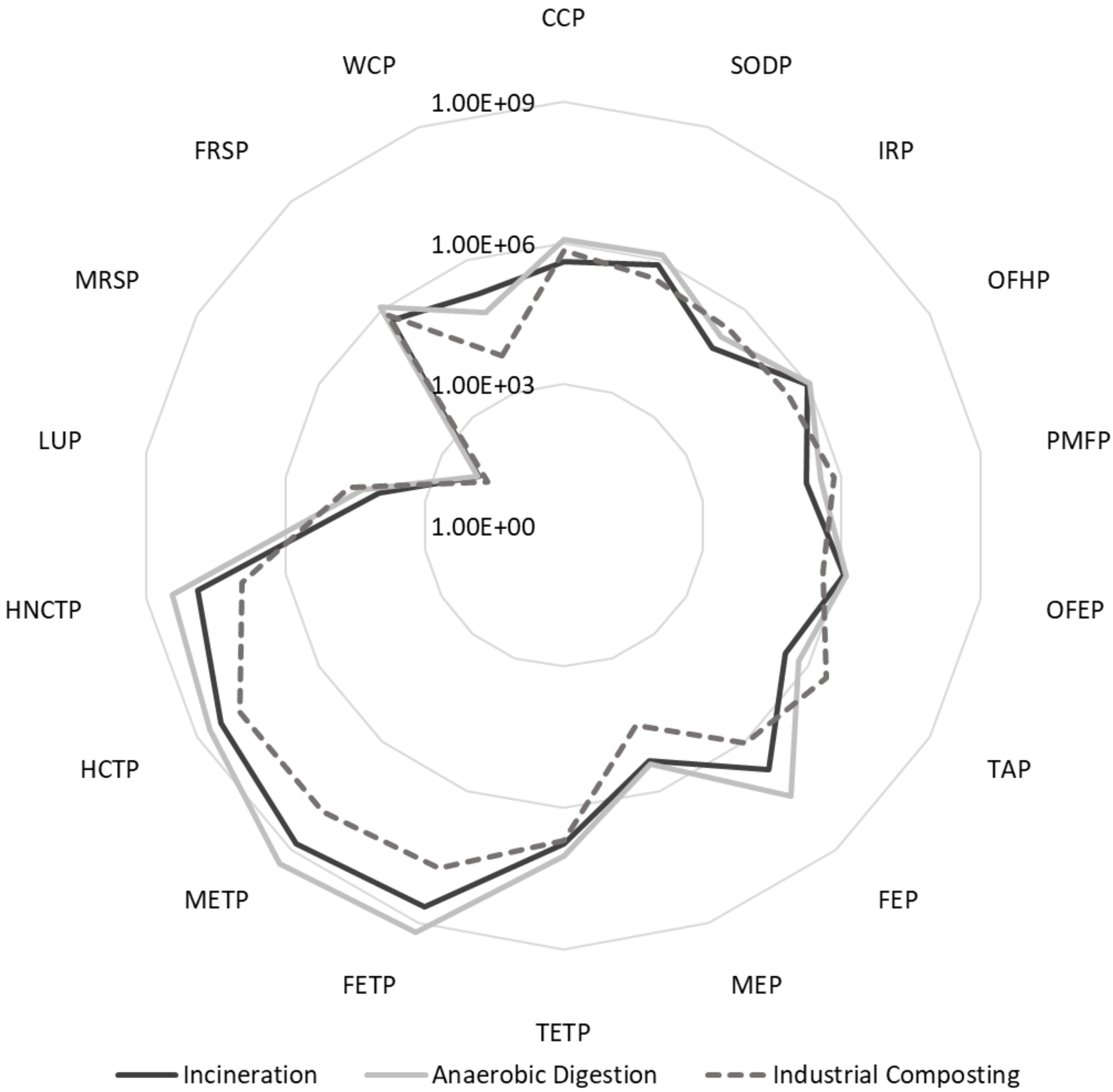

Figure 7 – Recipe Midpoint (H) normalisation for the incineration, anaerobic digestion and industrial composting of the EU28 generated biowaste (W091+W092) (Acronyms according to Table 2).

Table 6 and Figure 8 respectively show characterised and normalised LCA results for the anaerobic digestion and the direct spreading of manure (W093). The two systems show a similar trend related to most and least impacted categories. Figure 8 clearly shows AD as the most impacting system, with a difference with manure spreading, in terms of characterised impacts, from one order of magnitude (IRP, OFHP, TETP, MRSP, FRSP, WCP) to three orders of magnitude (SODP, TAP, MEP, HNCTP).

Table 6 – Recipe Midpoint (H) characterised impacts for the spreading and the digestion of the EU28 generated manure (Acronyms according to Table 2).

Impact category	Unit	Spreading	AD
CCP	kg CO_2 eq	5.0E+07	1.9E+09
SODP	kg CFC11 eq	2.3E+01	2.3E+04
IRP	kBq Co-60 eq	1.5E+06	2.1E+07

OFHP	kg NO_x eq	4.1E+05	5.2E+06
PMFP	kg PM2.5 eq	1.2E+05	1.6E+07
OFEP	kg NO_x eq	4.2E+05	5.3E+06
TAP	kg SO_2 eq	2.4E+05	1.2E+08
FEP	kg P eq	1.2E+04	5.4E+06
MEP	kg N eq	8.1E+02	5.8E+05
TETP	kg 1,4-DCB	1.6E+08	2.4E+09
FETP	kg 1,4-DCB	1.1E+06	5.1E+08
METP	kg 1,4-DCB	1.6E+06	6.7E+08
HCTP	kg 1,4-DCB	2.6E+06	3.4E+08
HNCTP	kg 1,4-DCB	8.5E+07	1.1E+10
LUP	m^2a crop eq	2.2E+06	2.2E+08
MRSP	kg Cu eq	4.9E+05	3.3E+06
FRSP	kg oil eq	1.3E+07	1.6E+08
WCP	m^3	1.9E+05	8.9E+06

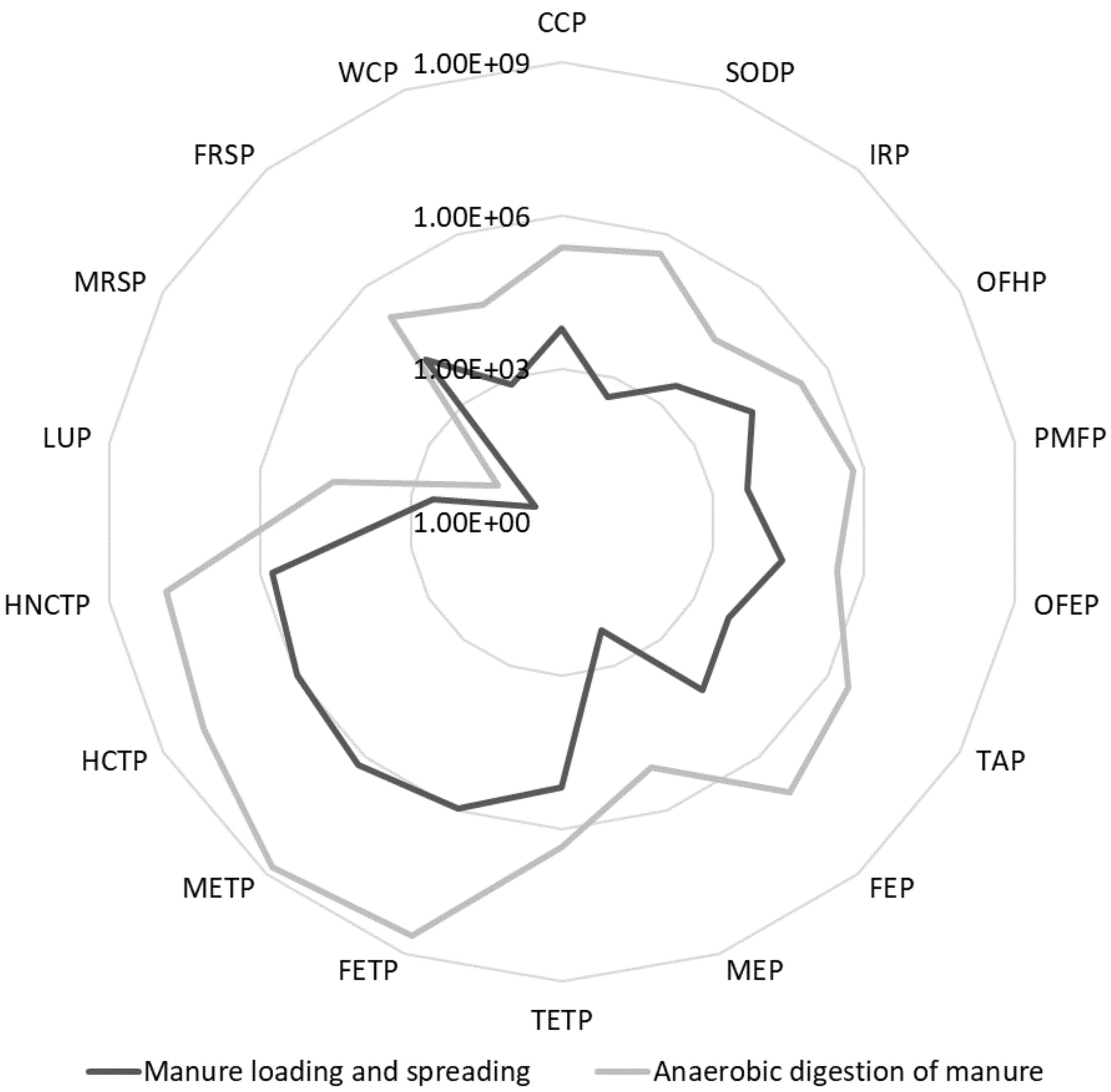

Figure 8 – Recipe Midpoint (H) normalisation for the spreading and the anaerobic digestion of the EU28 generated manure (W093) (Acronyms according to Table 2).

A complementary perspective about the disposal of waste could be achieved by means of EMA, to ascertain the environmental investment and environmental performance linked to disposal of the reported EU28 food-related waste. Figure 9 reports the total emergy U (i.e. total demand of direct and indirect support by biosphere processes) associated to the incineration (Liu et al., 2017), the composting (Liu et al., 2017) and the anaerobic digestion (After Moss et al., 2014) of 2016 EU28 generated W091 + W092. Here the situation is different if compared to LCA results. Figure 9 highlights Incineration as the worst performing system, and AD as the better one, with just 0.1E+21 sej more than IC without L&S.

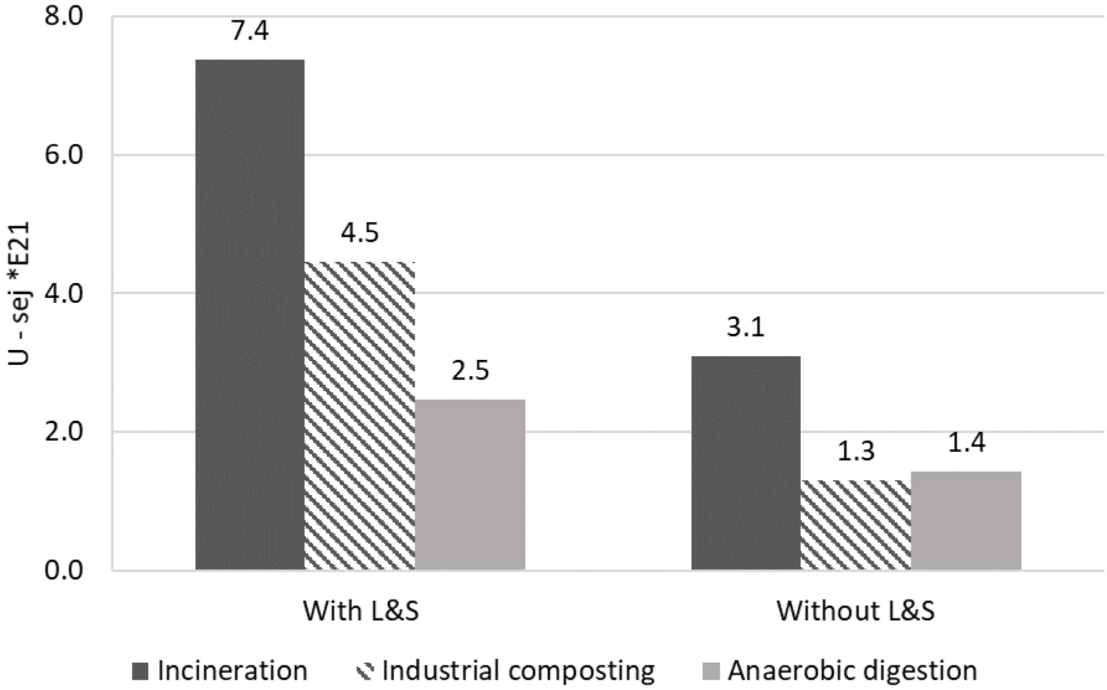

Figure 9 – Total Emergy U with and without L&S related to the incineration, industrial composting and anaerobic digestion of EU28 generated biowaste (W091+W092).

Figure 10 reports the total emergy needed for the anaerobic digestion (After Moss et al., 2014) as well as for the loading and spreading (estimated from ecoinvent database) of EU28 generated W093 in 2016. There is a huge difference in terms of U when including or not including L&S, mainly due to the huge amount of human labor needed in the direct spreading of manure.

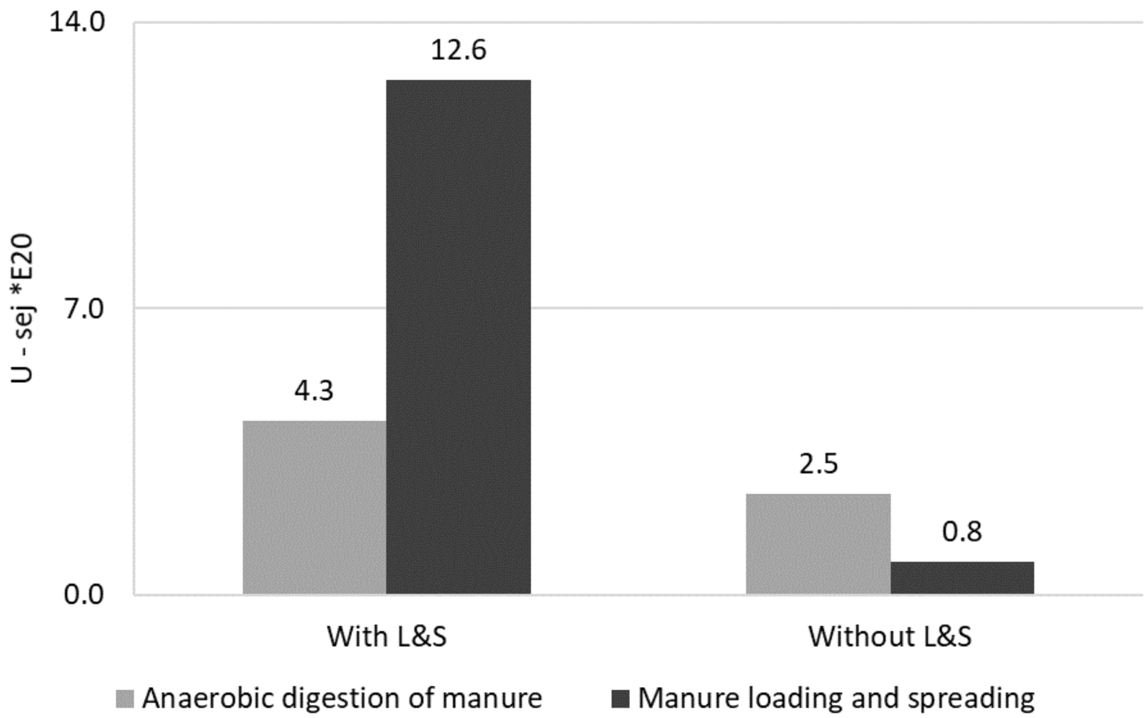

Figure 10 – Total Emergy U with and without L&S related to anaerobic digestion and loading and spreading of EU28 generated manure (W093).

4. Discussion

4.1. Impacts and performance of the recovery of EU28 food-related waste

When considering W091+W092 biowaste, LCA results shown in Figure 7 highlight how the overall impacts for incineration are smaller than those related to the anaerobic digestion, while lower impacts are related to industrial composting. On the other hand, Figure 9 highlights how the total emergy U needed (environmental support from the larger space-time scale of biosphere), considering the same processes, is higher for incineration (7.4E+21 sej with L&S and 3.1E+21 sej without L&S), while U values associated to industrial composting (4.5E+21 sej with L&S and 1.3E+21 sej without L&S) and to anaerobic digestion (2.5E+21 sej with L&S and 1.4E+21 sej without L&S), are significantly lower. Incineration is capable of recovering a certain amount of electricity and/or heat from the combustion of waste, also producing fly ash and bottom ash as by-products. Both of them are potentially dangerous materials, containing heavy metals and toxic substances. Anaerobic digestion results in the production of biogas and digestate, the latter to be employed in agricultural systems. The result of composting is a bio-fertiliser, used for food or non-food crops based on the composition of the starting material.

As for the treatment of W093, Figure 8 show how the LCA impacts of anaerobic digestion of manure are higher than the simple loading and spreading in crop fields. Figure 10 shows that U related to the AD processing of manure is 4.3E+20 sej with L&S and 2.5E+20 sej without L&S, while U for the loading and spreading of manure is 12.6E+20 sej with L&S and 0.8E+20 sej without L&S. These numbers are very representative of the two compared processes. Anaerobic digestion is a kind of conversion system very relying on machinery and external input sources, resulting in a very slight difference when considered with and without contribution of direct and indirect labor, while the spreading of manure on crops is very dependent on direct labor contributions.
The type of assessment presented in this work shows how different solutions can be implemented when dealing with a problem, in this case FW management and recovery in a bioeconomy perspective This is clearly a multiscale and multilevel problem that requires multilevel and multiscale solutions,

that needs to be addressed by a multi-methods assessment. Of course, the presented results are from a general, broader perspective, taking into account average processes from the Ecoinvent database. Another very important aspect is represented by the correct characterisation of the material under consideration and its properties, to be carefully assessed from case to case. Household and restaurants FW, for instance, present different characteristics and different main causes for their generation. Household FW, accounting for more than a half of European food waste generation (Stenmarck et al., 2016), is strictly linked to behaviors and social aspects (among others demographics, attitude, regulations, awareness) (Boulet et al., 2021), and more than 1/3 of it seems to be avoidable (Bernstad Saraiva Schott and Andersson, 2015). The hospitality sector is responsible of enormous amounts of FW (e.g. 920,000 t/yr in UK, 1,700 /day in Beijing), of which globally 56% is coming from restaurants and 28% from hotels (Gandhi et al., 2020). FW in hospitality sector can happen before preparation to improper handling, or after preparation, mainly due to non-edible parts, over-portioning, inability to meet consumer expectancy, use of buffet systems generating large amounts of FW (Papargyropoulou et al., 2016). In these cases, FW composition is very variable depending on location and to eating habits, asking for different approaches and management options, to be planned in advance. Planning and implementation actions of new design and recovery pathways in a bioeconomy perspective cannot neglect to investigate local constraints and features, in order to provide proper benefits. The added value of using a multi-method approach, namely a combination of LCA and EMA in this work, is the holistic understanding from different perspectives. LCA and EMA answer to different questions from different point of views: the first adopting a consumer side, burdens related assessment of activities and processes under human control; the latter providing a donor side set of indicators expanding over the entire biosphere and over time for the generation of materials needed in activities and processes. Addressing only one aspect of the issue (e.g. focusing only on the reduction of CO_2 or the reduced dependence from fossil fuels) may result in the disregarding of other, perhaps more important, perspectives. A multi-dimensional focus allows to operate on different aspects in order to achieve a better performance that can be maximised on minimised on choice. LCA and EMA are capable of highlighting the benefit of circular pathways converting co-products or by-products to be fed back in the same system or becoming useful in outside systems. When broadening the scale, both physically and temporally, the joint use of LCA and EMA can provide very interesting and useful insights than other, mono-dimensional indicators.

5. Opportunities and challenges

LCA and EMA provide an assessment of the environmental burdens and perspectives of the proposed alternatives. What still remains to be discussed is the actual worth of starting new patterns compared to old ones as far as other aspects (social, economic, employment, wellbeing, among others), all related to decreased resource waste and increased recovery of still useful materials. Food waste recovery may, for example positively affect some economic sectors and increase jobs, while pulling down other sectors and activities. Although nobody can provide 100% certainty of achievable benefits, technically feasible and environmentally friendly alternatives need to be put within a more complex context in order to address the multiple demands that arise from present daily life and planning of future. Opportunities (namely, achievable benefits) and challenges (unknown variables to be addressed and solved) can be evaluated from different points of views and perspectives. The simultaneous consideration of different dimensions may be very helpful in the general understanding of the matter, i.e. bioeconomy and food waste, in order to recognize benefits and barriers. Unfortunately, the presented literature review did not show significant focus on such crucial complexity, which calls for increased efforts towards broadening and deepening the view over actual opportunities and viable challenges.

As a starting point, Table 7 summarizes the opportunities and challenges addressed by the 9 “Review” articles. As highlighted, a strong connection between academia and policy-making is much needed, clearly defining the actions and strategies to tackle FW issues in a way capable of addressing also environmental and financial constraints. The vast majority of the reviewed processes are still at laboratory scale, calling for major efforts to convert them to industrial scale.

Table 7 – Opportunities and Challenges addressed by Review items.

Item	Opportunities	Challenges
A	Anaerobic digestion (AD) converts waste in energy and simultaneously produces a digestate used as bio-fertiliser. AD is an effective kind of treatment to avoid harmful impacts on human health and environment.	Technical-operational, economic and regulatory challenges have to be mutually addressed by decision-makers, researchers and end users. Resources availability, financial issues and institutional competences are crucial aspects for the long-term feasibility.
B	Food recovery actions can be addresses as strategies for the restoration of a potentially lost value, addressing environmental, economic and social aspects.	The exact fraction food that could be redistributed is hard to estimate.
C	Carbon-rich waste conversion to polyhydroxyalkanoate (PHA) products offers new opportunities to reduce issues related to waste disposal, avoiding industry generated environmental impacts and preserving food resources.	Different branches of scientific and academic areas should cooperate together with industry to implement at industrial level techniques still at laboratory level.
D	The efficiency within food supply chain can gain benefits from microbial protein and organic fertilisers.	Technological applications for the recovery of added value components from waste streams need to be broadly implemented.
E	The initial highly expensive investments for the implementation of biorefineries could be balanced by the minimal price of food waste, avoiding burdens and disposal costs.	Most of the presented techniques are only at the lab scale and only a few have been carried out at pilot scale.
F	Economic benefits could be achieved by using inexpensive biomass as FW.	FW biorefineries are not yet implemented at industrial scale, making economic assessments (including difficulties and costs related to collection and transportation operations) impossible.
G	Bioconversion of FW to energy is economically viable. Additional improvements can result from further research.	Preliminary feasibility studies must include collection and transportation costs.
H	The reduction of the demand of fossil phosphate could lower burdens and improve phosphate security in the future	P recycling must address problems related to recovery efficiency, hygiene and contaminating substances

R	Bio-plastics, fuels and added value components can be generated from the conversion of FW.	Conversion strategies and information campaigns must be modeled according to the specific locations.

In addition to the features summarised in Table 7, an extensive analysis of opportunities and challenges has been performed to recognize where, within FW management, favorable circumstances can be exploited in a bioeconomy perspective and where more efforts are needed to overcome possible issues. In this work, technological, economic and cultural aspects, identified based on the assessed scientific works, are considered: technological refers to, among others, the benefits and barriers due to technology involved, design and technical skills; economic including matters regarding cost/benefits, viability and prices; cultural mainly regarding to stakeholders acceptance/denial, regulations and behaviors. In the next section, each aspect is addressed, trying to summarize the outcome of the review papers in Table 7 and the needed research and actions. An important outcome of this section is highlighting the consensus reached by different authors on the need to address a set of issues in order for CE to be a viable transitional framework.

5.1. Opportunities

5.1.1 Technological Opportunities

FW is recognised as a main point to address the global waste challenge. In the first place, FW could be reduced by a better management throughout the whole supply chain (Facchini et al., 2018), in addition to sustainable food management (Girotto et al., 2015) and food redistribution (Kirby et al., 2017), acknowledged as viable methods to reduce FW (Facchini et al., 2018; Girotto et al., 2015; Kirby et al., 2017). Performances associated with recovery operations are based on geographical characteristics and on the availability of the different types of feedstocks, defining an optimal service area to overcome waste disposal problems (Ohnishi et al., 2018), avoiding industrial pollution and protecting food resources, since the feasibility of these kind of operations is strongly distance related (Tanguy et al., 2017). Thus, new research can be developed and adapted in order to design and control new closed-loop supply chains (Sgarbossa and Russo, 2017). FW is a valuable source of renewable energy for developing countries (Ohnishi et al., 2018), in substitution of common, more impacting ones (i.e. coal, firewood, crop residues, etc.) (Safar et al., 2016), at the same time disposing waste in a more environmentally feasible way (Uçkun Kiran et al., 2014b). Practices like AD recovery (Breitenmoser et al., 2019) significantly reduce CO_2 emissions (Prasad, 2016), taking into consideration also the fuel replacement within the power grid (Slorach et al., 2019; Verstraete et al., 2016). FW is also beneficial to polymers production (Uçkun Kiran et al., 2015), from bacteria processing carbon-rich material (Tamis et al., 2015), and as potential feedstock for the production of value added chemicals and for cosmeceutical valorisation (Piccolella et al., 2019). FW could be crucial in the perspective of phosphorus recovery (Carraresi et al., 2018), avoiding rock mining for the phosphorus used in agri-food, medical, construction and industrial systems (Reijnders, 2014; Verstraete et al., 2016).

5.1.2 Economic Opportunities

10% of annual FW production is food surplus still suitable for consumption (Facchini et al., 2018). Food redistribution and reuse initiatives can be seen as a value recovery strategy (Tamis et al., 2015), side-products of FW processing can be fed back to the economy, offering additional economic benefits (i.e. digestate, side product of biogas production in AD systems, used as fertiliser and soil enhancer) (Verstraete et al., 2016). Processes can also benefits from the exchange of side streams of carbon-rich materials (i.e. from processing of bio-diesel, olive oil, cheese, sugar, etc.) (Carraresi et al., 2018) assisting the labor market situation in countries with economic problems (Koller et al., 2017). Various processes needing carbon rich materials as feedstock could reduce their expenses by using FW (Prasad, 2016). Energy production from FW follows this outlook, avoiding also costs for disposal (Sgarbossa and Russo, 2017). In a biorefinery perspective, the high initial cost of developing a biorefinery would be balanced by the inexpensive cost of the FW feedstock (Uçkun Kiran et al., 2015).

5.1.3 Cultural Opportunities

FW recovery practices may be capable in reducing energy scarcity and reduce wood burning in the countryside of low income nations (Breitenmoser et al., 2019). Recovery processes recognize an added value in materials, previously considered of low or no value (Piccolella et al., 2019), showing the same potential as raw materials (Sgarbossa and Russo, 2017). Efficient supply chain management and consumers behavior are the most important hot-spots to be considered in order to implement food redistribution activities, suitable surplus food can be redistributed, through appropriate organisations, charities, etc., to underprivileged people (Facchini et al., 2018). Recovery of phosphorus from FW could be of importance in a geopolitical framework, since the vast majority of phosphorus reservoirs are located in politically unstable countries (Reijnders, 2014).

5.2. Challenges

5.2.1 Technological Challenges

In a bioeconomy perspective, the importance of recovery technology determining product quality is highlighted, together with hygienic challenges (Breitenmoser et al., 2019), very important when dealing with specific materials like FW or faecally contaminated waters (Verstraete et al., 2016). Different factors have to be put into account when planning FW recovery actions (Ohnishi et al., 2018), like large amounts of water needed by certain AD systems (Wang et al., 2017). Installation of factories need to consider the source of feedstock (Breitenmoser et al., 2019), source segregation, theoretical yield of products, like the yield of AD biogas (Girotto et al., 2015), depending on the contents of organic constituents in biomass (Safar et al., 2016). Food losses occur at all levels of food supply chain (Carraresi et al., 2018), mainly due to technical and infrastructural reasons (Facchini et al., 2018); technical limitations, spillage and contamination eventually occurring at processing level also contribute to FW and losses (Sgarbossa and Russo, 2017). Almost all reviewed items agree on the need of further assessments and broad implementation of solutions to effectively improve resource efficient usage and reduce waste (Piccolella et al., 2019). Most of the assessed pathways are at laboratory level (Ghosh et al., 2019), but they seem to have a good potential scalability, after further analysis and scale up studies (Uçkun Kiran et al., 2015, 2014a). Future studies need to increment the attention about local characteristics (Carraresi et al., 2018), other technological options, and time series analysis (Ohnishi et al., 2018). Local characteristics strongly influence waste quality, separation policy, and collection costs (Reijnders, 2014). The feasible recovery of resources from FW must understand how to implement different configurations of food supply chain (Carraresi et al., 2018), to reduce the output flow of FW and introduce new relations between the nodes currently in the supply chain (Eriksson et al., 2017). Further, energy self-sufficiency in food supply chain could help in reducing impacts of food production/processing (Sgarbossa and Russo, 2017). Better data is needed for the assessment of potentially redistributable food (Facchini et al., 2018). Recovery processes need to be assessed in order to understand the impacts of large scale integration starting from laboratory scale, so to avoid potential environmentally dangerous pathways (Ohnishi et al., 2018). Feedstock should meet the demand (Hu et al., 2018), and, in certain cases, high carbon concentrations (Koller et al., 2017).

5.2.2 Economic Challenges

Often, the use of FW as feedstock represent an opportunity to reduce industry and disposal cost (Carraresi et al., 2018), at the same time producing commodities and/or energy (Ohnishi et al., 2018), only if proper governmental incentives are implemented, reducing the high initial costs (Uçkun Kiran et al., 2015). Another factor affecting the economic feasibility of FW recovery sector is the low price of fossil fuels, enhancing the production from raw materials: in order to really implement FW recovery, products should be able to compete in a market framework (Verstraete et al., 2016). Moreover, extensive economic analyses of biorefineries are still missing, due to the absence of real biorefineries implementations (Uçkun Kiran et al., 2014a). Costs are also very important when producing electric energy, in order to assess the total benefits, and when considering collection and transportation of FW materials (Ohnishi et al., 2018). In cases like the recovery of phosphorus (Carraresi et al., 2018), alternative pathways are still more expensive than the traditional production from raw materials (Reijnders, 2014). Economic related matters are also important with regards to food losses at agricultural level, in particular when occurring in developing countries due to economic constraints (Facchini et al., 2018).

5.2.3 Cultural Challenges

In order to reduce the amount of FW produced, the very first step is the reduction of the unwanted food surplus (Facchini et al., 2018), preventing over-production and over-supply (Sgarbossa and Russo, 2017). Cultural/regulatory matters are addressed as the primary cause, in developed countries, of food wastage at industry and consumers level (Facchini et al., 2018), related to changing lifestyles, dietary patterns, and aesthetic demands (Piccolella et al., 2019). Food wastage can occur also because of problematic relationships between producers and retailers (Eriksson et al., 2017) and because of food standards, contractual conditions and wrong product forecasting (Girotto et al., 2015).

Also, the household level plays a crucial role in FW generation (Slorach et al., 2019). In this context, FW mainly occurs due to bad management (Breitenmoser et al., 2019), in varying forms from whole materials to fractions or mixtures (Uçkun Kiran et al., 2014a). Different definitions of FW cause a difficult monitoring and present regulation may be contrasting with food redistribution in order to preserve human health (Girotto et al., 2015). Feedstock chosen for the different recovery practices should, anyway, not interfere with food and feed productions (Breitenmoser et al., 2019). The logistics for different systems is still challenging (Ohnishi et al., 2018), and losses may occur throughout the feedstock supply chain (Sgarbossa and Russo, 2017). Also, previous literature has highlighted how the value of recovered products is strictly depending on its acceptance by stakeholders (Carraresi et al., 2018): products recovered starting from waste streams should marketed and presented in a way that the association with waste is removed (Verstraete et al., 2016). Further, policies for recovery of specific substances (e.g. phosphorus) are held back by the uncertainty in forecasting current reserves (Facchini et al., 2018). Often recovery facilities and know how are located in developed countries, while the feedstock markets are in developing countries (Reijnders, 2014).

5.3. FW recovery in a bioeconomy perspective

As made clear by the FW conversion database and from Figures 5 and 6, it seems that the main focus within FW research is the recovery of different types of FW or mixed FW after consumption, and of waste from the processing of food elements. A minor interest seems to be addressed towards agricultural/livestock preliminary phases for food production, probably because in developed countries, where scientific research is more developed, food losses are believed to happen the most within retail and consumption stages (FAO, 2019). It is also clear that almost the totality of the conversion pathways investigated are of biological nature, for the recovery of chemicals and the generation of energy and fuels, reflecting how fossil fuels are still the main drivers of the processes of human societies and are still acknowledged by researcher as responsible of the largest part of environmental impacts and resource depletion (Ritchie and Roser, 2017). This reflects the need and the will, whether it being driven by ecological awareness or by the opportunity of new 'green' markets, of some modern societies to reduce their dependence on resource depletion and to implement operations for achieving more environmentally feasible materials, energy and fuels.

In a bioeconomy perspective, the promotion of pathways that encourage the recovery of materials still presenting an added value that otherwise would be lost is a priority. As such, biological conversion processes (such as composting and anaerobic digestion) of waste biomass have been proposed for a long time due to their nature-alike perpetual cycling (and related avoided burden). Unlike the products of thermal processes (that do not return nutrients and organic matter to soils), biobased processes close the biological cycle of nutrients and organic matter through a biological route. Furthermore, biobased processes involve a biological treatment instead of very impacting and resource-demanding thermal or physical operations. This kind of framework may provide materials and energy; as such, the large-scale implementation of these schemes might result in more sustainable production pathways. Also, the idea of "closing the loop", so much advocated within CE theoretical approach, should be really taken in consideration when dealing with FW issue. A very effective way of doing this could be avoiding fertilising nutrients to be dispersed in the environment and become pollutants (Scholz, 2017). Valorising the on-site use of biomass and FW, also from an economic and regulatory perspective, could avoid, or partially avoid, the chemical production of mineral fertilisers towards a more feasible bio-based one, at the same time reducing the amount of waste to be transported, managed and disposed (Chojnacka et al., 2020). A large number of processes and framework for giving back to the earth the nutrient from FW as fertilising materials already exist; it a revision of fertiliser regulations should be promoted, in order to implement frameworks for the promotion of recycled fertilisers (Hukari et al., 2016).
Following the data obtained by literature review showing the most common FW conversion processes, LCA and EMA analyses of selected, broadly available, biological conversion processes have been performed, reflecting how this category of treatments seems to be the most investigated one for FW transformation, resulting in bio-based materials and energy useful in avoiding the common fossil-based extraction and processing of resources.

6. Conclusions

This work reviewed recent scientific production about food waste recovery pathways in a bioeconomy perspective. Within the so actively announced transition to a Circular Economy framework worldwide, the reduction of waste is the main aim both from a business and scientific point of view. Food waste is of particular importance, because it engages social and cultural features, in addition to technological and economic ones. The reduction of food losses and the recovery of lost parts through food supply chain could provide food to currently starving communities. FW is a carbon rich waste stream that can be used for the recovery of a wide range of energy and materials, from fuels/energy to chemical components to bio-plastics, among others. The so generated commodities show different benefits like the reduced environmental impacts, deriving from the avoided disposal and the avoided extraction of natural resources, and the reduced economic cost of FW as a feedstock. However, FW exploitation is also affected by different constraints, the more relevant one being that there's no one fits all solution. Recovery pathways must be carefully designed and planned, based on local characteristics. Care should be devoted to the fact that such pathways should not interfere with food supply, also regarding geopolitical aspects, and keeping in mind that the overall main goal is the reduction of food losses and wastage. Resulting materials and energies should be competitively priced on the global market in order to be fully implemented. Another major problem is related to the so called Jevons Paradox: improving the efficiency of a sector, meaning in this case a better use of resources through recovery to reduce the exploitation of raw materials, could result in an even larger increase of the rate of consumption of the specific resource of concern. For this reason, already available tools and methods, like the presented LCA and EMA frameworks, should be actively implanted within decision making, and policy makers have to carefully acknowledge and thoroughly coordinate the guidelines suggested by different categories of stakeholders, including local communities and scientific experts.

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