FOOD WASTE DIGESTION

Anaerobic Digestion of Food Waste for a Circular Economy

IEA Bioenergy Task 37

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Executive summary

There is increasing awareness of the quantities of food that are lost every year across the globe; while the quality of available data varies, estimates suggest the total is around 1.3 billion tonnes. These losses occur at all stages of production, from pre-harvest on the farm through to post-harvest losses during processing, distribution, retailing and consumption. This report considers only those harvested food materials that are never consumed, but ultimately find their way into the waste stream.

By far the largest proportion of this material is generated at the point of consumption, in the home or in cafeterias, canteens and restaurants. Some of this waste is avoidable, but a proportion is unavoidable as it consists of parts of the product that are not edible (such as shells, bones and peels). Better understanding of the origins and fates of unconsumed food has led to the development of food waste hierarchies where prevention is the first objective, and only material that is unfit for human or animal consumption becomes waste. Where food wastes are generated, however, the first option to consider is anaerobic digestion or industrial use in biorefineries as these offer the greatest opportunities for both resource and energy recovery.

The proportion of food entering the waste stream reflects socio-economic and other factors. It is still only poorly quantified, but where good quality data exist anything from 25 to 65 % of the municipal waste stream may be comprised of food materials, depending on geographical region. In Europe this equates to approximately 173 kg per person per year. Although the appearance of food waste may differ depending on its origin, due to local food preferences and habits, in biochemical terms it is generally very similar. It shows roughly the same distribution of proteins, fats, carbohydrates and essential elements, is easily biodegradable and has a high biochemical methane potential (BMP). Despite these apparently ideal properties, the first food waste digestion systems showed signs of severe inhibition after some months of operation. This was caused by the build-up of ammonia, which reached concentrations that are inhibitory to some groups of methane-producing microorganisms. Improvements in our understanding of the complex interactions between acid-producing bacteria and methanogens made it possible to identify a solution; this was to promote alternative metabolic pathways to methane production that are mediated by more ammonia-tolerant species. This process requires some trace elements that are normally only present in low concentrations in human food and must therefore be supplemented for stable food waste digestion.

Food waste digestion is now commonly undertaken commercially at a large scale. It is most widespread in the UK, where there are currently 94 digesters producing over 220 MW_e of power from food processing residues, supermarket wastes and kerbside collected source-separated domestic food waste. These processes are efficient, with as much as 85% of the degradable material being turned into biogas, and a similar percentage conversion of the calorific value of the food waste into a usable energy product. A second benefit of the digestion process is that it allows the return of plant nutrients to farms, since the digestate can be applied as a nitrogen-rich fertiliser product without risk to animal health or the environment when the production process is properly controlled and regulated. Although the main policy aim should be to minimise avoidable food waste, the unavoidable fraction can now be successfully recovered through the anaerobic digestion process as a single feedstock or can be used in co-digestion schemes to maximise the overall potential for recovery of energy and nutrients from manures and wastewater bio-solids. Food waste digestion has only emerged relatively recently at a commercial scale, but case histories for different countries show there is now global interest in taking this technology forward. This report outlines case studies from eleven countries, namely; Australia, Canada, China, Indonesia, Japan, Malaysia, Singapore, South Korea, Thailand, the United Kingdom and Vietnam.

1. Food Waste as a Global Challenge

1.1 Definition of Food Waste

There is no universally accepted definition of 'food waste', although it is now becoming widely accepted that any definition should include food that is lost in the primary production phase (including farming, fishing and aquaculture). This includes food crops that are: not harvested and ploughed in; harvested and exported not for food use but to another market (e.g. sent for composting, digestion or ethanol production); harvested and then disposed of (e.g. incinerated, landfilled, sent to sewer or disposed of to sea). Food waste also includes all material that enters the food supply chain but is not consumed, i.e. both edible and inedible materials which may be generated in food processing, marketing and preparation, and also post-preparation food that is not eaten. These categories are now reflected in the definition for food loss and waste (FLW) recommended by the European parliament to the Commission and Member States. This states: *'food waste means food intended for human consumption, either in edible or inedible status, removed from the production or supply chain to be discarded, including at primary production, processing, manufacturing, transportation, storage, retail and consumer levels, with the exception of primary production losses'* (EU Parliament, 2017). There is still, however, a lack of consensus on terminology and definitions, and a critical appraisal of these is given in a JRC technical report (2017). It is therefore unsurprising that estimates of the amount of FLW vary considerably depending both on how it is defined, and on the methodology used to quantify it.

In 2010 Parfitt et al. (2010) commented that there was a lack of information on food waste composition worldwide. Based on a more recent publication by Xue et al. (2017), this statement still stands: from the 202 publications examined, which reported food losses and food waste data for 84 countries and 52 individual years from 1933 to 2014, the authors found that most existing studies were conducted in a small number of industrialised countries mainly in Europe and North America. Over half of the estimates were based only on secondary data, indicating high levels of uncertainty in the existing global FLW database. This led to the conclusion that more consistent, in-depth studies based on primary data, especially for emerging economies, were urgently needed to better inform policy-making on reduction of FLW and mitigation of its environmental

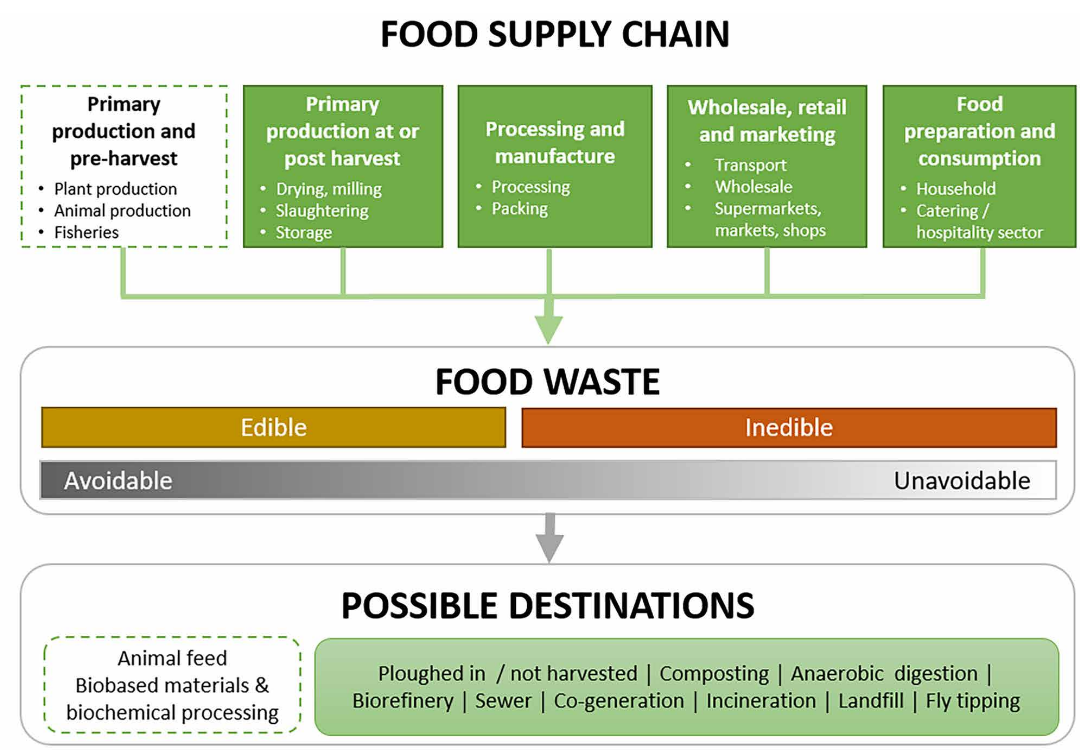

Figure 1: Framework defining the food supply chain and food waste destinations (based on JRC, 2017)

impacts. To meet the requirement for better and more uniform data, a multi-stakeholder partnership (WRI, FAO, WRAP, UNEP, and WDCSD) developed the 'Food Loss and Waste Accounting and Reporting Standard' (FLW Standard), which was published in June 2016 (Hanson et al., 2016). The standard is intended to enable countries, cities, companies and other entities to develop consistent inventories of FLW generated and its destination (Figure 1) (JRC, 2017).

The adopted European definition for food waste used above is wider than the scope of this report, which excludes food losses on farms. This report is primarily concerned with the post-farm food chain. This is the largest fraction, which represents around 90% of FLW and includes: waste from food production, by-products or co-products; food in the food supply chain that no longer has value through spoilage or sell-by date expiry; trimmings, peelings and scraps arising from the making of meals in food outlets and at home; uneaten leftovers; and spoiled food as a result of over-buying.

1.2 Food Waste Quantities

Globally the Food and Agriculture Organisation of the United Nations (FAO) has estimated that one-third of food produced for human consumption is lost or wasted, equivalent to about 1.3 billion tonnes per year. Although this number is widely quoted, there is insufficient data from many countries to allow accurate quantification.

The proportion of municipal solid waste (MSW) that is made up of food waste varies quite widely: according to the Intergovernmental Panel on Climate Change (IPCC) regional classification, the range is from about 23% in southern Africa and northern Europe, to 67.5% in Oceania excluding Australia and New Zealand (IPCC, 2006). The original data used is from around 2000, however, and is calculated from national composition data which as already noted is often incomplete or unreliable.

Even in Europe, where most work has been carried out, there is still uncertainty about the accuracy of data reported by many of the member states (Figure 2). The EU

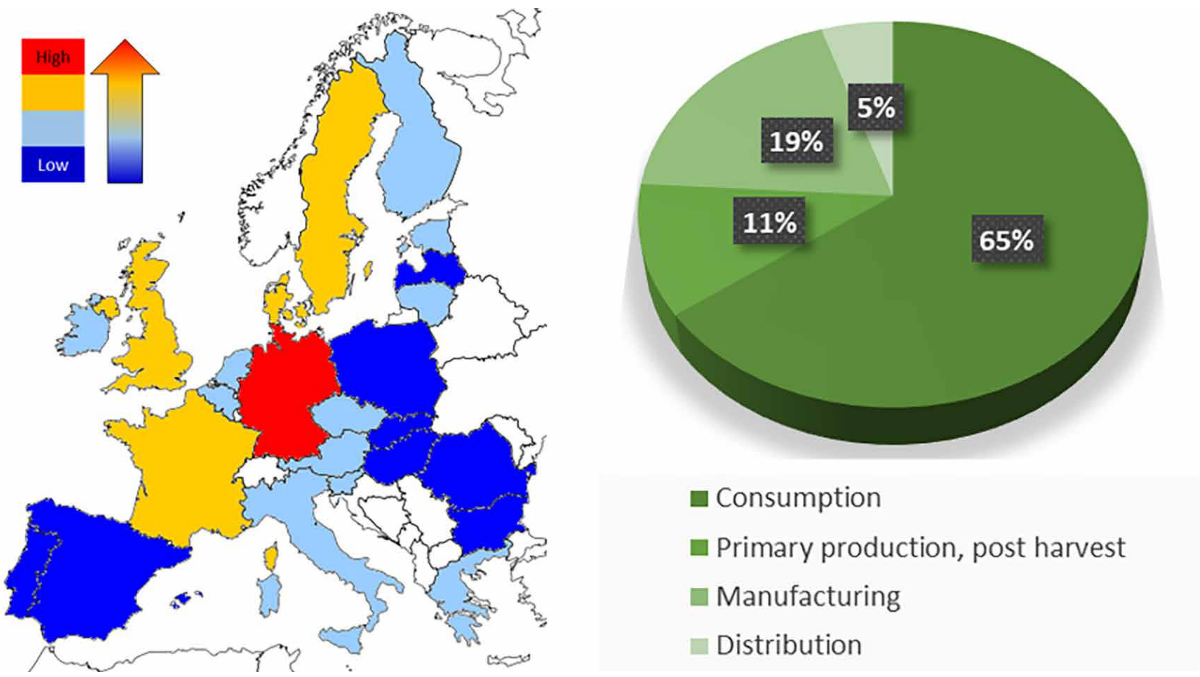

Figure 2: Left – Quality of available data on Food Loss and Waste (FLW) in EU (based on FUSIONS, 2016a). Right – Proportion of FLW in different categories (based on JRC, 2017)

FUSIONS project (Food Use for Social Innovation by Optimising Waste Prevention Strategies, www.eu-fusions.org) which ran between 2012-2016 built upon earlier studies. The outputs of this project together with the JRC report (2017) provide the best interpretation of currently available data across Europe, with food waste generation estimated at 173 kg person^{-1} year^{-1}.

1.3 Food Waste Hierarchy

By far the largest proportion of food waste is from household consumption. It is now well recognised that household food waste components can be categorised as unavoidable or avoidable, with an additional category of possibly or partly avoidable being used in some cases. The first category of unavoidable or inedible food waste generally consists of residues and by-products from food preparation, such as inedible peels or seeds. Avoidable food waste consists either of: unused food, often discarded due to excess purchasing and/or the passing of a 'best before' date; or of part-consumed items such as left-overs from meals. The possibly or partly avoidable category has been defined as "food and drink that some people eat and others do not (e.g. bread crusts), or that can be eaten when a food is prepared in one way but not in another (e.g. potato skins)" (WRAP, 2009).

Interest in food waste prevention is reflected in the growing number of studies since 2000, which highlight the economic significance of wastage. This is providing an impetus for change, which is reflected in the promotion of food waste hierarchies by a number of countries in Europe, North America and worldwide. Considerable effort is now going into the identification and quantification of food waste in relation to these emerging hierarchies, with prevention and alternative use as animal feed as the preferred options.

Figure 3 shows schematics from the UK and USA; other examples include Australia (Australian Government, 2017), Ontario (Sustain Ontario, 2016) Hong Kong (Environment Bureau, 2014). While there is a degree of consensus between the many available versions, there are also differences, for example in distinguishing between aerobic composting and anaerobic digestion (AD) at different scales of operation, or in classifying AD as either a resource recovery technology or a less preferred energy recovery option (Zero Waste Europe, 2016; Australian Government, 2017). Where there are significant quantities of unavoidable and inedible food wastes, then anaerobic digestion (AD), which offers both material and energy recovery, should generally be the first preference for this material within the hierarchy.

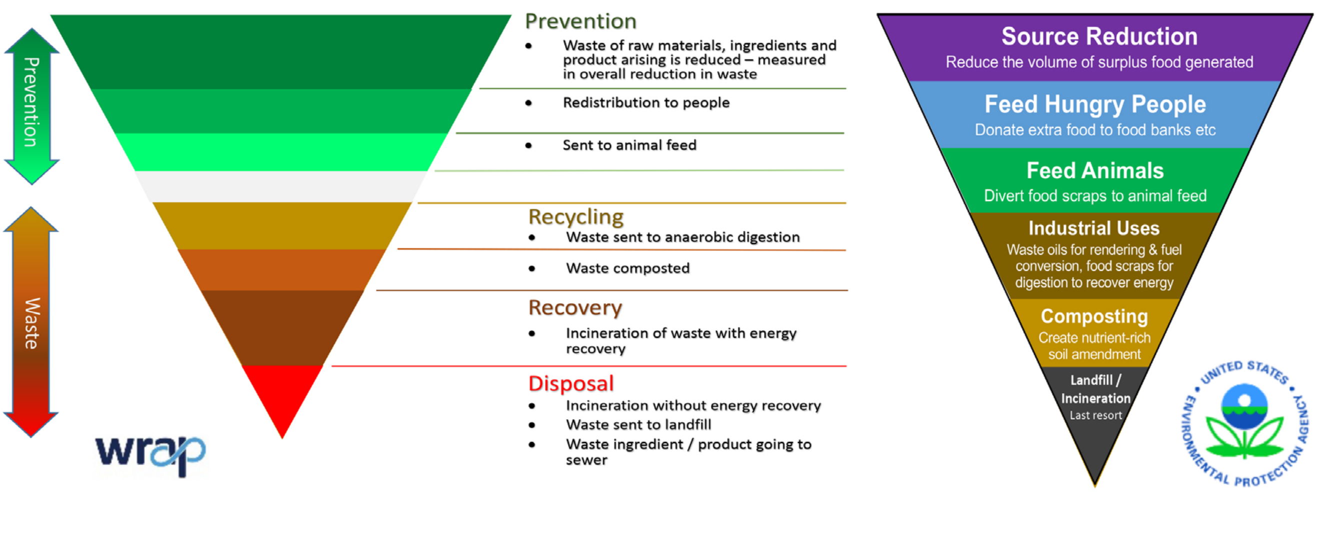

Figure 3: Examples of Food Waste Hierarchy. Left – based on WRAP (2017), Right – based on US EPA (ND)

2. Source Separated Municipal Food Waste

2.1 Economic Drivers & Sustainability of Collection Systems

Major studies on food waste collection schemes have been carried out by the UK's Waste and Resources Action Programme (WRAP) and on behalf of the Australian Government, in both cases leading to best practice recommendations (Hyder Consulting, 2012; WRAP, 2016). IEA Bioenergy Task 37 has also produced a Technical Brochure on source separation of the digestible fraction of municipal waste as a feedstock for AD, which covers collection systems, set-up and economics and includes case studies of successful schemes in Korea, Sweden and the UK (Al Seadi et al., 2013).

The FP7 VALORGAS project reviewed a number of food waste collection schemes in Europe, including for Flintshire (UK), Malmö (Sweden), Bilund (Denmark), Landshut (Germany), Forssa (Finland), Vicenza (Italy) and Lisbon (Portugal). These locations were chosen to cover a range of collection types, and to reflect the broad issues encountered in the schemes investigated. The work considered fuel consumption and other factors as a basis for assessing the energy footprint of the collection schemes and looked at development of modelling and LCA tools specifically for assessment of waste collection systems (Gredmaier et al., 2013). A web-based survey of source-separated food waste collection schemes in 27 European countries was also conducted, assessing factors that might influence yield, capture rates and efficiency (Heaven et al., 2012). It was concluded that food waste only (FW-only) collection schemes were not yet widespread in Europe, but their numbers were growing rapidly, especially in countries that had only recently introduced source-separated collection of other recyclables. Schemes to collect household biowastes (composed of food waste, garden wastes and some types of paper and card) were more common. In many cases, however, the operating conditions meant that these were effectively the same as FW-only schemes; this was due to the definition of acceptable materials, or to the fact that the schemes served urban areas where the majority of inhabitants lived in apartments without gardens and thus did not generate garden wastes. The study found widespread inconsistencies between schemes with respect to which materials were accepted, however, and suggested that this may contribute to confusion and poor performance on the part of participants.

From the viewpoint of renewable energy production through anaerobic digestion of food waste, with beneficial use of the digestate, the most important features of the collection system appear to be what it accepts, and what type of container is used for collection (large or small). FW-only collections using small containers tend to have a very low degree of contamination, which can minimise pre- and post-processing requirements and their associated energy demands. Collection systems that minimise contamination may allow even a simple AD plant to produce a high quality digestate output (VALORGAS. 2012a).

Extensive work has also been carried out on what are often described as human factors in the performance of food waste collection schemes. A study of a collection scheme in high-density urban housing in Shanghai identified a number of key factors for success, including a 'personal' approach based on volunteers (Xu et al., 2016a). This contrasted with information-only campaigns, which have shown relatively limited success (Bernstad et al., 2013; Dai et al., 2016). One key requirement for a successful study is to combine qualitative information on participants' opinions with quantitative data from analysis of the waste collection itself. This approach allows comparison of users' perceptions with the actual performance of a scheme. Without this, there are potential issues of data reliability as self-reported behaviour and statements of preference are often influenced by a desire to 'say the right thing' or create favourable impressions (Xu et al., 2016; Bernstad et al., 2013).

There has been continuing debate about disposal of household food wastes in sink grinders for discharge to the sewer system and processing at wastewater treatment plants. A UK-based study by Iacouvidou et al. (2012) suggested there could be benefits if this approach is adopted at a large enough scale, but it could lead to increased costs if uptake is limited. A study by Bernstad and la Cour Jansen (2012) compared four different systems based on collection of source-separated food waste in paper bags (with and without pre-drying at 18-25 °C in a drying facility before collection), vacuum transport from the kitchen sink to a central grinder before collection by tanker, and individual sink grinders with tanker collection of solids and disposal of supernatant to sewer. Vacuum systems and collection of pre-dried waste appeared to have several advantages from the viewpoint of life cycle assessment but have not been trialled at large scale.

Work has also been carried out on modelling of the energy footprint of food waste collection systems, both alone and as an integrated part of the municipal waste collection. Edwards et al. (2016) developed an energy and time model for kerbside waste collection, which was verified and used to model a set of scenarios for introduction of source-separated food waste collections. The results suggested an increase of up to 60% in fuel consumption depending on the collection system adopted. Chu et al. (2015) developed the WasteCAT scoping tool for assessment of energy and resource use in source separated collection of municipal waste as part of the FP7 VALORGAS project: the model is freely available for download from http://www.bioenergy.soton.ac.uk/WasteCAT_tool.htm.

2.2 Characteristics & Composition

Food waste can differ significantly in visual appearance, even for materials collected from similar sources in close proximity. Taking source separated domestic food wastes as an example, households may have differing age distributions, family sizes and cooking and eating habits, so it is not surprising their food waste differs. Coupling these variations with possible differences in attitudes towards how their wastes are managed and in purchasing habits, it is quite likely that even within a single street or a apartment block the composition and weight of waste collected from each household will be very different. Visual differences in food waste are even more apparent as geographical separa-

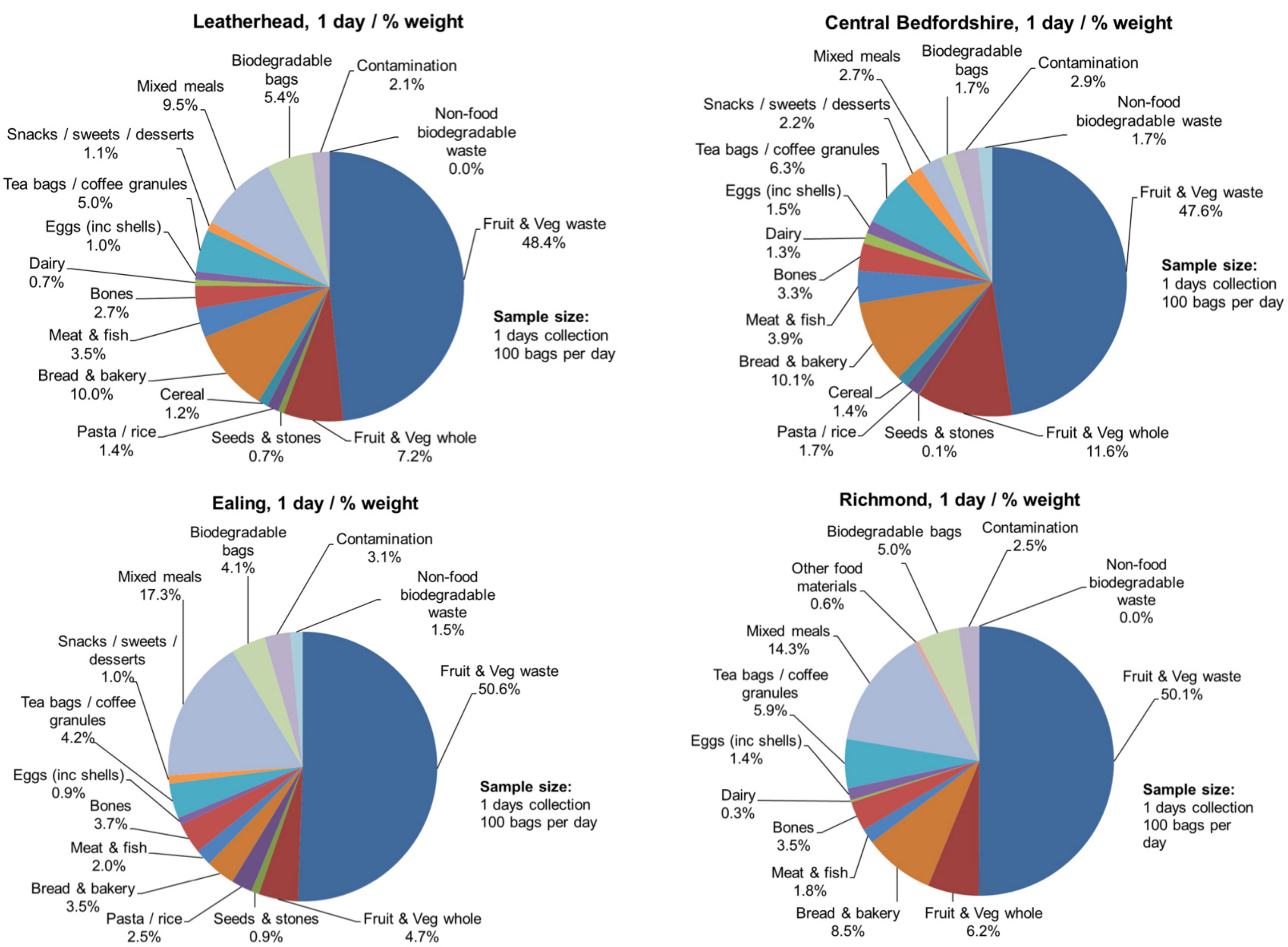

Figure 4: Food waste composition from four UK collection schemes based on a one-day sample (VALORGAS, 2011)

tion increases, and are strongly influenced by differences in cuisine, local availability of produce, and economic wealth of the region. The latter also influences the quantity of waste produced, with industrialised countries typically generating more waste per capita than those in economic development.

Collection of reliable data for a geographical region therefore requires a well-designed sampling programme to ensure that a representative part of the population is included, that samples are taken over a period of time to reflect any seasonal differences, and that the categorisation of components used is functional, easily transferable and helpful in developing a food waste management strategy. If the FLW Standard (Hanson et al., 2016) is widely adopted, future data should be more consistent and useful. Data collected and presented prior to the development of this standard is still valuable, however, and forms the basis for much of the work currently presented.

Compositional analysis

Food waste characterisation is most frequently carried out by compositional analysis, which involves sorting and itemising items by type. A number of different methodologies and categorisation systems have been used, including the well-established MODECOM (ADEME, 1997) which was developed for mixed residual waste streams and contains a relatively broad set of categories. To support the food waste hierarchy, however, a more refined analysis is needed. In the original work carried out in the UK by the Waste and Resources Action Programme (WRAP, 2008; WRAP, 2009) household food waste was characterised into 174 specific types and grouped into 13 major categories. Results of extensive analyses carried out for the UK at a national level are available from WRAP (2009). Guidance on waste compositional analysis and its scale-up into food waste reporting is also available in FUSIONS (2016b).

A study was undertaken to characterise UK food waste collected from source-separated material destined for biogas production (VALORGAS, 2011). This evaluated a number of schemes with weekly collections in which householders were provided with biodegradable bags, a small kitchen caddy and a larger bin to be left at the kerbside. The samples in Figure 4 were collected on a single day, and showed some variability, while those across a 3-week period (Figure 5) appeared slightly more consistent. Relatively little variation was observed in studies carried out in different seasons (VALORGAS, 2012a).

Even the most rigorous methodologies may face complications as a result of the condition or state of the food waste sample: for example if the material has been stored for some time in warm conditions biodegradation will have begun, making separation of items and accurate weighing of the fractions more difficult. Similarly, a high proportion of liquid or semi-liquid components will affect both sorting and weight (FUSIONS, 2016b); this may be a particular

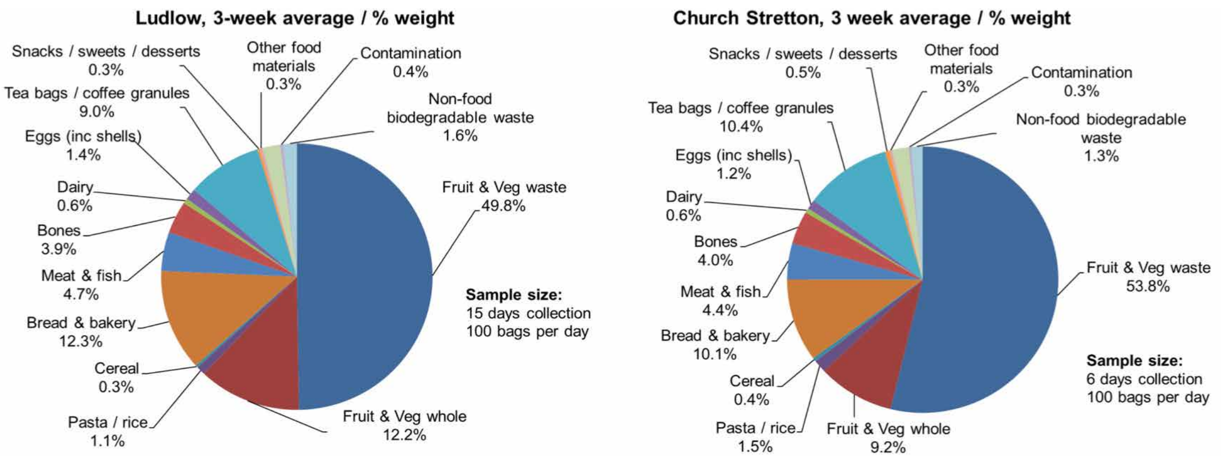

Figure 5: Food waste composition from two UK collection schemes based on average of 3 weeks' sampling (VALORGAS, 2011)

problem in regions such as south and south east Asia where catering and household food wastes often have a much higher water content than in Europe.

In addition to providing insights on the nature of food wastes and on potential strategies for reduction, another reason for carrying out compositional analysis is to generate consistent recipes for simulated food wastes for research and experimental purposes. The scale of operation and the amounts collected mean that day-to-day variability in food waste from households is insignificant for a commercial plant but could seriously affect pilot and laboratory-scale trials that use only a few grams or kilograms a day. One option is to homogenise a large-scale representative sample, but another is to characterise the ingredients and then manufacture smaller quantities when needed. This also allows experimenters to vary the proportions of different components in order to observe the effect of any changes in composition on pre-treatment or digestion processes (Alibardi and Cossu, 2015).

Compositional analysis is a useful tool in identifying materials categorised as unavoidable or avoidable (Figure 1) and has allowed the United Nations to define a Sustainable Development Goal with a specific target (SDG 12.3) referring to food waste. It asks: *'By 2030, to halve per capita global FW at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses'.* The European Commission has adopted this goal and has defined FW as a priority within its Circular Economy Action Plan (EC, 2015).

Chemical and biochemical analysis

Accurate weight data and chemical or biochemical analyses are essential for developing treatment and resource recovery technologies to recycle food and process residues, avoidable and unavoidable, that end up in the waste stream.

Chemical and biochemical analysis generally covers a range of parameters, of which the most common are moisture and solids content (total (TS) and volatile (VS) solids, the latter also known as organic dry matter); biochemical composition (proteins, lipids, carbohydrates and fibre); macro and trace nutrients; and potentially toxic elements (PTE). Finding comparable data from across the world is difficult since as noted above there are many variables associated with collection, sample size, analytical methodologies used and reporting of data. This uncertainty has led to considerable debate over the degree of variability in food waste composition from different locations and regions. A meta-study based on statistical analysis of 70 papers containing food waste characterisation data reported high variability between samples and estimated that 24% of this was attributable to the geographical origin of the material (Fisgativa et al., 2016). The analysis covered a wide range of types of food waste, however, including restaurant food waste, household food waste, FW mixed with green waste, FW of large producers and organic fractions of municipal solid waste (OFMSW). In practice, there were some significant differences between OFMSW and food waste collected with green waste on the one hand, and restaurant, household and large producer food on the other; but the available data shows little difference between source-separated FW collected from any of the latter three types of source. Micolucci et al. (2018) analysed source-separated food waste from Treviso, Italy for both composition and biochemical characteristics, and compared the results with data from five European Union (EU) countries (Italy, Finland, UK, Portugal and Greece). Again, no significant differences were found. This result is not entirely unexpected, as food is both grown and prepared to meet human dietary requirements, and the daily intake of protein, fat, carbohydrate, roughage and liquids has evolved with humankind over millennia. Food may differ greatly in appearance in different geographical regions: for example, carbohydrate may be represented by potato in northern Europe, by pasta in the Mediterranean region and by rice in south and south east Asia. Protein may be predominantly from livestock in central Europe, but from fish in the Pacific Rim regions, and from eggs and pulses in parts of India. The data on chemical and biochemical analysis given in Table 1 is taken from analysis of representative samples and shows considerable similarity between household source-separated material from various sources.

Based on the results of these and other studies, some typical values for a European food waste that could be used for estimation and modelling purposes are shown in Table 2.

Table 1: Physico-chemical and biochemical properties of some source-separated food wastes

Source	UK[a] Eastleigh	Finland[a] Forssa	Italy[a] Treviso	USA[b] San Francisco	China[c] Beijing	S. Korea[d] Yongin
Basic characteristics for AD						
pH	5.02±0.01	5.34	6.16	–	4.2±0.2	6.5±0.2
TS (% fresh matter)	25.89±0.01	27.02±0.12	27.47±0.03	30.90 ±0.07	23.1±0.3	18.1±0.6
VS (% fresh matter)	24.00±0.03	24.91±0.05	23.60±0.09	26.35 ±0.14	21.0±0.3	17.1±0.6
VS (% TS)	92.70±0.12	92.26±0.26	86.60±0.40	85.30±0.65	90.9	94±1
TOC (% TS)	48.76±0.87	–	–	–	56.3±1.1	–
TKN (% TS)	2.91±0.05	2.39±0.04	2.55±0.03		2.3±0.3	–
TKN (g kg^{-1} fresh matter)	7.53±0.13	6.45±0.1	7.02±0.1	–	5.31	5.42±0.26
Calorific value (kJ g^{-1} TS)	20.97±0.02	21.39±0.11	20.50±0.01	–	–	–
Biochemical composition on a VS basis (g kg^{-1} VS)						
Carbohydrates	458±14	194±0.8	206±0.6	–	420	653.2±36.2
Lipids	149±1	156±0.5	202±0.5	–	364	136±3
Crude proteins	197±4	162±0.4	186±3	–	186	192±8
Hemi-cellulose	88.6±1.2	135±10	114±4	–	–	–
Cellulose	66.1±0.1	121±13	176±3	–	109	–
Lignin	21.7±0.1	40.4±5.4	32.3±0.8	–	–	–
Nutrients on a TS basis (g kg^{-1} TS)						
TKN (N)	29.1±0.5	23.9±0.4	25.5±0.3	–	23±3	29.9±1.4
TP (P)	2.82±0.13	2.73±0.05	3.47±0.06	5.2±0.8	–	8.23±0.50
TK (K)	8.59±0.27	10.0±0.2	10.0±0.1	9.0±1.1	23.0±0.4	6.83
Potentially toxic elements on a TS basis (mg kg^{-1} TS)						
Cadmium (Cd)	<0.05	0.35±0.04	1.07±0.1	<3	–	0.29
Chromium (Cr)	4.21±0.62	2.2±0.1	12.1±0.2	10±3	–	2.1
Copper (Cu)	4.69±0.84	11.6±0.2	13.8±0.7	100±3	–	38.3
Mercury (Hg)	–	0.0074	0.025	–	–	–
Nickel (Ni)	2.8±0.1	14.2±2.7	37.3±0.7	6±3	–	2.4
Lead (Pb)	< 0.6	13.65±1.88	17.97±3.9	13±10	–	2.3
Zinc (Zn)	22.4±0.8	28.5±0.5	38.8±0.9	250 ±70	693±130	103
Essential trace elements (mg kg^{-1} TS)						
Cobalt (Co)	0.15±0.03	1.85±0.2	4.72±0.2	–	–	< 0.4
Iron (Fe)	111±1	538±32	1558±72	2480±1300	433±100	39.6
Manganese (Mn)	86.5±2.5	41.1±0.2	84.6±1.3	190 ±100	476±411	12
Molybdenum (Mo)	2.8±0.6	4.3±0.4	8.7±0.3	–	–	0.31
Selenium (Se)	0.42±0.20	–		–	–	–
Tungsten (W)	–	–		–	–	–
Elemental analysis (%TS)						
N	2.91±0.05	2.46±0.03	2.58±0.05	3.16±0.22	–	3.54
C	48.8±0.9	49.4±0.04	47.2±0.01	46.78±1.15	–	46.67
H	6.37±0.19	–	–	–	–	6.39
S	–	–	–	0.81±0.03	–	0.33
O	34.7±0.9	–	–	–	–	36.39

[a] From VALORGAS (2011); [b] From Zhang et al. (2007); [c] From Zhang et al. (2013) and Shen et al. (2013); [d] From Zhang et al. (2011).

Table 2: Model values for a typical European food waste

Parameter	Unit	Typical value
TS	% fresh matter	24
VS	% fresh matter	22
TKN	$g\ kg^{-1}$ fresh matter	7.4
Calorific Value (CV)	$MJ\ kg^{-1}$ TS	22
Carbohydrates (starch and sugar)	$g\ kg^{-1}$ VS	480
Lipids	$g\ kg^{-1}$ VS	150
Crude proteins	$g\ kg^{-1}$ VS	210
Hemi-cellulose	$g\ kg^{-1}$ VS	70
Cellulose	$g\ kg^{-1}$ VS	60
Lignin	$g\ kg^{-1}$ VS	30
N	$g\ kg^{-1}$ TS	31
P	$g\ kg^{-1}$ TS	4
K	$g\ kg^{-1}$ TS	13
C	% VS	52
H	% VS	6.9
O	% VS	38
N	% VS	3.4
S	% VS	0.3
Biochemical Methane Potential (BMP)	$m^3\ CH_4\ kg^{-1}$ VS	450

2.3 Handling & Pretreatment

Organic material from plants and animals used as food is by its very nature easily digestible in the relatively uncomplicated human alimentary canal. Our food contains very little lignin, and much of our fibre intake has been milled in the food preparation process. It is therefore not surprising that food waste from domestic and catering establishments is readily digestible in an AD plant without any pre-treatment other than particle size reduction. The latter should be undertaken in any case, as a step to facilitate effective pathogen destruction downstream. Typically, source separated food waste fed to a single-stage mesophilic digester will show a VS destruction of greater than 85%, and the extent to which any form of pre-treatment will be viable from a financial or energy perspective is thus limited. This is because pre-treatment techniques generally employ either: (i) energy-intensive mechanical or thermal processes aimed at exposing and increasing the surface area of the feedstock and making it more accessible to microbial attack; or (ii) materials-intensive chemical/biochemical methods to 'dissolve' the non-biodegradable structural components that protect the more degradable components. There are, however, a considerable number of research papers reporting the results of pre-treatment techniques, albeit normally at a small scale, and with mixed results. Techniques considered include:

- Physical and mechanical pre-treatments such as chopping, grinding, milling and ultrasound
- Physico-chemical and chemical pre-treatments including use of chemicals such as alkalis, acids and ozone
- Thermal pre-treatments including use of heat and hot water
- Biological and enzymatic pre-treatments using specialized microorganisms and enzyme treatments

In the case of domestic food waste, pre-treatments should be considered with caution as the effect of biodegradability enhancement procedures may be limited, negligible or even negative! The latter is possible as pre-treatment may also result in detrimental effects through the formation of refractory/toxic compounds and the removal of organic material, both of which counteract any positive benefits. An example is heat treatment, which can bring about Maillard reactions in substrates containing proteins and carbohydrates, resulting in the formation of melanoidines (Jin et al., 2009; Müller, 2000). In another case autoclaving of food waste reduced methane yield simply because proteins were denatured, making them less susceptible to enzyme attack (Tampio et al., 2016); a slight positive benefit was that the biogas H_2S content was also reduced, as the sulphur remained locked up in the protein. An initial aerobic composting stage to promote rapid hydrolysis and enzyme production is likely to result in a net decrease of organic material available for methane production.

The degree of contamination of source-separated domestic food waste is generally much lower than that found in material from co-mingled OFMSW (Hoornweg and Bhada-Tata, 2012), and the number and intensity of pre-treatments required is therefore lower.

In the case of residues from food processing factories, pre-treatments may be beneficial, as one of the aims of food processing is to remove the hard-to-digest fractions of the food such as the skin, seed case, peel or other non-edible parts.


Figure 6: Valorsul AD plant in Lisbon, Portugal. Left – incoming waste. Right - manual sorting cabin (VALORGAS 2012b)

Pre-treatment options

Where it is necessary to apply pre-treatments, they can be divided into 3 main types: sorting, separation and homogenisation.

Sorting. The first step of pre-treatment is to remove non-biodegradable and inert materials that can negatively affect downstream processes or digestate quality. Ideally, this should happen at source, and the effectiveness of a collection scheme in removing unwanted materials will determine what sorting is required at the treatment plant. Most AD plants, irrespective of the collection system, will have at least visual inspection of the incoming material to protect the plant from damage to downstream equipment and processes. Where gross contamination is a regular problem, larger items of paper, plastic, textiles and metals may be manually sorted (Figure 6).

Separation. If necessary mechanical separation can be used downstream for further contaminant removal. The design of this is based on knowledge of the waste obtained from compositional analysis and historical collection data. Food waste typically has a high moisture content of the order of 75-80%. Many of the pre-treatment technologies developed for separating the organic fraction from MSW, such as rotating drum or disc screens, are thus not appropriate since they rapidly blind when the waste adheres to surfaces or tends to 'ball' as a result of the rotational movement. Typically, for high levels of contamination densitometric separation techniques are used either in conjunction with or following particle size reduction.

When dealing with supermarket and other retail wastes de-packaging equipment may be needed, and a number of proprietary devices are available. These are typically designed to remove the outer packaging and utilise a combination of mechanical and centrifugal forces coupled with screening to separate out the denser food waste from the lighter card and film packaging components (Figure 7). Where a food waste stream is to be co-digested, additional pre-treatment of other input streams may be required, such as grit and stone removal from animal slurries or manures.


Figure 7: Left – Food de-packaging machine. Right – Linde hydropulper in operation at Valorsul AD plant (courtesy FP7 VALORGAS).

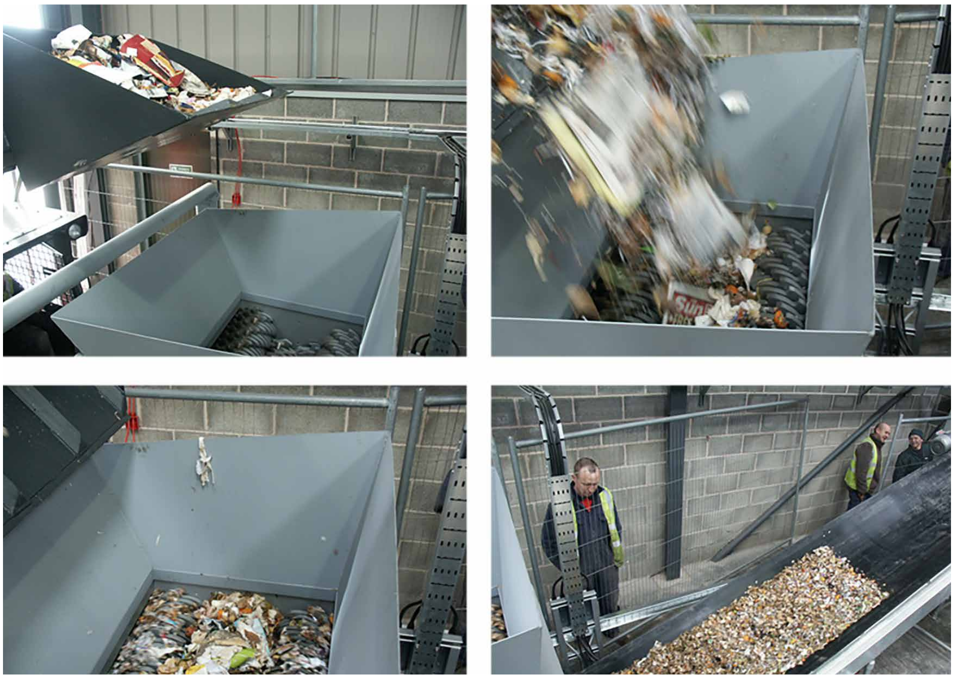

Figure 8: Food waste shredder at Biocycle South Shropshire AD plant (Pictures: C J Banks)

Homogenisation. Homogenisation is an important procedure to promote degradation and prevent clogging, settling or formation of floating layers inside the digester. The first step is size reduction, using shredders (Figure 8) and screw cutters, or mills for drier types of material. For ease of pumping and mixing the chopped material may then be converted into a slurry using macerator pumps and recycled digestate before direct feeding to the digester.

Homogenisation of food waste is generally simpler than processing of co-mingled OFMSW or biowastes, where the addition of water may be required to reach a suitable dry matter content for contaminant removal using densitometric techniques. One of the most common techniques for this purpose is the use of a 'Hydropulper' (Figure 7), which allows the separation and removal of light floating materials and denser settleable particles.

Pasteurisation and Pathogen Reduction

Food waste may contain a range of pathogens, and as a result of the emergence of Bovine Spongiform Encephalitis (BSE) and the catastrophic impacts of foot and mouth, swine fever and other animal diseases, the European Commission has introduced regulations to control the end use and disposal of animal by-products (ABPR) (EC 1069/2009 and 142/2011). These cover food waste, which falls into different categories depending on its origin. In the EU only materials in categories 2 and 3 can be processed through anaerobic digestion, with most food waste falling into category 3. With the exception of some category 2 materials, all food waste must be treated to meet a minimum standard in terms of pathogen indicator organisms.

In general, this has to be achieved in a two-stage process which involves particle size reduction followed by heat treatment and biological stabilisation, for which anaerobic digestion is a suitable process. The degree of treatment depends on both the temperature and the holding time. Sterilisation can be achieved by at least 20 minutes of exposure at a core temperature of more than 133 °C and an absolute steam pressure of no less than 3 bar; this is required for some category 2 materials. Category 3 food processing waste requires particle size reduction to 12 mm and heat treatment for 60 minutes at 70 °C; whereas catering wastes (including household food waste) can be treated in a number of ways provided they meet an end-of-process microbiological standard. In addition to specific process requirements, there is also a requirement to implement strict hygiene controls to prevent bypass between potentially contaminated incoming ABP material and the final digestate product.

These requirements are onerous and may add considerably to both the capital and operating costs of running an anaerobic digester, yet the direct and indirect costs of a major animal health incident fully justify this precautionary approach.

3. Anaerobic Digestion Systems

The mono digestion of food waste has so far found its greatest popularity in the UK where there are now 94 plants producing biogas from mixed commercial and residential food waste, the largest proportion of which is used to generate 218 MW of electricity in CHP units (IEA Bioenergy, 2017a). The Scandinavian countries have also been early adopters of food waste digestion, with some interesting examples where biogas is used mainly as a vehicle fuel. Food waste digestion plants can also be seen in parts of Spain and Portugal. These plants are usually operated at a 'natural' retention time i.e. without addition of water or other liquids. Even though the input material typically has a TS content of around 24% the digesters are operating at low solids concentrations in a 'wet' digestion process, since at approximately 85% VS degradation the resulting TS concentration is less than 6%. As such food waste digestion is distinct from biowaste schemes in which the food component is comingled with garden waste and sometimes with paper and card, giving a higher TS and lower digestibility than for food waste alone. Biowaste collection is more common in central Europe and requires either a 'wet' digester design in which water is recycled or added, or uses a plug flow 'dry' digestion system.

There are many historical reasons why different systems have developed, and each has its advantages and disadvantages; but once an infrastructure is in place it is difficult and costly to change. Thus all technical options should be carefully evaluated early in the planning process alongside any financial drivers, regulatory issues and opportunities for nutrient recycling.

3.1 Historical Issues in Mono-Digestion of Food Waste

The biochemical and other characteristics of food waste make it very attractive as a digestion substrate as it has a high methane potential and is readily degradable. Early trials with mono-digestion of source segregated food waste as a sole substrate showed good gas productivity and high solids degradation over the first several months of operation. After prolonged operating periods, however, signs of inhibition were observed with reductions in the specific methane yield, increases in volatile fatty acid (VFA) concentrations (Banks et al., 2008, 2011; Neiva Correia et al., 2008; Park et al., 2008; Zhang et al., 2012), and in extreme cases a fall in digester pH and failure of the digestion process.

This behaviour is now known to be a consequence of the composition of food waste, and in particular of its relatively high nitrogen content. Food waste contains a nitrogen-rich protein fraction which, on digestion, is degraded to ammonia. This provides an essential nutrient for the growth of microorganisms in the anaerobic consortium, but at higher concentrations it is also inhibitory. Inhibition thresholds vary depending on a number of factors, including the type of organism and the digester conditions. Of the two main groups of methanogens present in a typical anaerobic digester, however, the acetoclastic methanogens are generally more sensitive to ammonia. As total ammonia nitrogen (TAN) concentrations increase, the acetoclastic population is progressively reduced, leading to accumulation of first acetic acid and then other VFA, in particular propionic acid.

Finding solutions to the mono-digestion of food waste

The acetoclastic pathway can be replaced by hydrogenotrophic methanogenesis by stimulating this initially smaller part of the archaeal population and promoting the degradation of acetic acid through a two-stage process. This first involves converting acetic acid to CO_2 and H_2 by syntrophic acetate oxidation, then the CO_2 and H_2 are used by hydrogenotrophic methanogens to produce methane. The trace element requirement of this combined process is different from that of the acetoclastic pathway, and Selenium has been shown to be essential for the mesophilic digestion of food wastes at TAN concentrations above approximately 4.5 g N L^{-1} or free ammonia nitrogen concentrations above about 0.7 g N L^{-1}. Once this alternative hydrogenotrophic route is established then process loadings can be increased, although at higher organic loading rates (OLR), deficiencies in other trace elements such as Cobalt may become apparent (Banks et al., 2012). There is also some evidence that Molybdenum and Tungsten play a role in food waste digestion; it is necessary to look for specific deficiencies in trace elements associated with different food waste types. Recommended minimum values for six key trace elements are shown in Table 3. In practice some of these elements such as Nickel, Molybdenum, Tungsten and Iron are generally present in domestic and commercial food waste in sufficient amounts and do not require supplementation.

Table 3: Recommended minimum trace element concentrations when food waste is used as an AD feedstock

Metal	Amount for addition to feedstock in g m^{-3}
Selenium (Se)	0.2
Cobalt (Co)	0.35
Nickel (Ni)[a]	1.0
Molybdenum (Mo)[a]	0.2
Iron (Fe)[a]	10.0
Tungsten (W)[a]	0.2

[a] Generally present in sufficient quantities in food waste

Trace element addition should be minimised with respect to both the elements and the concentrations used, due to concerns over dispersion into the environment (including to agricultural land), as well as cost aspects. More research is needed in this area, as trace element supplementation is a complex issue and affected by many factors including interspecies competition between different microbial groups, bioavailability, interaction between different elements, and the organic loading rate applied. Current work has demonstrated that Se and Co dosing of 0.2 and 0.35 g m^{-3}, respectively, is sufficient to operate UK food waste at OLR of up to 5 kg VS m^{-3} day^{-1} without VFA accumulation.

Work by a number of research groups around the world has now elucidated the metabolic pathways and microbial community structures involved in both the failure of unsupplemented food waste digestion and the subsequent successful resolution of the problem. This outcome provides an outstanding example of the insights new tools in microbial and analytical sciences can offer and the practical application of these in full-scale engineered systems (Banks et al., 2012; Zhang and Jahng, 2012; Zhang et al., 2015; Fotidis et al., 2014).

3.2 Estimating the Energy Potential of Food Waste Digestion

Biochemical and elemental compositions can be used as a basis for prediction of the actual and maximum theoretical methane potential of a feedstock, in some cases providing a reality check on quoted methane yields. This is discussed in detail in the IEA Bioenergy Report on the value of batch tests for biogas potential analysis (Weinrich et al., 2018). Table 4 shows theoretical methane yields from some typical biochemical components; again this is discussed in more detail in Weinrich et al., (2018). For food waste in particular, these values usually provide a reasonably good estimate of the Biochemical Methane Potential (BMP) and biogas composition of a feedstock; the values can be modified if the actual elemental composition of the lipid, protein or carbohydrate is known and differs from the typical formulas shown. Cellulose and hemi-cellulose can be regarded as carbohydrates but lignin is not normally degradable in a conventional anaerobic digester; a high ratio of lignin may indicate that the lignocellulosic fraction of the material will be resistant to degradation.

The elemental composition can be used in conjunction with the Buswell equation (Symons and Buswell, 1933) to calculate the maximum theoretical methane potential of the feedstock, assuming all components are converted. This provides an upper bound for the methane yield (Angelidaki and Sanders, 2004). The high biodegradability of food waste means that a relatively high proportion of this theoretical yield can be achieved, and the biogas composition is typically close to the predicted value.

BMP values for source separated domestic food waste in Europe are typically in the range 0.42–0.47 m^3 kg^{-1} VS,

Table 4: Typical methane yields for biochemical components (adapted from Angelidaki and Sanders 2004)

Substrate	Typical composition	Methane yield [a] [L CH_4 g^{-1} VS]	CH_4 [% Vol]
Simple sugars – e.g. glucose	$C_6H_{12}O_6$	0.373	50
Carbohydrate – complex	$C_6H_{10}O_5$	0.415	50
Protein	$C_5H_7NO_2$	0.495	50
Lipid	$C_{57}H_{104}O_6$	1.013	70
Cellulose	$C_6H_{10}O_5$	0.415 [b]	50
Hemicellulose	Variable	0.424 [c]	50

[a] At standard temperature and pressure of 0 °C and 101.325 kPa
[b] Maximum, depends on degree of accessibility and crystallinity
[c] Maximum, assuming pentose polymers only. In reality will also contain hexose, uronic acid etc with lower methane yields

and compositional data suggest values elsewhere will be broadly similar. The specific methane production (SMP) in a well-run mesophilic digestion plant can reach a very high proportion of both the BMP value and the measured or theoretical calorific value, with 75% or more of the higher heat value (HHV) recovered in the form of methane, making this a highly efficient conversion process for a wet organic material. Factors affecting BMP and SMP values include the proportion of lignocellulosic materials in the feedstock, which in addition to their intrinsically lower BMP are also slower to degrade. Although lipids have a high biomethane potential, in high concentrations they may be problematic for digestion.

Operating limits and strategies

Most commercial food waste digesters operate at mesophilic temperatures and there has been a steady increase in organic loading rates (OLR) from the 'safe' loading of less than 2 kg VS m^{-3} day^{-1} applied in the early days, when the need for trace element supplementation was not understood, to typical values today of 3-5 kg VS m^{-3} day^{-1}. At a feedstock VS content of 22% and an OLR of 5 kg VS m^{-3} day^{-1} the retention time is around 44 days; in these conditions a digester is likely to achieve 80% or more of the BMP value of food waste. In terms of extracting the maximum amount of energy from the feedstock and producing a well-stabilised digestate, this performance leaves relatively little room for improvement.

Further increases in loading are possible but it is important to know the limitations that will ultimately apply. With correct trace element supplementation, OLR of up to 8 g VS L^{-1} day^{-1} have been demonstrated over long periods at laboratory scale, without any loss in SMP. At OLR over 8 g VS L^{-1} day^{-1} there are signs of a reduction in the SMP. The most likely reason is simply that, at this OLR, the retention time in the digester is reduced to the point where not all of the potential degradation can be achieved during the average period for which the food waste remains in the digester.

Some operators prefer to work in the thermophilic range (between 55 and 60° C), citing higher reaction rates, potential improvements in biogas yield due to improved degradation of lignocellulosic fractions, and greater ease of complying with ABPR and digestate sanitisation requirements. Thermophilic operation presents some challenges for typical source separated food wastes. At the higher operating temperature, a higher proportion of the TAN is present in the form of free ammonia, which is more inhibitory to micro-organisms. The safe working threshold for TAN is reduced, and signs of inhibition are likely to appear at TAN concentrations of between 3–4 g N L^{-1}. This is below the TAN concentration typically found in domestic food wastes when digested under thermophilic conditions; long-term stable operation at thermophilic temperatures is therefore not possible without further interventions. Despite several studies, no trace element supplementation has yet been identified that allows stable operation in thermophilic conditions. A number of possible options to allow thermophilic operation have been tested. The most common approach, which has been successfully demonstrated at both laboratory and commercial scale, is dilution of the feedstock to bring the ammonia concentration down below the toxicity threshold. This has potential disadvantages, as dilution requires a continuous input of water or other low-nitrogen liquid, thus increasing the required digester size and the volume of digestate for disposal. An alternative is a downstream treatment process to strip ammonia and other compounds from the dilution medium before recycling. A recent study indicated, however, that the impact on the overall process energy balance when compared to mesophilic digestion may be small as, although dilution means larger volumes of digestate must be processed, the need for pre- or post-pasteurisation is eliminated (Zhang et al., 2017a).

Another approach is to strip the ammonia from the contents of the digester itself in order to reduce the concentration below the toxicity threshold. Stable thermophilic digestion of undiluted domestic food waste has recently been demonstrated for the first time at pilot scale using a side-stream biogas stripping process, in which the digestate TAN concentration could be controlled by the degree of stripping applied, without adverse effects on the SMP (Zhang et al., 2017b). Other studies have looked at stripping using a range of gases from air to nitrogen and CO_2 mixtures, and a variety of process configurations; these approaches also offer the potential for recovery of ammonia in a form suitable for use as a chemical fertiliser, with the option of creating designer digestates tailored to local soil and crop types. In many parts of Europe, the amount of digestate that can be applied is controlled by regulations to protect nitrate vulnerable zones. One of the potential benefits of ammonia stripping may be an increase in allowable application rates, which reduces the energy requirement for transporting digestate. In future a range of novel techniques such as electrochemical, absorption and membrane techniques are likely to become available for recovery of ammonia and other nutrients.

Mass and energy balances for the Biocycle and Valorsul food waste digesters

A number of energy balance studies have been carried out on food waste digestion looking both at full-scale plant and at theoretical scenarios.

One of the earliest studies carried out was on the Biocycle South Shropshire Digester in Ludlow, UK as part of a national monitoring programme for various types of waste management demonstration plant (Banks et al., 2011). The flow sheet for the plant is shown in Figure 9 and, as can be seen, it has a simple linear configuration where feed enters the plant, is shredded, fed to the digester, pasteurised and sent to the digestate storage tank before reuse through land application. A small amount of digestate is recycled to the raw waste buffer tank to facilitate maceration and pumping. Over a 14-month period, the plant received just under 4000 tonnes of feedstock, consisting primarily of source separated domestic food waste from local collection schemes, with a small proportion of commercial food waste. The total volume of the digester was 900 m^3 and it was maintained at 42 °C, towards the high end of the normally recommended mesophilic range. The digester operated at an average organic loading rate of around 2.7 kg VS m^{-3} day^{-1} and a hydraulic retention time (HRT) of around 90 days. One key benefit from the study was to show that methane yields and degradation rates close to those found in laboratory and pilot-scale studies could be achieved at large scale in a conventional single-stage mesophilic digester. The mass balance closure for the study period based on fresh weight of materials was 90.3%, and 95.7% on a VS basis. Specific methane production was around 400 m^3 tonne^{-1} VS, a little below typical values for this type of material: this was possibly related to the absence of trace element supplementation in this period. A comprehensive energy balance carried out for the monitoring period showed that for each tonne of input material the potential recoverable energy was 405 kWh. Table 5 summarises some of the key components in the energy balance. It should be noted that the capacity of the AD plant was based on serving local needs rather than bringing in materials from long distance, and it is therefore at the lower end of the typical size range for commercial food waste digesters.

Another mass and energy balance study was carried out using data from the Biocycle plant over an even more extended period (1919 days) and from the Valorsul AD plant in Lisbon, Portugal (372 days). The digesters at each plant

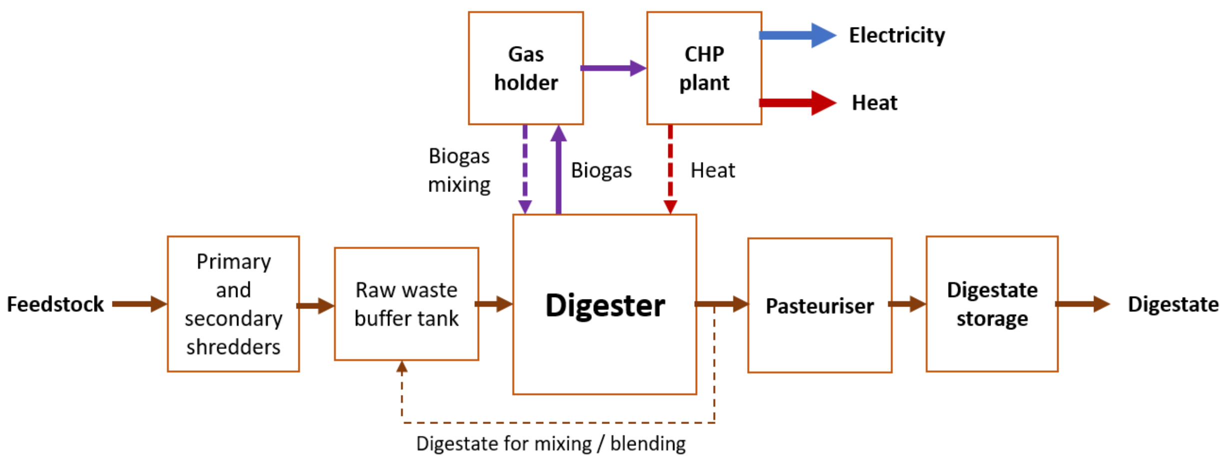

Figure 9: Biocycle plant flowsheet

Table 5: Energy requirements, losses and outputs for Biocycle AD plant (based on Banks et al., 2011)

Parameter	kWh $tonne^{-1}$ of input	% of CHP gross energy output
CHP gross energy output	706.9	100.0
CHP unrecoverable energy	115.9	16.4
CHP electrical output [A]	216.5	30.6
Parasitic electrical requirement of process plant [B]	59.1	8.4
Net energy output as electricity [A-B]	157.4	22.3
Recoverable heat output from CHP [C]	374.5	53.0
Parasitic heat requirement of plant [D]	113.4	16.0
Net energy output as heat [C-D]	261.1	37.0
CHP natural gas used [E]	4.7	0.7
Energy required for biofertiliser use [F]	8.7	1.2
Total potentially recoverable energy (heat and electricity) [A-B]+[C-D]-[E]-[F]	405.1	57.3

are shown in Figure 10. The Valorsul AD plant was designed to process 40,000 tonnes of source separated food waste per year, primarily from commercial sources such as restaurants, wholesale and retail markets, supermarkets, schools and hospital canteens, with a small proportion of source separated domestic food waste. At the time of the study, waste delivered to the plant was discharged into one of two lines, depending on the level of contamination. The more contaminated materials were passed through a wet pre-treatment process consisting of manual sorting, ferrous metal separation, shredding, pulping and sieving, after which the resulting suspension was sent to a hydrolysis tank. Materials with little contamination passed through hammer mills then water was added to create a suspension that was pumped to the hydropulper.

Biological treatment involved a thermophilic (51 °C) digestion process after which the suspension was dewatered. The solid fraction was mixed with wood chips and pre-composted in tunnels with forced aeration, then post-composted in windrows in a covered area. The final compost was refined by sieving and use of a densitometric table to remove contaminants. The water fraction was sent for treatment in an Activated Sludge plant with nitrification/denitrification, followed by ultrafiltration modules, before recycling as process water. The biogas produced was stored in a gasholder and sent to two generators to produce electric energy (installed capacity of 1.6 MW). Excess heat from the exhaust gas was used to heat water to maintain the digester temperature and to supply heat to the composting tunnels. A simplified flow sheet for the Valorsul plant is shown in Figure 11.

The overall mass balances for each plant on a wet weight and a volatile solids basis are shown in Figure 12. The results were good in both cases, although mass balance closure was slightly better on the less complex Biocycle plant. The major notable difference was in the proportion of re-

900 m^3 mesophilic digester, buffer tank, gas storage and digestate storage at the South Shropshire plant

Two 3500 m^3 thermophilic digesters at the Valorsul AD plant in Lisbon

Figure 10: Digesters at Biocycle (left) and Valorsul plant (right) (courtesy FP7 VALORGAS)

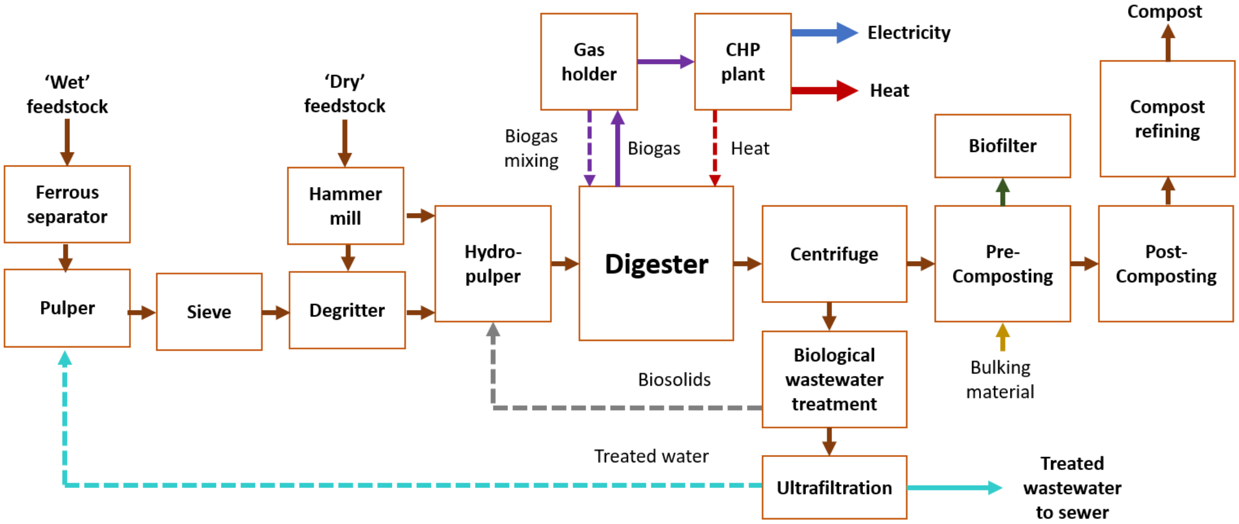

Figure 11: Flowsheet for Valorsul AD plant

ject material, which was much higher for the Valorsul plant at 20% of incoming wet weight than for the Biocycle plant at 1.6%. A significant part of this was due to the presence of non-biodegradable plastic bags in the Valorsul waste stream, making up 6% of the wet weight.

Table 6 shows the calculated energy balances for both plants. The overall results for the percentage of surplus heat and electricity were similar for both plants. The results for the Biocycle plant included an input of natural gas to start the CHP plant, and a proportion of flared gas. The Valorsul plant is larger, which should lead to greater efficiency of the CHP plant, while parasitic energy demand for some ancillary processes should represent a smaller proportion of the overall energy yield; on the other hand the greater complexity of the plant including the need for effluent treatment creates additional energy demands. This is clearly seen in the ratio of parasitic energy demand to gross energy input, which is 6% for Biocycle and 13% for Valorsul. The parasitic heat demand for Biocycle at 29% is higher than for Valorsul at 22%, due in part to the smaller size of the plant but also to the need to pasteurise the digester contents.

The reason the Valorsul plant has a more complex flowsheet, including additional composting and effluent

Table 6: Energy balances for Biocycle and Valorsul plants from FP7 VALORGAS project

			Biocycle		Valorsul	
			MWh	% gross input	MWh	% gross input
PRODUCT	methane	raw	18174	100%	30074	100%
OUTPUTS	electricity	CHP gross	3907	21%	8673	29%
	heat	CHP gross	8302	46%	18429	61%
		CHP useable	6470	36%	14364	48%
		boiler gross	5966	33%	2957	10%
		boiler useable	4999	28%	2513	8%
PARASITIC	electricity	CHP	164	1%	364	1%
		non-CHP	958	5%	3535	12%
		total	1122	6%	3899	13%
	heat	process*	2417	13%	2191	7%
SURPLUS	electricity		2785	15%	4774	16%
	heat		9052	50%	14686	49%
	total		11837	65%	19460	65%

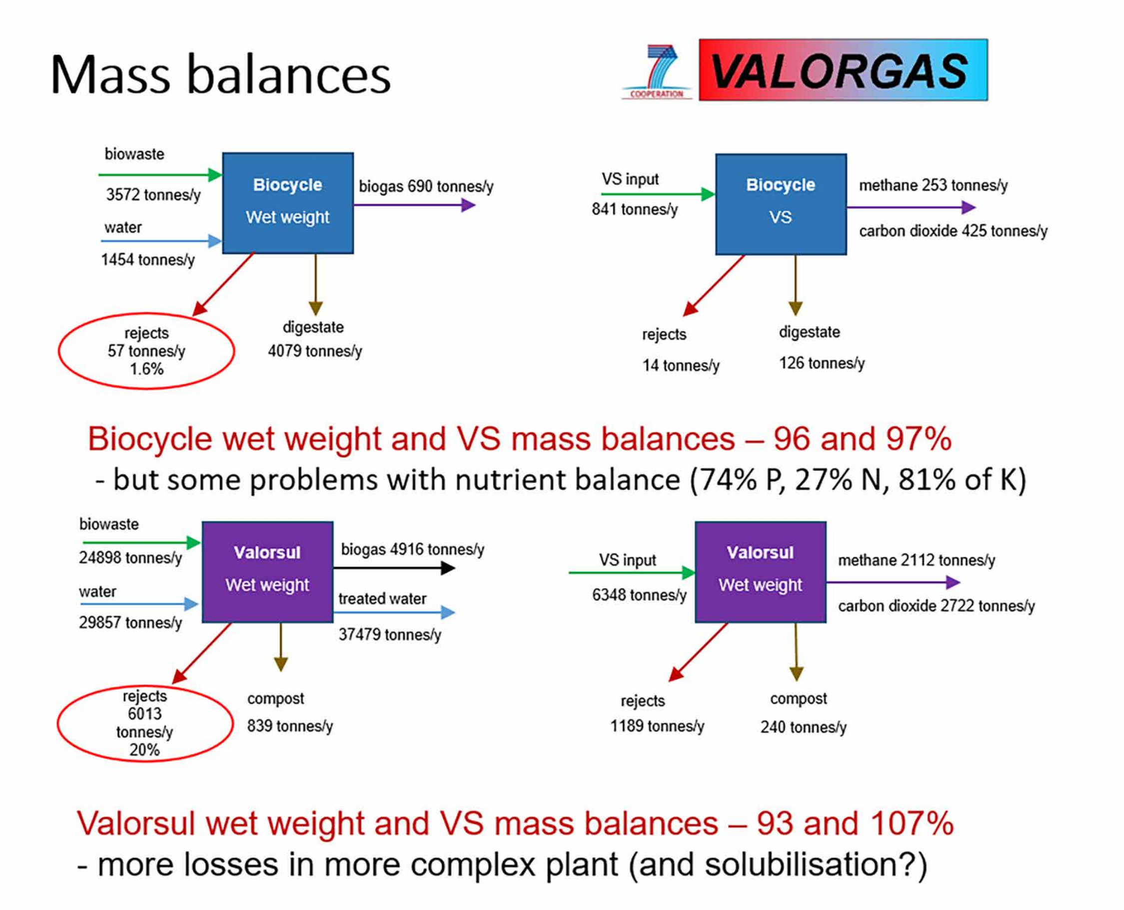

Figure 12: Mass balances for Biocycle and Valorsul plants from FP7 VALORGAS project

treatment stages, is because of regulatory restrictions on the land application of digestate. Although more capital and energy-intensive, this configuration allows the plant to produce smaller volumes of compost for disposal.

It is interesting that, even given its much smaller size and lower electrical conversion efficiency, the simple mesophilic digestion plant achieves a performance similar to that of the more complex thermophilic plant. The VS destruction achieved by the Biocycle plant was 85% based on the mass balance of VS entering and leaving, or 82% based on the mass of dry biogas expressed as a proportion of the VS entering the plant. For the Valorsul plant, the corresponding values were 95% and 94%, respectively.

The SMP for the Biocycle plant was 421 m^3 CH_4 $tonne^{-1}$ VS, and for Valorsul was 465 m^3 CH_4 $tonne^{-1}$ VS. These results are for two different feedstocks and thus cannot be compared directly; but they fall within the typical range for European food waste, and once again confirm that high methane yields similar to those found in laboratory trials can be achieved in full-scale commercial plant. SMP values based on VS destroyed were similar at around 496 and 487 m^3 CH_4 $tonne^{-1}$ VS for Biocycle and Valorsul, respectively.

3.3 Co-Digestion

Co-digestion of food waste is an attractive option that is rapidly gaining favour. Both sewage sludge and animal slurry are ideal co-substrates as they have low biochemical methane potential and a high moisture content. These two factors mean that digestion performance of the sludge or slurry alone is limited by the hydraulic retention time and not the organic loading rate. This allows extra loading to be applied to the digester, provided it does not reduce the retention time significantly. The digester thus has capacity for inputs of high energy substrates with lower moisture contents. Co-digestion with food waste can provide an additional income stream from a gate fee, and in many cases can double the volumetric biogas production. This can change the economics of digester operation, in the best case turning a loss-making facility into a profitable one. Where regulatory, grant aid and renewable energy subsidy considerations permit it co-digestion could be one of the most favoured options for food waste recycle/recovery, particularly where the resultant digestate is applied as a fertiliser to farmland or is used in horticulture. The US EPA collated publicly available information for a report on 'Anaerobic Digestion Facilities Processing Food Waste in the United States in 2015', which found an estimated 184 plants processing 12.7 million tonnes of food waste. Of these 61 were 'merchant' digesters processing mainly food wastes, 43 were on-farm digesters co-digesting food waste with animal slurry and the remainder were wastewater treatment facilities co-digesting food wastes with wastewater sludges. The concept of centralised manure co-digestion has been applied in Denmark since 1987. It is based on production of biogas by co-digesting animal manure and slurries (mainly pig and cattle) with other digestible feedstocks (also known as alternative biomass), mainly organic wastes. The alternative biomass has the role of increasing the biogas yield of the manure digestion. It typically includes abattoir waste, digestible wastes from food- and agro-industries, by-products and residual vegetable biomass from the agricultural sector, food waste and source separated organic waste from, municipalities, households and catering. The governance of environmental sustainability supporting this initiative is presented in the IEA Bioenergy report (Al Seadi et al., 2018). The Green Growth Initiative in Denmark has as its objective the treatment of 50% of livestock manures in biogas plants by 2020, with a possible four-fold increase in total biogas production using a variety of co-substrates including source separated household materials (IEA Bioenergy, 2017b).

3.4 Food Waste Digestion and the Cicular Economy

Food waste can play a central role in the circular economy, with particular importance due to its potential to capture nutrients and return these to the agricultural production system. Waste management practice has tended to exclude this in the past, through its reliance primarily on landfill and incineration for the disposal of wastes. In both of these systems nutrients leave the farm as a part of the harvest and are never returned, but enter the air, groundwater or leachate treatment systems, followed by further transformations and losses to the atmosphere, freshwater ecosystems or the oceans. Although there has recently been an increase in the popularity of mechanical biological treatment systems (MBT) using either aerobic or anaerobic processes for stabilisation of the organic matter, this has not solved the problem of nutrient recovery. With MBT systems, the resultant digestate or compost is not suitable for agricultural use, except in some cases for the growth of industrial rather than food crops. This is because of the high levels of cross contamination: Table 7 shows an example of heavy metals concentrations in digestates from MBT recovered organics and from FW, although other persistent organic contaminants are of equal or greater concern. Another emerging issue is the presence of even small pieces of non-

Table 7: Chemical analysis of digestate from MBT organics and food waste (Zhang et al., 2012)

	MBT recovered organics		Food waste	
Digestate component	fibre	liquor	fibre	liquor
% of whole digestate	22	78	1.2	98.8
TS (% WW)	35.0	6.57	14.7	5.84
VS (% WW)	21.2	3.28	12.1	4.16
VS (% TS)	60.5	49.9	82.6	71.2
TAN (g N kg^{-1} TS)	4.8	22.4	23.6	65.1
TKN (g kg^{-1} TS)	16.2	48.1	54.7	112
TK (g kg^{-1} TS)	3.9	17.5	18.0	46.1
TP (g kg^{-1} TS)	3.4	4.5	10.5	11.9
Cd (mg kg^{-1} TS)	1.4	2.4	< 1.0	< 1.0
Cr (mg kg^{-1} TS)	64	166	10.9	29.1
Cu (mg kg^{-1} TS)	146	291	19.7	37.8
Ni (mg kg^{-1} TS)	58	138	11.4	25.2
Pb (mg kg^{-1} TS)	170	265	< 10	< 10
Zn (mg kg^{-1} TS)	438	840	128	151

biodegradable plastic materials, which may break up in the environment to produce micro-plastics. Source separated food waste on the other hand is generally regarded as being a safe material with respect to chemical and pharmaceutical materials, since it was destined for human consumption.

The major plant nutrients Nitrogen (N), Phosphorus (P) and Potassium (K) are generally regarded as being conserved in anaerobic digestion, unless special steps are taken to remove them: the feedstock characteristics can thus be used to predict digestate nutrient content. With food waste, however, a simplified mass balance approach is recommended for estimation due to the high biodegradability of the feedstock. For example if we consider an input of 1 tonne wet weight of the model food waste in Table 2, with an assumed VS degradation rate of 80%, approximately 176 kg of VS will be converted into biogas leaving 824 kg of digestate as a residue. The NPK of the digestate will therefore be higher than that of the feedstock by around 1000/824 or a factor of 121%. Potentially Toxic Elements (PTE) are also conserved, leading to the same concentration effect. Actual values for PTE in food wastes vary depending on the collection method, with source separated food waste typically

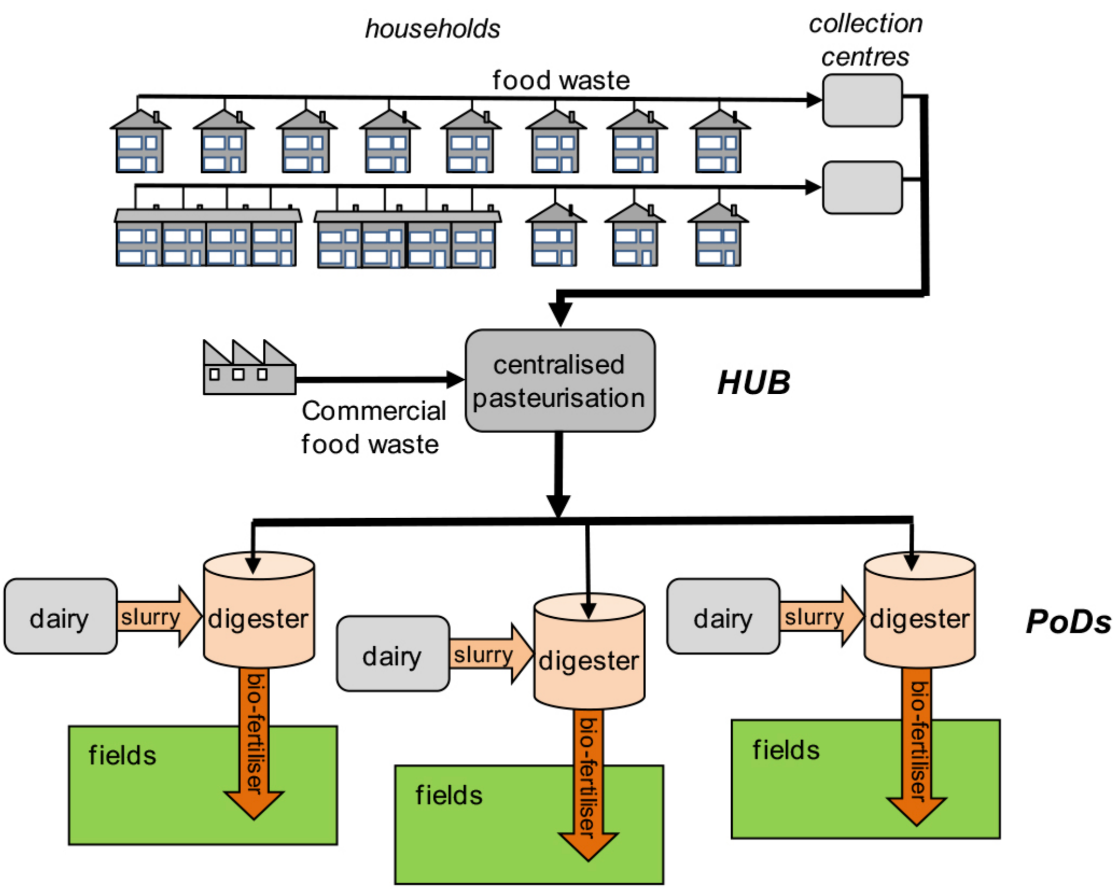

Figure 13: Hub and PoD System for Food Waste nutrient management (WRAP, 2013)

having low or very low concentrations reflecting its origin as food grade materials.

There are potential concerns over the spread of animal diseases through human food, and this remains a problem in many parts of the world where food waste is fed directly to animals without any treatment. In Europe and North America, stringent regulations are in force to ensure that food waste does not come into contact with animals, either domestic or wild, without first being treated. Pasteurisation and anaerobic digestion provide a double barrier to the transmission of disease and it is accepted that, if adequate precautions are taken, the NPK content in the digestate can be beneficially returned to land.

In the UK where food waste digestion is relatively common a rigorous approach has been adopted to the use of digestate. This was designed to ensure that if specified criteria are met the digestate can be considered a quality product rather than a waste and is suitable for application to farmland without perceived risk. It thus aims to protect human and animal health and the environment. The Anaerobic Digestion Quality Protocol (Environment Agency, 2014) includes compositional standards for the final digestate. It also adopts a precautionary principle in restricting the types of material that are acceptable as digestion substrates. The protocol necessitates licensing of facilities and operational monitoring and defines acceptable good practice for the use of quality digestate in agriculture, forestry, soil/field-grown horticulture and land restoration.

The UK approach was set up mainly to cover historic practice in which urban-generated wastes were generally treated or disposed of in or near to the centres of population that produced them. This minimises transport and other infrastructure requirements for waste collection but increases the cost and difficulty of recycling nutrients from this source. In the section above the model adopted in Denmark was outlined, where on-farm co-digestion of food waste with animal slurry is promoted and practiced. This improves the volumetric methane potential of animal slurry digesters and thus reduces the associated pay-back periods. Making slurry digestion economic also helps to reduce on-farm greenhouse gas emissions associated with slurry storage tanks (Liebetrau et al., 2017) and allows recovery of energy from a greater proportion of the total biomass resource. The Danish model can be further refined to provide a nutrient management strategy based on farm nutrient exports and requirements in a concept described as a 'Hub and PoD' system (WRAP, 2013) (Figure 13). The basis of this idea is that source-separated food waste collected from households is taken to a centralised processing facility (the Hub) where it is homogenised, blended and pasteurised to ensure it is safe. This could be on an existing site such as a landfill or waste-to-energy plant that already has facilities for waste handling and may also have a CHP plant producing spare heat for pasteurisation. Pasteurised food waste is then transported by tanker to farms, the 'points of digestion' (PoD) where the material is used as feedstock for the digester. Biogas produced is used to meet farm energy needs, with any excess exported. The digestate provides a valuable organic fertiliser with a nutrient balance similar to that required for crop production, so that it can be used to replace mineral fertilisers.

Using available data for food waste generation rates and UK farm statistics, it was estimated that the 8.3 million tonnes of potentially available food waste (WRAP, 2009a) would be enough to supply the nitrogen requirements of all UK dairy farms (1494) with over 200 dairy cows, and 2444 out of the 6307 farms with between 100 and 200 dairy cows in the UK (Banks et al., 2011b).

4. Case Studies

This section provides some brief case studies giving a snapshot of the development and status of food waste collection and digestion in different countries.

4.1 Australia

Source segregated collection of household food waste with or without garden waste is increasing in popularity, with 10% or more of the population having access to a council-operated kerbside food waste collection service by 2013 (Hyder Consulting, 2012; Planet Ark, 2013). Most of the material collected is currently composted rather than digested for biogas production.

In 2009–2010, ten South Australian councils took part in a food waste collection and recycling pilot involving 17,000 households. Average food waste yields for the most effective system of fortnightly collection were 1.86 kg household^{-1} week^{-1} with participation rates of 66% (Zero Waste SA, 2010). Detailed guidance sheets for best practice in collection have been developed (Hyder Consulting, 2012).

In February 2016 the State Government of Victoria announced funding of AUS$300,000 (€188,000) to support local government and businesses installing small-scale AD technology. The aim was to demonstrate the viability of organics recovery and processing and generate examples that could easily be replicated. At the National Food Waste Summit in November 2017 the Department of the Environment and Energy launched the National Food Waste Strategy, with a goal of halving Australia's food waste by 2030. While the key focus was on reduction, it was noted that *"Investment in regional infrastructure that centralises the collection of surplus, or off-specification produce or food waste, would allow greater volumes to be collected and sold for repurposing, or donated to food rescue organisations"*. The strategy identifies the role of AD in both recycling and energy recovery (Australian Government, 2017).

Mapping of AD facilities in Australia is available from the University of Southern Queensland (USQ, ND). The majority are still operated by the water, agro-waste or food processing industries. The number of plants accepting post-production food waste is increasing but at present these focus on the commercial sector.

In 2007, EarthPower Technologies constructed Australia's first food waste-to-energy facility designed and licensed to accept solid and liquid food wastes from municipal, commercial and industrial sectors in Camellia, NSW (Veolia, 2017). Feedstock is sourced from businesses involved in food processing and manufacture, transportation, distribution, storage and sales, and from commercial and local government kitchens. The plant consists of two 4600 m^3 digesters with a capacity of up to 50,000 tonnes year^{-1}. Biogas is used to fuel CHP units and the electricity is sold to the grid. Digestate is dried and granulated for sale as a fertiliser into the agriculture and horticultural markets. Heat from the CHP plant is used in the drying process and to heat the digesters.

In March 2016, an AD facility opened at Jandakot near Perth in Western Australia (WA), which can process more than 35,000 tonnes of commercial and industrial organic waste per year. The plant receives solid and liquid waste from commercial and industrial sources such as markets, supermarkets, abattoirs, agricultural companies, and food manufacturers, and includes a de-packaging stage. The material is fed to two 2500 m^3 gas-mixed mesophilic digesters with a 1.2 MW$_e$ CHP plant. Electricity is exported into the grid while surplus heat is used to heat hothouses (WMR, 2016).

In May 2017, Yarra Valley Water opened an AD plant in Wollert, near Melbourne in Victoria (VA), which accepts commercial food wastes, and will process around 33,000 tonnes year^{-1} (YVW, 2017). The plant is located next to an existing wastewater treatment plant and will generate enough energy to run both sites with surplus electricity to be exported to the grid (WMW, 2017).

A facility at Shenton Park plant in Perth WA, to be operated by Eastern Metropolitan Regional Council, is due for completion in 2021. The plant will have a capacity of 60,000 tonnes year^{-1}, but is being designed to accept co-mingled MSW (Bioenergy Australia, 2017). [Acknowledgements: Prof Bernadette McCabe].

4.2 Canada

Canada's federal system of government means the policy framework to facilitate the development of AD varies between the 13 provinces and territories, with significant variations in the uptake of AD as a result. The three provinces that currently have the greatest operating AD capacity are British Columbia, Ontario and Quebec. These are also the most populous provinces in the nation.

There are very few plants that solely digest food waste, or Source-Separated Organics (SSO) as it is termed in Canada. The majority of plants taking SSO co-digest it with other feedstocks, most commonly agricultural manures at on-farm facilities, or less commonly with sewage sludge at waste water treatment plants (WWTPs); there is currently one operating WWTP co-digesting SSO in Saint-Hyacinthe, Quebec, and a further co-digestion WWTP in development in Stratford, Ontario. Stratford's proposed design will process 54 tonnes day^{-1} of food waste in addition to sludge and liquid wastewater. There are a few examples of AD plants digesting SSO as the primary feedstock; these include the City of Toronto's 2 AD plants (total capacity 130,000 tonnes year^{-1}), five municipal SSO AD plants for Quebec municipalities which were in construction or early operational stages at the time of writing, and three private commercial plants all in Ontario.

In Ontario between 2010 and 2017, a Feed-In Tariff (FIT) programme for renewable electricity supported incremental AD market growth, resulting in 40 operational AD plants. The majority of these are smaller on-farm facilities co-digesting agricultural wastes with SSO from commercial or residential sources. In Ontario there are currently four facilities with permitted capacity over 80,000 tonnes year^{-1} licensed to process domestic food waste. These are: the City of Toronto, Woolwich Bio-En Inc, StormFisher Environmental Ltd and Seacliff Energy Ltd.

With the end of the FIT Program, no new AD development has occurred. A number of provinces, however, are pursuing policies to support Renewable Natural Gas (RNG) – methane derived from renewable sources including biogas from AD and landfill gas (LFG), and delivered via the existing gas grid. More detail may be found in the IEA Bioenergy report on Green Gas (Wall et al., 2018).

British Columbia and Quebec have the most supportive RNG policies. British Columbia has direction from its Climate Leadership Plan to support investments that will increase the use of RNG and reduce GHG emissions. The natural gas utility, FortisBC, is enabling the supply and use of RNG and has the ability to procure up to 5% by volume per year. Quebec has similar policy direction aligned with waste management goals of diverting organic materials from landfill by 2022. A draft regulation in Quebec sets a minimum target of 1% RNG by 2020 and progressive increases to 5% RNG by 2025 of natural gas distributed. There are approximately 12 RNG plants currently operating in Canada, many of which are processing some percentage of food waste.

The Canadian Biogas Association provides more information on the recent situation and potential for development of AD in Canada, including the 2013 *Canadian Biogas Study: Benefits to the Economy, Environment and Energy* by Kelleher Environmental (Canadian Biogas Association, 2013). [Acknowledgements: Jennifer Green and Dr Martha Climenhaga].

4.3 China

China's Medium and Long Term Renewable Energy plans of 2006 gave a target of 44 billion m^3 of biogas per year by 2020. In 2000 the Ministry of Housing and Urban-Rural Development (MOHURD) designated eight cities (including Beijing, Shanghai, Guangzhou, and Shenzhen) as pilots, forcing the municipalities to implement innovative policies to resolve urban garbage problems.

Table 8 Food waste digestion capacity in China based on Xu et al. (2016b)

Location	Substrate	Scale (tonnes day^{-1})	Established
Chongqing, Heishizi	Food waste	167 (stage 1)	2012
		500 (stages 2–3)	2014
Lanzhou, Gansu	Food waste	200	2011
Ningbo, Zhejiang	MSW	200	2007
Sanming, Fujian	Food waste and waste oil	30	2009
Erdos, Inner Mongolia	Food waste	100	2010
Kunning, Yunnan	Food waste	200	2011
Beijing	Food waste – co-digested	150	2011
Dongcun, Beijing	Food waste	200	2012
Qingdao, Shandong	Food waste	200	2012
		600	Under construction
Shenzhen	Municipal organic waste	100	2011
Suzhou, Jiangsu	Food waste – after hydro-thermal hydrolysis	100 (stage 1)	2008
		600 (stage 2)	2012
Changchun, Jilin	Food waste	200	Under construction
Longgang, Shenzhend	Food waste – co-digested	200	Under construction

In March 2017, the National Development and Reform Commission and MOHURD selected 46 cities for mandatory garbage sorting, with the goal of achieving a minimal 35% recycling rate by 2020. According to its classification standards, the 'wet' garbage (food waste) must be separated from the 'dry' garbage (other types of waste) in order to reach the recycling threshold. All public institutions, supermarkets, hotels, restaurants, and office buildings are required to follow the rules or face a penalty (Liu, 2017). The pace of adoption in China is indicated by the list of facilities in Table 8 (Xu et al., 2016). [Acknowledgements: Dr Song He].

4.4 Indonesia

Since 2012 the social enterprise Waste4change (http://waste4change.com/collect) has run a source segregated collection serving 100,000 households in Depok, which takes organic waste for composting (Jakarta Post, 2017); it also offers a 3 times per week collection service for source segregated organics. In general, however, there is little separate collection or treatment of food waste in Indonesia. Small amounts of food waste are processed in local schemes using home or small-scale centralised composting and vermiculture. There is very little anaerobic digestion, especially of food wastes, although a number of initiatives (e.g. Indonesia Domestic Biogas programme) exist to promote AD for other feedstocks. The Badan Pengkajian dan Penerapan Teknologi (BPPT, Agency for the Assessment and Application of Technology) carried out some work in 2013 on small-scale digesters modelled on Indian designs. An AD plant has operated on source segregated domestic food waste from 100 households in Cibangkong, Bandung since 2010, and the scheme was expanded to include more small-scale digesters in 2013. An assessment carried out in 2015 suggested that the main economic barrier to uptake was re-usability of digestate (Amir et al., 2015). In 2017 the Ministry of Energy and Mineral Resources introduced favourable tariffs for electricity generated from municipal wastes and biomass, while Indonesia also has a rapidly growing market for Liquid Petroleum Gas (LPG). These factors create favourable conditions for biogas production but given the partial coverage of existing municipal waste collection systems the commercial and small producer sectors may be the first to take up this option. [Acknowledgements: Dr Sri Suhartini].

4.5 Japan

The Japanese government enacted a law on the reuse of food waste (Syokuhin risaikuru hou) in 2001. The main emphasis is on reduction and re-purposing, but anaerobic processing of food waste is included as a route for reuse.

Anaerobic digestion is in use and promoted for agro-wastes but is not common for municipal wastes due to the dominance of incineration for waste resource recovery. Some large companies use anaerobic digestion to process waste from manufacturing of soy sauce and shochu production as well as other food products.

The first biogas plant for domestic food waste started in 2000 in Niigata Prefecture, before the introduction of the law on food waste. A scheme collecting domestic food waste for biogas production started in 2003 in Kitasorachi, Hokkaido. The digestion plant received an average feed of 9 tonnes day^{-1} and produced approximately 1000 m^3 day^{-1} of biogas. The biogas was used to generate electricity in a CHP plant with a capacity of 94 kW; some of the produced heat was utilised for heating roads in winter to prevent ice (Sawayama, 2009).

At Oki in Fukuoka Prefecture 3.8 tonnes day^{-1} of source separated household food waste is co-digested with 14.3 tonnes day^{-1} of septic tank and human wastes. The food waste is collected twice a week in special containers. The biogas produced is used for electricity generation in two 30 kW CHP units, while the digestate is applied to rice paddies and wheat fields (MAFF, ND). The scheme started in 2006 and is part of the Biomass Town initiative supported by the Japanese Government in locations across south-east Asia (MAFF, 2017). [Acknowledgements: Dr Chihiro Masusawa].

4.6 Malaysia

The majority of food waste goes to landfill, apart from backyard composting for personal use and some small-scale community or business schemes. In Kuching South city, for example, organic wastes from markets are collected for composting, and the vendors receive around 1 kg of compost each month for contributing vegetable waste to the project (Borneo Post, 2012; Star2, 2015). A similar collection scheme at a wet market in Serdang has a small-scale AD plant operated by Subang Jaya Municipal Council and Universiti Putra Malaysia (UPM, 2012, 2013).

At a national level, the Solid Waste Management & Public Cleansing Corporation (SWCorp) identified food waste as an issue in its 2015-2020 Action Plan; it is planned to introduce 20 pilot schemes aimed at collection and composting. It has been noted that one issue with implementing new schemes is the fact that types of waste requiring similar treatment are regulated by different bodies; for example food waste is regulated by the National Solid Waste Management Department (Jabatan Pengurusan Sisa Pepejal Negara, JPSPN) and sewage by the Ministry of Energy, Green Technology and Water (Kementerian Tenaga, Teknologi Hijau dan Air, KeTTHA).

A detailed review on solid waste management strategies and targets was carried out by the Solid Waste Management Lab Government Transformation Programme (KPKT, 2015a), and considerable emphasis is being placed on development of life cycle assessments to identify the best systems. The National Solid Waste Management Department has a Food Waste Management Development Plan for Industry, Commercial and Institution Sector (2016 – 2026) (KPKT, 2015b) and is currently developing a National Strategic Plan for Food Waste Management in Malaysia in conjunction with the government of Japan (UNCRD, ND). Separation at source of solid wastes became mandatory in some states in Malaysia from 1 September 2015 (KPKT, ND). [Acknowledgements: Jethro Adam]

4.7 Singapore

AD of food waste is not well developed in Singapore as around 84% of the total food waste produced (around 0.81 million tonnes year^{-1}, making up 10% of total waste in 2017) is incinerated. The National Environmental Agency has set up a pilot scheme, however, to co-digest food waste collected from schools, army camps, markets, food courts and manufacturers with sewage sludge with the aim of achieving energy neutrality in wastewater treatment (Today on Line, 2017). The CO-DIGESTION pilot-scale programme is still on going. If successful, it will be rolled out at all sewage treatment plants. While the majority of initiatives are focused on reduction of food waste, there are also some small-scale collections with on-site AD and composting demonstration schemes in hotels, shopping malls, supermarkets and educational institutions (Wong, 2016). [Acknowledgements: Dr Yongqiang Liu].

4.8 South Korea

South Korea banned food waste from landfill disposal in 2005. In 2010, the Ministry of Environment in collaboration with the Ministry for Food, Agriculture, Forestry and Fisheries, and the Ministry for Health, Welfare and Family Affairs launched a major food waste reduction initiative based on voluntary agreements with different outlets including restaurants, hotels and schools. The first steps in promoting pay-as-you-throw systems were also introduced. Since 2013 Seoul and a number of other cities have charged for source separated food waste collection from households on a volume or weight basis with tracking systems to monitor the status of the collection and the charge per household. As a result of these and related initiatives South Korea is considered to have one of the most advanced food waste management systems in the world, which complies closely with the food waste hierarchy and has led to significant reductions in the amounts generated.

A proportion of the collected food waste is processed into animal feeds, and much of the remainder is sent for anaerobic digestion. In 2012 there were 12 food waste digesters producing 31.3 Mm^3 biogas/year and 9 co-digesting food waste and animal manures producing 13.3 Mm^3 biogas year. Seven food waste plants and 8 co-digestion plants were in construction and a further 5 in the planning stage. By 2016 there were 32 biowaste (food waste and co-digestion) plants producing 709 GWh year^{-1} according to IEA Bioenergy Task

37 Country report (IEA Bioenergy, 2017a). The current trend is for co-digestion with animal manures and sewage sludges. The current Bioenergy Strategy has a target to increase biogas production by a factor of 4 by 2030. The majority of the biogas is utilised for electricity production but there is a growing trend for biogas upgrading and utilisation as a vehicle fuel, with 6 biomethane filling stations established by 2016.

The Ministry of Environment has also funded research on Organic Wastes to Energy with a budget of US$74 million from 2013–2020. This includes construction of a 1800 m^3 food waste AD plant for food waste and research into biogas upgrading, odour control and digestate application as well as operation and maintenance training. [Acknowledgements: Dr Soon-Chul Park]

4.9 Thailand

Anaerobic Digestion for food waste in Thailand is still a complex issue and the technology is not currently in widespread use. There have been many pilot schemes, but most were unsuccessful or not sustainable. One example of a scheme which is operating regularly is at Nakorn Ratchasima City Municipality, Nakorn Ratchasima Province. The municipality manages 422 tonnes day^{-1} of MSW. Of this 21 % or 88 tonnes day^{-1} of source separated waste enters the anaerobic digestion facility producing 0.8 MW of electricity. The rest of the waste, 79 % or 333 tonnes per day, is disposed of in a landfill. The source separated wastes are collected from markets, schools and canteens; households in the city do not separate food waste. The Development of Environment and Energy Foundation has operated this facility since 2012.

Sung Noen Municipality in Nakorn Ratchasima Province has a dry AD facility for mixed MSW but is not yet able to sell the electricity to the grid, so the biogas is burned off in a flare.

Other pilot schemes include smaller units in schools or educational institutions, though these may suffer from lack of food waste during school holidays. Some communities operate small units but often encounter problems of lack of staff and budget for proper operation and maintenance. In rural areas there have been pilot schemes to promote small, simple AD units to co-digest household food waste and waste from farm animals to produce cooking gas.

The Bangkok Metropolitan Administration (BMA) is planning to build an AD facility, and a private company intends to build a facility taking food waste from hypermarkets, department stores and malls; but details of these schemes have not yet been released. [Acknowledgements: Anuda Tawatsin]

4.10 United Kingdom

The Waste Resources Action Programme estimates that the UK's post-farm gate food waste is approximately 10 million tonnes $year^{-1}$, of which 7.3 million tonnes $year^{-1}$ is household food waste, with 4.4 million tonnes $year^{-1}$ designated as avoidable food waste (WRAP, 2017).

Since 2007 a number of initiatives have been put in place, in order to reduce food waste across the supply chain and in households. This has resulted in a 2007-2015 reduction in avoidable household food waste of 17% with an equivalent value of £2.7 billion. Retail food waste dropped 15% between 2009 and 2015, with manufacturing food waste dropping by approximately 10% from 2011 to 2014 (WRAP, 2017).

In 2014-15, 93% of households in Wales, 75% of households in Northern Ireland (NI), 57% of households in Scotland and 46% of households in England had access to food waste collection (WRAP, 2016). With the devolved administrations implementing clear policies for separate household food waste collections, by 2016/17 these had increased to approximately 97%, 84% and 80% for Wales, NI and Scotland, respectively, with access decreasing for English households only to just over 40%. Poor figures for England are due to a number of reasons, including budgetary constraints, a larger population than in the devolved administrations and the diversity of Local Authority collection arrangements. Nevertheless, where implemented, the majority of collections are now FW-only collections, as opposed to food and garden waste collections.

WRAP provides AD operators and Local Authorities with a range of tools to increase household food waste collected for recycling (WRAP, ND). ADBA analysed 2012-13 data from 64 UK Local Authorities and found that the capture rates varied from 0.28 to 2.2 kg $household^{-1}$ $week^{-1}$ (ADBA, 2018).

There are numerous drivers to remove food waste from landfill and to create dedicated food waste collection systems. The EU's Circular Economy Package, whilst not yet enshrined in UK legislation, obliges member states to arrange for separate biowaste collection by 2023 and the Department for Environment, Food and Rural Affairs (Defra) is working towards zero food waste to landfill by 2030. WRAP's Food Waste Recycling Action plan is an industry led initiative to improve the capture, supply and quality of household and commercial food waste with several aims, including the provision of long-term sustainable feedstocks for the AD and in-vessel composting (IVC) sectors.

Currently, there are 84 AD plants in the UK solely treating municipal/commercial wastes and 32 plants treating a mixture of agricultural and municipal/commercial wastes, with approximately 8% of the UK's food waste is being sent to AD (ADBA, 2018). Ninety-three AD plants produce electricity, with 73% of those producing between 0.5 – 5 MW_e. Under the Renewable Heat Incentive (RHI) introduced in 2011, there are currently 23 UK AD plants producing biomethane. The Feed-In Tariff (FIT) for renewable electricity production closes on 31 March 2019 and successive rate degression means that RHI (biomethane) plants are currently the favoured option for energy utilisation. One of the new rules introduced for the RHI on 22 May 2018, following more than a year of uncertainty and delay, stipulated that new plants must produce at least 50% of their biogas from waste or residues in order to be eligible for full support. This is likely to act as a further driver to recycle these materials through AD.

With increasing competition, particularly in England, gate fees for AD plants receiving food waste have continued to fall from £35 $tonne^{-1}$ in 2014-15 to £23 $tonne^{-1}$ in 2017, with operators reporting commercial contract median gate fees at £11 $tonne^{-1}$ and the lowest fees dropping below £0 (i.e. facilities paying for material) (WRAP, 2018).

The RHI scheme is due to close by 2021 and there are currently no policies to replace it. Industry is working with government in order to bridge the policy gap between current UK policy on climate change and its Climate Change Act commitments, with estimates of separate food waste collections achieving 1-1.5 $MtCO_{2e}$ reduction and helping to close 10-15% of the policy gap (ADBA, 2018). [Acknowledgement: Angela Bywater].

4.11 Vietnam

In Vietnam there is little or no separate collection of food waste and to date no anaerobic digestion schemes have been applied to deal with this type of waste. The National Environment Report of Vietnam (MONRE, 2011) stated that strategies to 2025 will focus on methods to recover energy and materials from MSW in cities. Recently, the Government of Vietnam has also approved adjustments to the national strategy for general management of solid waste to 2025 with a vision towards 2050. The strategy sets a target that 90% of the total MSW generated from cities must be collected and treated to meet environmental standards with progressive technologies to boost technological innovation in reuse, recycle and waste-to-energy processes (Vietnamese Government, 2018).

In 2015 the total MSW generated in urban areas in Vietnam was about 38,000 tonnes per day (13.87 million tonnes annually), in which food wastes account for about 60%. The increasing rate of MSW annually is about 12% (MONRE, 2016). However, currently, all 35 MSW treatment plants in Vietnam are using landfilling, incineration or composting (MONRE, 2016). Some recent studies have indicated that there is a very high potential in producing biogas via anaerobic digestion process from MSW in Vietnam (Nguyen et al., 2014; Nguyen et al., 2016).

Small-scale anaerobic digestion of animal wastes is widespread in rural areas. It was estimated that in 2013, nationally there were more than 500,000 household-scale digesters with volumes from 7-20 m^3 (USTA, 2017; FAO, 2012). Some biogas programmes have been sponsored in Vietnam to contribute to the Vietnamese government's target of 2 million small biogas plants by 2020 (FAO, 2012; SNV, 2018). [Acknowledgement: Dr Hoa Huu Nguyen].

5. Conclusions

The anaerobic digestion of post-harvest food waste arising from processing and consumption of food is energetically favourable and, because of the high moisture content of food waste, is a more effective approach for energy recovery than thermal processing. Stable food waste digestion has now been shown to be possible at commercial scale, despite the high ammonia concentration, through selective trace element addition to promote a more resilient microbial community. The elucidation and verification of this has been a useful example of research delivering a solution to allow anaerobic digestion to be applied to what were previously thought to be very difficult substrates. There are still further measures that could be undertaken to recover nutrients from food waste as a contribution to the circular economy; but perhaps one of the largest contributions of food waste digestion was unforeseen when work to promote it began in the UK 15 years ago. The very act of collecting source separated food waste has raised our awareness of this material, and seeing it in our homes, canteens and restaurants has led to the development of the food waste hierarchy and to reductions in the overall amount of food waste generated.

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IEA Bioenergy

Task 37 – Energy from Biogas

IEA Bioenergy aims to accelerate the use of environmentally sustainable and cost competitive bioenergy that will contribute to future low-carbon energy demands. This report is the result of the work of IEA Bioenergy Task 37: Energy from Biogas.

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