Household Food Waste Treatment Technologies

- A Systematic Review

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Introduction

Household consumption and associated waste management issues have a significant environmental impact (UNEP 2014). Of all household generated waste, food waste (FW) makes up 30 - 68% of the total municipal solid waste (MSW) in developed countries and 20 - 45% in developing countries, Fig. 1. In this regard, it is predicted that the world's urban population will increase rapidly from 50% (in 2008) to 64.1% in developing countries and 85.9% in developed countries by end of 2050 (Department of Economic and Social Affairs of the United Nations Secretariat 2013). This increase in urban population will mean even greater and more complex sustainability challenges in the future in relation to household waste.

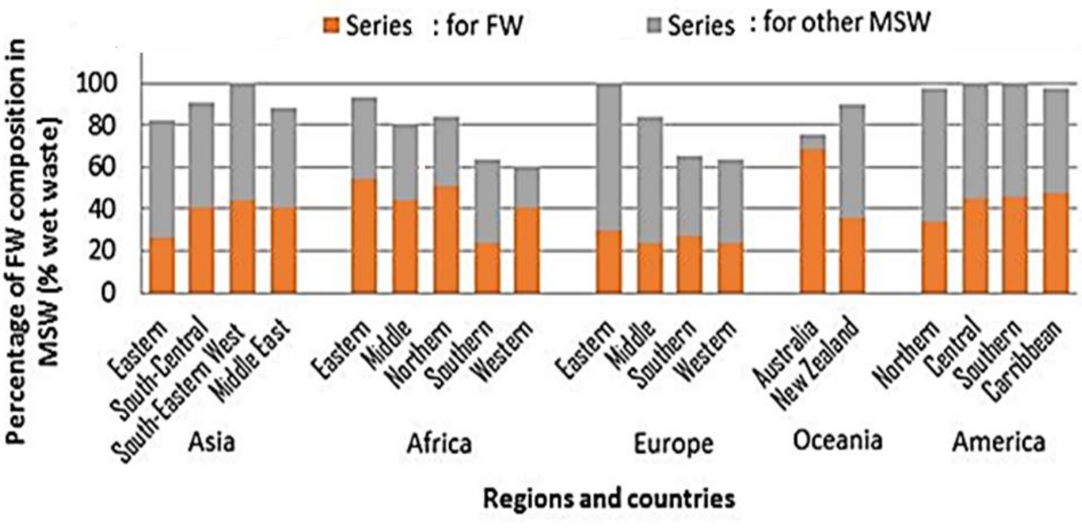


Fig. 1 The percentage of different waste types in municipal solid waste in different regions and countries (reproduced from Pham (2015)).

Over the last 23 years the International Union for the Conservation for Nature and Natural Resources (IUCN) finally developed and released a plan for sustainable development (Thiele 2013) in order to realign and strengthen the design and deployment of human activities internationally. The concept of "Toward Zero Waste" has been adopted and implemented by some governments worldwide. Thus strategies such as 3R; namely, Reuse, Recycle and Recovery; and Circular

Economics are now common practices in waste management, especially in the food industry (Mirabella 2014). However, all these activities are on a macro scale requiring considerable resources including land, manpower and energy, which have significant implications for the environment. Palmer (2004) has said: “The money that is wasted on garbage collection and dumping is money that is spent to destroy our planet”. Thiele (2013) stated that the concept of sustainability always provides room for improvement and must be based on balancing ecological health, economic welfare and social empowerment.

Sustainability is not just simply minimising negative impacts but is also concerned with maximising positive impacts on our environment. It may also be argued that management or development will not be sustainable without an economic benefit. Indeed, since 2012 the physical environment has been linked with economics as “asset flows” in the System of Environmental-Economic Accounting – Central Framework (United Nations 2014).

Due to the wide range of substances in FW and its lower calorific value and methane generation potential, a dedicated treatment system(s) for this waste is required. However, any development and use of household FW treatment and management systems will be affected by a wide range of factors including a country’s GDP, transparency index, educational levels, religion and culture, policy planning, availability of appropriate technology, waste collection, characterisation and separation techniques, the market for recycled material and people's awareness of sustainability (Rousta, Richards & Taherzadeh 2015). For this reason, innovation and development of FW technology and management systems, especially those that can be used at the community or household level, is extremely challenging.

Through reviewing current international research papers and reports, this paper aims to identify and compare the advantages and disadvantages of current technologies and relevant operating systems for the management of Household Food Waste (HFW) worldwide. The papers/reports that have been selected place an emphasis on Life Cycle Assessment (LCA) as a tool for comparing various food waste management methods. An attempt is also made to relate this information to our concept of “Micro Circular Economics” (MCE) – an offshoot of Circular Economics (CE) (Ellen MacArthur Foundation 2015). Thus we attempt to relate new technological developments to innovative management systems in order to ensure that the management of HFW will benefit both the environment *and* the economy.

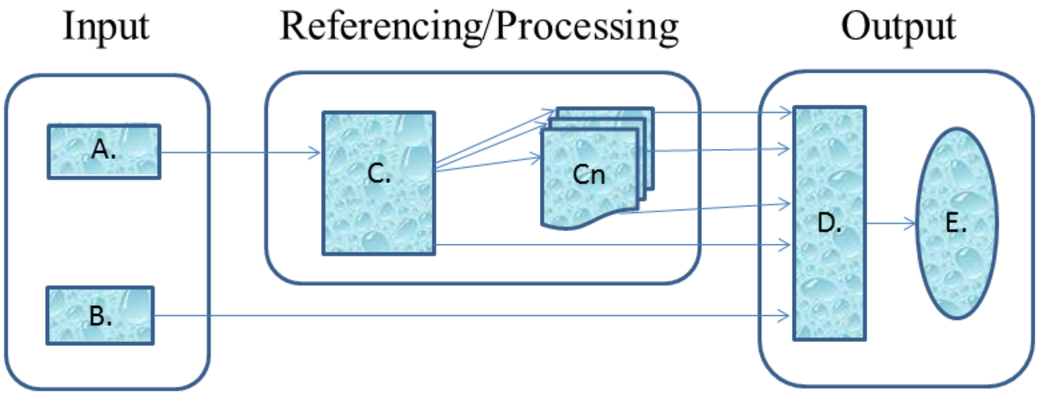
Methodology

Literature search strategy

This review uses standard desktop searching tools including Google Scholar, Web of Science and Science Direct, as listed in Table 1. Citation collections will also be included in the review using the Snowballing method (Mason 2011). Information from public databases, post 2009 (Laurent, Clavreul, et al. 2014), will also be accessed from government and organisational websites. Fig. 2 shows the process that will be used to undertaken this literature review. The United Nations (UN), the European Unit Commission (EUC) and available Government databases will also be used in searching for relevant data of selected research papers.

Table 1 List of academic databases and search engines

Name	Discipline(s)	Description	Provider(s)
EBSCO Information Services	Multidisciplinary	Online research service which includes 375 full-text databases and over 600,000 e-books	EBSCO Publishing (https://www.ebsco.com)
Elsevier including • Science Direct, • Scopus, and • Elsevier Research Intelligence	Multidisciplinary	Elsevier is a world-leading information and analytics provider. It covers 2,500 journals and contains over 13 million documents. It publishes over 400,000 articles with over 900 million downloads annually. It also the world's largest peer-reviewed research literature database which contains over 20,500 titles from more than 5,000 international publishers.	Elsevier Publisher (https://www.elsevier.com)
Google Scholar	Multidisciplinary	Includes the most peer-reviewed online academic journals and books, conference papers, theses and dissertations, preprints, abstracts, technical reports, and other scholarly literature, including court opinions and patents. Covers approximately 80-90% of all articles published in English.	Google (https://scholar.google.com)
SpringerLink	Multidisciplinary	SpringerLink is a global publishing company that publishes books, e-books and peer-reviewed journals in science, technical and medical (STM) publishing. It also hosts a number of scientific databases.	Springer (http://www.springer.com/gp/)
Web of Science	Multidisciplinary	The Web of Science Core Collection covers over 12,000 of the highest impact journals worldwide.	Thomson Reuters (http://thomsonreuters.com/en.html)
WorldWide Science	Multidisciplinary	A one-stop database searching engine-a 'global science gateway' which comprises multi-government organisations. It "provides real-time searching and translation of globally dispersed multilingual scientific literature".	The United States Department of Energy, Office of Scientific and Technical Information serves as the operating agent for WorldWideScience (http://worldwidescience.org/)



A.: Scholarly articles selected from database listed in Table 1;
B.: Information from UN, EUC and available governments database;
C.: Reference; Cn.: processing of reference;
D.: Evaluation and comparison of relevant information; and
E.: Results and conclusion.

Fig.2 A schematic of the literature review process. The number of publications and references contained therein that cover waste treatment technologies is obviously very large. In order to establish a practical system for reviewing such literature, selection criteria need to be formulated. In this paper, there will be a focus on Life Cycle Assessment (LCA) and the biological treatment of waste using anaerobic digestion, whilst for other technologies, assessments will be based on.

Life cycle assessment (LCA)

LCA, as assessed by ISO 14044 (2006), has become an important measuring tool for monitoring sustainable waste management. The ISO 14040 and 14044:2006 Standards Handbooks have provided the basic framework for specific applications, along with international reference guides. Based on the ISO Standards Handbooks a number of models have been developed during the last two decades (Table 2). Each model has its own focus point and drawbacks.

As a science-based methodology, LCA has been used since the 1970s to study the environmental interventions and potential impacts throughout a life cycle from raw material acquisition to production, use and disposal (i.e. from cradle-to-grave). It is intended to quantify all environmental impacts in order to assist decision making and to choose appropriate waste management systems for different countries, cities or local communities (Abeliotis, Kalogeropoulos & Lasaridi 2012; Cherubini, FB, S; Ulgiati, S 2009; Cherubini, FS, A. 2011; Güereca et al. 2006; Hertwich 2005; Hoefnagels 2010; Messina 2012; Tonini, Martinez-Sanchez & Astrup 2013; Vandermeersch, TA, R. A. F.; Ragaert, P.; Dewulf, J. 2014).

Table 2 Life Cycle Assessment Models, application scenarios and critique

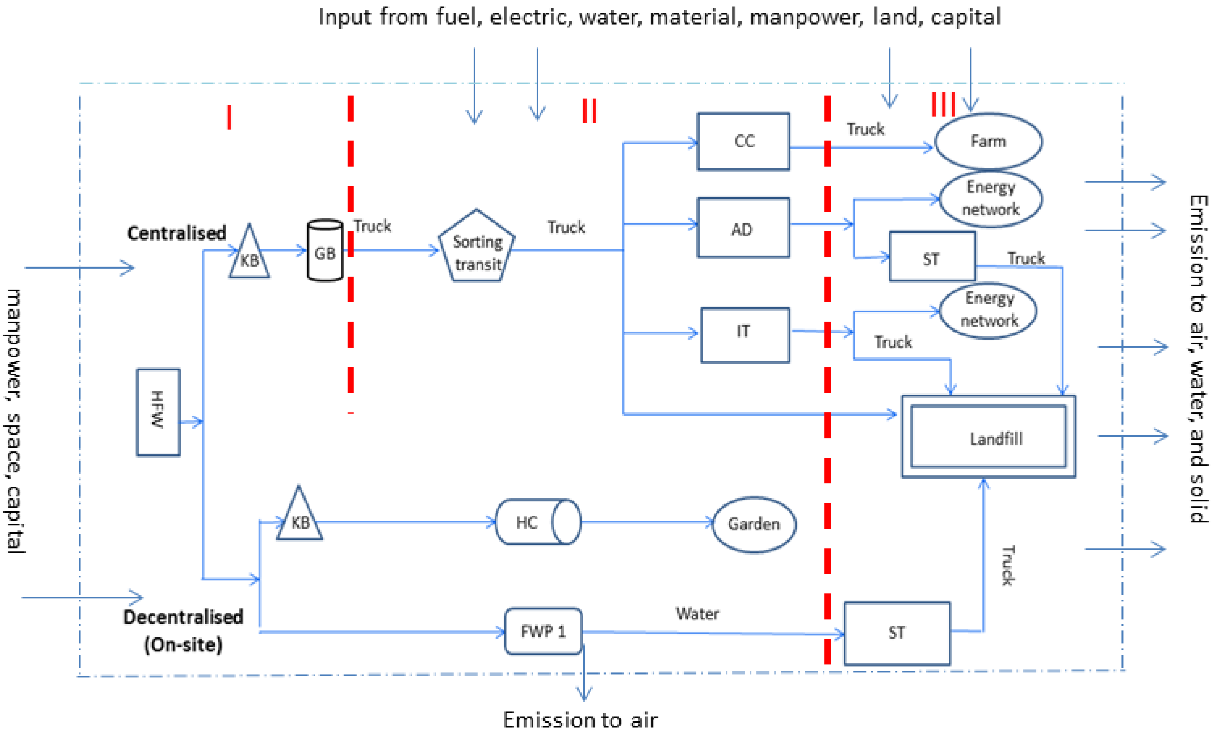
Model name	Framework	Mainly applies to:	References	Critique
SimaPro software	Based on input-output materials flow	Analysing environmental burden	Zaman, AU (2010) Bovea et al. (2010) (Spain): for assessment of alternatives Song, Wang and Li (2013) (China): for environmental performance of MSW-MS	Limited time frame
WISARD	Not available	Vague	Feo and Malvano (2009) (Italy): for selecting the best MSW-MS	Does not support the inclusion of other waste types and does not provide economic evaluation or geographical coverage.
Umberto 5.5 software	Not available	Vague	Pires, Martinho and Chang (2011) (Portuguese): for a future MSW-MS	
WRATE modeling	Not available	Vague	Tunesi (2011)(England): for the assessment of different energy recovery strategies	
EASEWASTE	Most commonly used model. Constructed from individual elements and includes and the quantitative relations between these elements. Describes the unit processes of the waste management system, such as waste collection by truck or an incineration technology.	Evaluation of the environmental performance of the various elements of existing or proposed solid waste management systems. Land assessment, material sorting and recycling, bottom and fly ash handling, material and Mainly developed for waste types from households and small commercial business units. Tracks the impact of individual technologies, waste sources, material fractions, or individual substances.	Slagstad and Bratteb ø (2012)(Norway): for assess different alternatives. Bernstad and la Cour Jansen (2012a) (Sweden): for HFWM. Merrild, Larsen and Christensen (2012) (Denmark) Bhander, Christensen and Hauschild (2010)	Does not support the inclusion of other waste types and does not provide economic evaluation or geographical coverage.
ORWARE	Rarely used		Eriksson et al. (2005) et al (Sweden)	

LCA FW management system boundary and function unit

System boundary and inventory: Over recent years LCA has progressed from focusing, not only on environmental impacts, but also on costings and on the impacts of socio-economic considerations. These developments have resulted in LCA becoming a comprehensive sustainability analysis tool (Korse 2015). Turner, Williams and Kemp (2016) have also demonstrated that LCA can give valuable information for decisions on waste management systems. Meanwhile the principles of Circular Economics (CE) ("cradle-to-cradle") have been also put into practice in more and more industries, especially following the influential publication of "The Economics of the Coming Spaceship Earth" (Boulding 1966). All of these different concepts have made the waste management options even more varied and complex. Therefore when considering difference waste management options, the definition of scope and system boundaries in avoiding uncertainty is essential.

The boundary in this research ranges from the collection of HFW to its final disposal point or to its residual, as shown in Fig. 3. More specifically, it includes direction and indirection of matter flow from natural sources to humans, Fig. 3. Within this boundary, the centralized line of 'formal disposal methods' is divided into three Sections, indicated as I, II, and III in Fig. 3. Section I represents the source of HFW and disposal on site, along with the on-site disposal of 'informal routes' which will also be covered in this section. Section II represents the first level of treatment of HFW, which includes the collection, sorting/separating, transportation, CC/AD/IT treatment, systems operation and management - as well as resource and energy flow. The increasing use of FWP from the on-site line will also be included in this Section. Section III will cover the transport of the product from CC to farm land or market, the AD residual second treatment in a sewage treatment (ST) plant and final product distribution. Transportation and landfill of the ash from IT, and all the activities management and the resource input will also be covered in Section III.

The impacts of HFW management affect not only individuals but the whole society. HFW starts from the household's kitchen, from internal to external storage, followed by a collection and sorting operation by council services or contractors using truck and transit facilities. For a centralized facility, the waste will be disposed of in one of three main directions: i.e. burned in a waste-to-energy facility or converted to compost or burial at a landfill. However, the last two options will result in the generation of methane gas – a major cause of global warming.



I = Section I; II = Section II; and III = Section III

AD: Anaerobic digestion plant; CC: Commercial composting plant; FWP: food waste processer; GB: garbage bin; HC: home composting; HFW: household food waste; IT: Incineration treatment plant; KB: kitchen bin; and ST: sewage treatment plant

Fig. 3 Road map of management system with upstream input and downstream outflow

Function unit: The function unit is established to assess the impacts on the environment and the economics (Carre, Crossin & Clune 2015). The unitary function unit is the foundation by which comparisons can be made using different management systems. In this paper the management of 1 kg FW is selected. All treatments, emissions, resources and materials flow calculations will be based this weight.

Selection of indicators

The HFW management comparison will be undertaken to include environmental, economic, and social considerations.

Environmental impact: The indicators for environmental impact comparisons will focus on three categories and nine sub-categories that commonly used in LCA. These indicators are commonly used for those basic assessments that are considered to be important for both the local and the wider community. They are:

- Non-toxic impacts that include: GHG emissions, acidification potential, eutrophication potential;
- Toxic impacts that include: human toxicity potential, eco-system toxicity potential including terrestrial and aquatic environments;
- Resource usage that include: energy, water and land.

Economic and social impacts: The socioeconomic impact of FW has been assessed separately under the sociological and economic topics:

- Sociological: in this topic we only discuss guaranteeing the reliability of energy supply; ensuring the safety of people, facilities, and regions with an emphasis on a long-term sustainability plans with regular monitoring.
- Economic: This topic involves maintaining viable production, distribution and consumption of goods and services, short and long-term profitability of feedstocks, interaction with technical advances, costs of production and transport and distribution costs and benefits. It is influenced by the price of production.

Another important consideration is that existing data shows that occupational accidents in the waste management industry are relatively common and, on the basis of epidemiological studies, are much higher than the national average for other occupations (Giusti 2009).

Systematic analysis tool

Qualitative interpretation: The management system of FW covers the period from household collection to waste disposal. Consistent with common practice, this review will include FW as part of MSW.

In the discussion of management systems, this review will also take into account economic, cultural and geographical factors together with new technological advances (Dellinger 2013; Rousta, Richards & Taherzadeh 2015).

A study undertaken by the Food and Agriculture Organization of the United Nations (FAO) (Food and Agriculture Organization of the United Nations 2011) reported that the amount of FW generated from developed countries is 10 times that of developing countries. Australia, as a developed country, will be compared with similar countries such as those in the European Union, in North America, Japan in Asia, as well as the two highest populated underdeveloped counties, China and India. (Department of Economic and Social Affairs of the United Nations Secretariat 2013; Oxford Dictionaries n.d.).

Results

Searching Results

Keyword combinations (and/or) used for this review include the terms “household food waste”, “household kitchen waste”, “MSW”, “treatment”, “management”, “life cycle assessment”, “comparative” and/or “comparison”. The initial search included all available sources including books and journals and included titles, abstracts, keywords, SU Subject terms and AB Abstracts. The time frame was from 2006 to 2016 and the search selected full text and peer reviewed articles in the English language. The Google Scholar search resulted in 781 articles. 776 were from academic journals, 4 were from dissertations/theses and 1 was conference material. 519 of these references included information on either LCA or environmental assessment and 222 included articles on MSW treatment. 74, 53, 60 and 130 articles included information on composting, anaerobic digestion, landfill and incineration, respectively. A search of ScienceDirect, resulted in a total 29 articles, of which 8 related to LCA or economical assessment, 7 related to anaerobic treatment issues and 2 to household attitudes. Searches using the keywords of “household food waste” and “treatment technology” resulted in 50 relevant articles. 28 articles were found from the other sources as listed in Table 1 and also from Pergamon Press and the American Chemical Society. Combined, all the HFW treatment results can be divided into two systems - centralized and decentralized, with four technologies; namely, biological, thermal, landfill and food waste processing.

HFW treatment systems

HFW has some characteristic properties, including a high moisture content (up to 80- 95%) and a high salt content. It also contains protein, starch, fat and other organic matter, and is rich in nitrogen, phosphorus, potassium, calcium and other trace elements. Other substances present in HFW may include harmful chemicals, pathogenic microorganisms, flies, cockroaches and rats. Because of these potentially harmful characteristics, HFW must be disposed almost every day in some countries or cities, especially where there are high temperatures. For example, the amount of HFW generated from a city of 200,000 households would potentially generate up to 200,000 kg of FW, assuming each household disposed of about one kilogram of food waste per day. The high amounts of HFW lead to a heavy workload and considerable expense for local authorities with respect collection, processing and disposal. In order to reduce the costs to councils, HFW has traditionally been mixed with other MSW prior to landfill disposal. However, this method of collecting waste has had a detrimental impact on our environment.

Following increasing concern by communities on the environmental impact of HFW, many governments around the world have started to change or adopt new food waste treatment (FWT) practices. However, existing disposal practices may be entrenched having been shaped by long-standing government policy and finances, politics, planning and geographical considerations. Other considerations include land availability, size and population density and the degree of urbanization. Other factors include water resources, income and lifestyle factors, cultural and eating habits, education levels and community environmental awareness.

Two system models for household FW disposal from primary processing points (Fig. 3) may be considered; namely, centralised treatment and on-site/decentralised treatment. The technologies employed in these two systems may be put into four categories: biological technologies, mechanical biological treatment, thermal technologies and landfill technologies (WSN Environmental Solution 2005).

Centralized treatment systems:

Centralised treatment is the major urban residential model and is mostly run by local government and/or private contractors. The centralised system includes collection, separation and treatment processes.

Collection and sorting: HFW starts from the household. For source-separation the FW is stored either wet or dry two. The wet method is the most common method that simply stores the FW inside a house bin prior to collection. The dry method is used in some countries or areas that involve putting FW in bench-top containers to firstly dry-off the liquid and then seal the waste into a biodegradable or paper bag. The dried food scraps are then stored in a garden organics bin for fortnightly or even three-weekly collection. In the summer time, the FW may also be stored in the fridge until the green organics collection day in order to reduce odour (ZWSA 2010). A common practice is the mixing of FW with other household waste in a MSW bin for council collection once a week/fortnight.

With both of these methods, the FW begins biological breakdown from the time it is placed in the storage container. Thus, during storage, large changes can occur with the FW including a loss of carbon and nutrients (Bernstad 2012). Bernstad and la Cour Jansen (2012b) stated that dewatering of FW using paper bags on-site before collection would have less impact on global warming when compared with the four other current systems. This view was made in relation to the Swedish context.. Rigamonti, Grosso and Giugliano (2009) commented that when the source-separated collection rate achieved 60%, the MSW treatment has less impact on the environment.

FW processing: It is common practice to mix FW with other MSW prior to being sent to a commercial garbage depot site or transfer station. The garbage stream is then transferred to up to four different treatment facilities depending on regulations. The four treatments are commercial composting, anaerobic digestion, incineration and landfill.

Decentralized/On-site treatment system:

With on-site treatment the FW is treated within households without being transferred to the council's garbage collection system. There are two most common practices in developed countries: home composting and the treatment of FW using a food waste processor under kitchen sink. Home composting is normally used by residents who live in a house with a certain size of backyard. For household FW composting a number of treatments are used including container composting, sheet composting, trench composting or vermicomposting (Wikiperdia n.d.). The FW is normally kept in the kitchen bin for later transfer to a compost bin. In order to avoid anaerobic reactions and to prevent insects and animals being attracted to the decomposing FW, there are some rules that need to be followed, such as no meat in the FW and the FW should be mixed with garden trimmings (Nair & Okamitsu 2010).

FW treatment technologies

Biological treatment

Anaerobic digestion (AD) is a commonly used biological treatment for FW together with aerobic composting. Anaerobic digestion is a process which generates biogas for electricity generation. Within the AD process, the organic material is broken down by microorganisms in the absence of oxygen to produce biogas. It includes the stages of hydrolysis, acidogenesis, acetogenesis and methanogenesis (Figs 4 & 5).

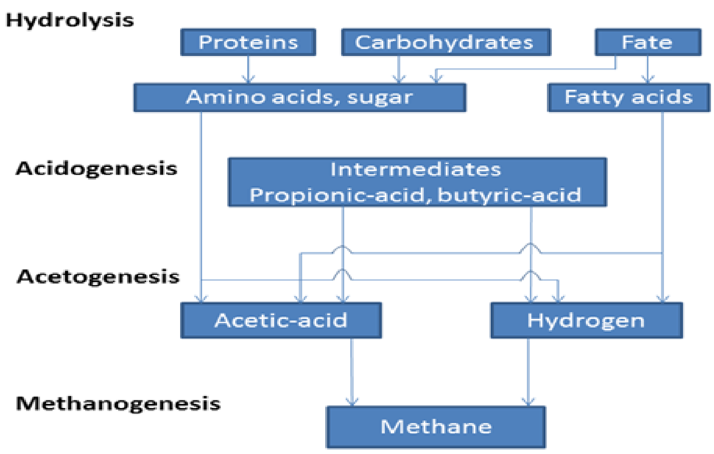


Fig. 4 The anaerobic digestion processes (reproduce from Tsang (2013))

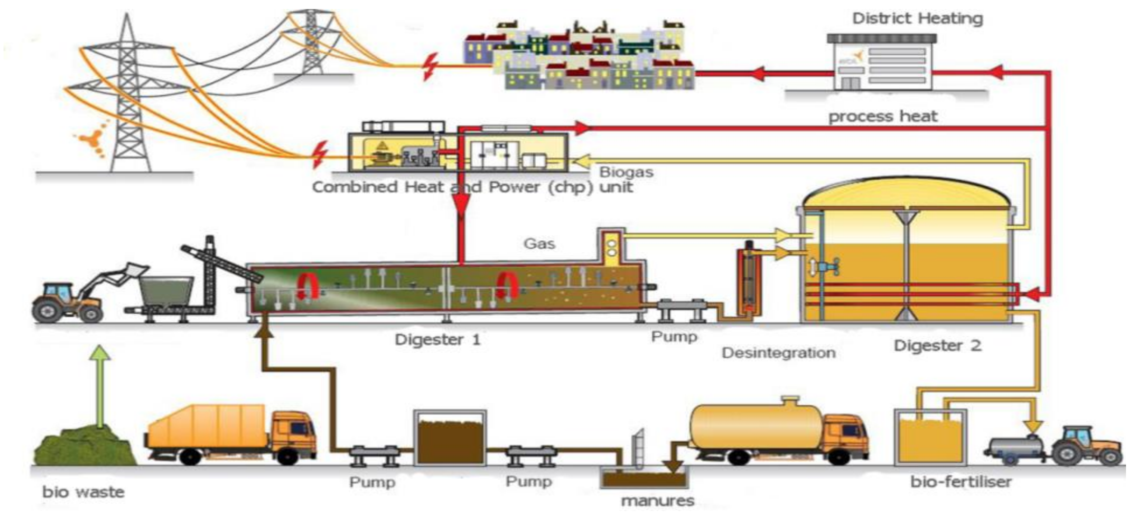


Fig. 5 Commercial anaerobic digestion plants (http://www.fabbiogas.eu/en/home/about-biogas/)

FW is an ideal substrate for AD as it contains 80-97% of volatile solid (VS)/ total solid (TS), 70-90% water per total weight and a carbon to nitrogen ratio (C/N) range from 14.7–36.4, (Zhang, C et al. 2014; Zhang, R et al. 2007). Four processes are involved in commercial scale AD: biodegradable waste separation and removal of contaminants, homogenization and pre-treatment, biogas generation by anaerobic digestion and residue post-treatment (Kosovska 2006). There is also a number of "small-scale" AD reactor units that have been installed worldwide, mainly in rural areas - because of the large size of the reactor units that have long reacting times of around 40 days.

For the main stage of AD, the pH, temperature, nutrient level, C:N ratio are important for the efficient operation of the process (Tampio et al. 2014; Zhang, C et al. 2014).

Given the advantages of AD in waste treatment for energy, environmental and economic considerations, in comparison with to other treatments (Ariunbaatar 2014), the AD process has attracted numerous research studies. Most developed countries in the world are now moving towards the banning of the transfer of FW to landfill. However, due to high moisture content and air pollution, incineration or gasification as alternative treatments is a problem, along with disease potential if animal feed is considered to be an option. More recently, AD treatment of FW has become increasingly popular due to environmental benefits and positive economic benefits. However, the development of small-scale of anaerobic digesters is still facing great challenges due to long reaction times and low methane gas production (Zhang, Q, Hu & Lee 2016).

Aerobic digestion (AD) - Composting: AD has a very long history as an important method for the biological treatment of FW. In this process FW and organic waste are degraded by microorganisms such as bacteria and fungi in the presence of oxygen, 60-70% of moisture content, heat and a carbon nitrogen ratio (C/N) of 30/1 for a period more than 6 weeks (Recycled Organics Unit 2007; Tweib, Rahman & Khalil 2012). The major elements involved in the composting process are shown in Fig. 6. However there are some organic wastes such as meat, fish and cooked food that cannot be composted (Diener et al. 1993).

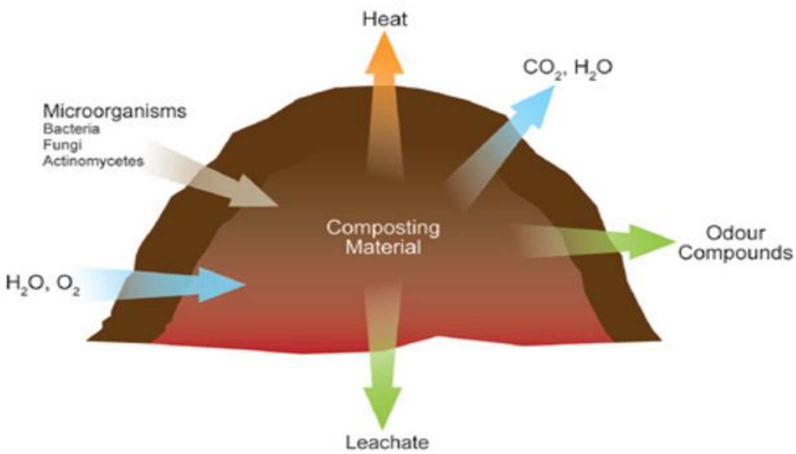
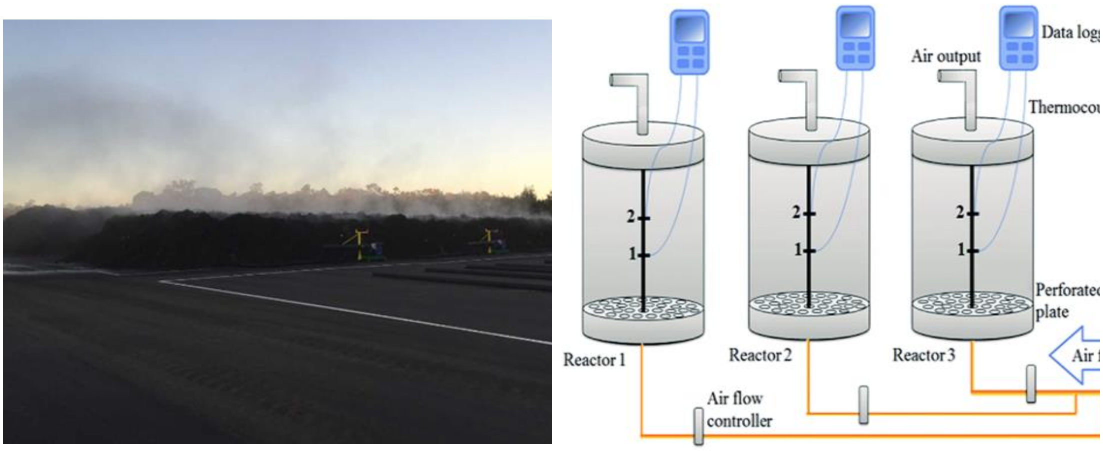


Fig. 6 The major elements of aerobic composting (https://www.google.com.au/search?q=composting&biw=1206&bih)

The important elements of oxygen, carbon and nitrogen, as well as water, are required for optimum composting. The microbial oxidation of carbon is required for energy, nitrogen is required for the growth of these organisms and oxygen is required for the decomposition process and sufficient water is required for optimal growth (Wikiperdia n.d.). In order to start the process, FW must be mixed with other bulking material such as plant trimmings, wood chips (Zafar 2014) or other dried crude plant fibers such as straw or sawdust etc. in certain ratios. Inoculates may also be added (Abdullah et al. 2011; Li 2015; Ohtaki 1998; Xi 2005) in order to achieve the most effective working conditions. The quality of compost is dependent on moisture, pH, electrical conductivity (EC), organic matter (OM), extractable P, nutrient levels, heavy metal content, particle size and stability and the pathogen levels (Tweib, Rahman & Khalil 2012). A C/N value below 12 indicates compost "maturity".

There are a number of different industrial composting systems which include aerated static pile composting (Fig. 7a.), high fiber composting, in-vessel composting (Fig. 8b.), tunnel composting, window composting, vermicomposting, and microbial composting. Also, there are other small scale composting processes such as the composting bin which have been used for residential and community decentralization waste treatment.



(a) (b)

Fig. 7 Composting facilities: (a) pile composting; (b) in-vessel composting process drawing

Thermal treatment

Incineration treatment (IT): Incineration treatment is one of three thermal technologies that require high temperatures to alter the chemical structure of waste, Fig 8. Thermal treatment of waste can result in a 90% reduction of the original volume and 70-80% of the mass (Lombardi 2015; Zhang, ZX, S; et al. 2014). Waste to Energy (WtE) (or Energy from Waste (EfW)) plants are now commonly used to use the heat produced from the thermal plant heat for electricity production. In some countries, which have less land available, incineration has become one of most important

MSW treatment methods, alongside with other thermal conversion technologies such as gasification and pyrolysis (Astrup et al. 2014).

Within the incineration process, the composition of waste with respect to moisture, ash and combustible content must be lower than 50, 60 and > 25%, respectively, as indicated in Fig. 9. In addition, the temperature of gaseous combustion must be > 850 °C and up to 1,400 °C for a minimum of two seconds, depending on the type of waste (Lombardi 2015). Therefore, the operation must be conducted under strict control to ensure that all waste has been completely burned off and that minimal quantities of hazardous chemicals are released into the environment.

The high moisture content of up to 80% in FW has led to the need to pre-treat and co-combust with coal in order to ensure that the incineration is operating efficiently (Lombardi 2015). However, even under optimum conditions, the energy efficiency is only 18-34% depending on the scale and the specific technology used. The final ashes are sent to landfill.

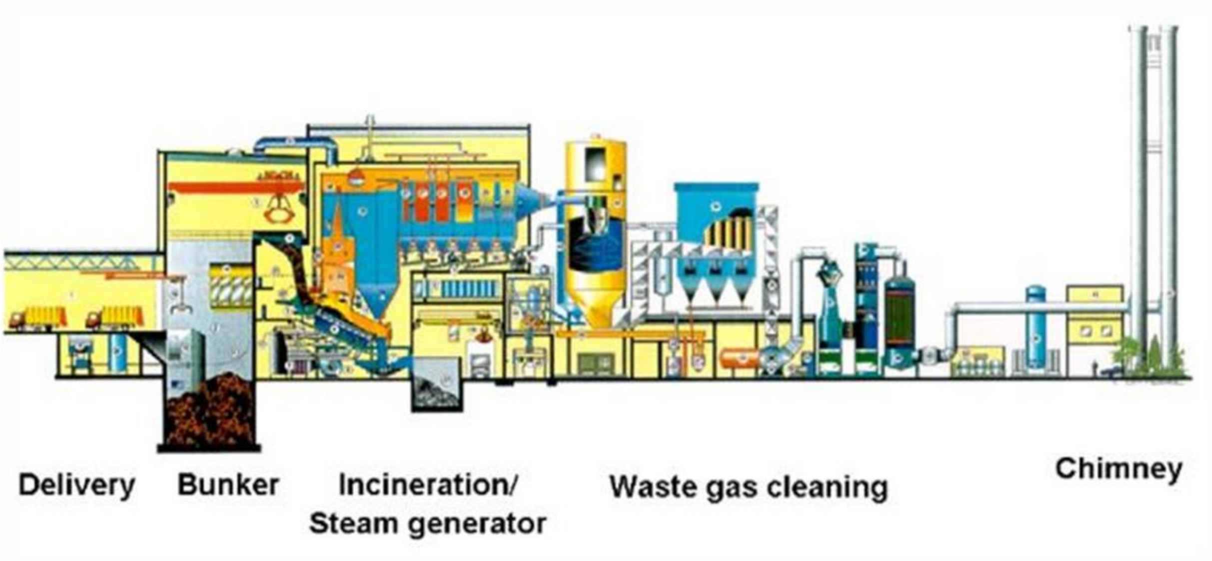


Fig. 8 Incinerate plant model drawing

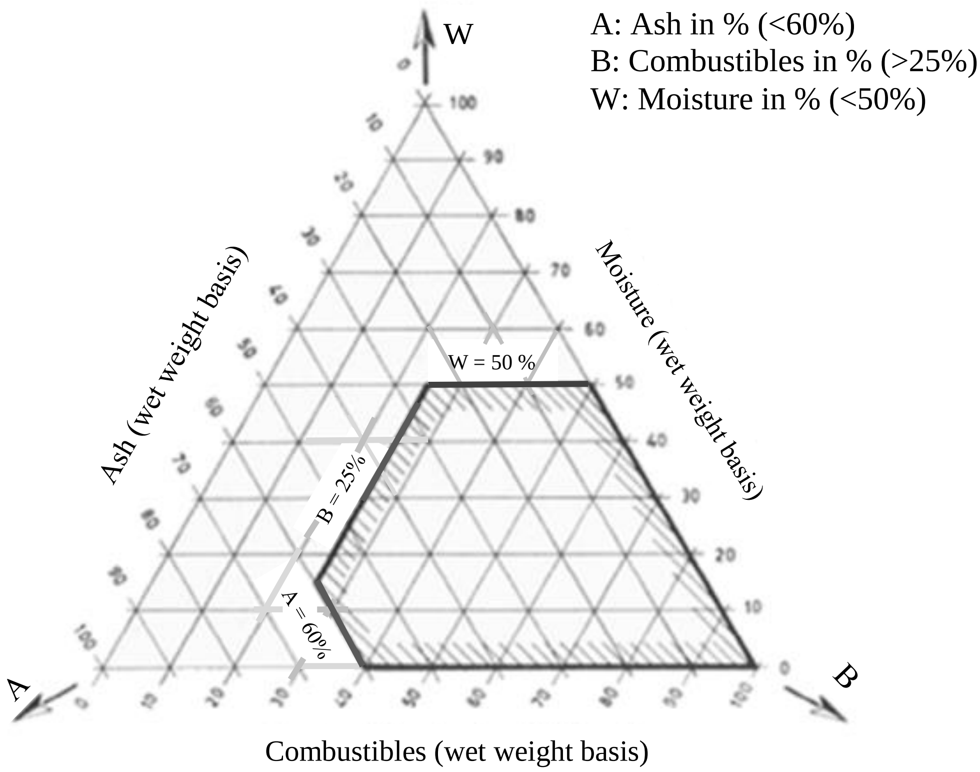


Fig. 9 The self-combustibility (shaded area) of MSW during incineration (Lombardi (2015)

Gasification/Pyrolysis (G/P): Gasification and Pyrolysis are both complex processes that involve physical and chemical interactions. They are more complex and costly to operate and maintain than IT (Lombardi 2015).

Gasification generally takes place at temperatures > 600 °C in the presence of oxygen-enriched air or pure oxygen. The net electricity production efficiency is ~ 23-31%, depending on plant size (Viganò et al. 2010).

Pyrolysis takes place at ~ 400-800 °C in a rotary kiln, which is indirectly heated by a portion of the flue gases (approximately 20%) from syngas combustion. This process produces steam which drives a steam turbine generator for power generation. The gross electric conversion efficiency is about 16%. However, it is limited to specific waste flows such as cooking oil (Lombardi 2015).

There are also other newly developed pyrolytic technologies such as Torrefaction which is a milder but slower process with lower temperatures of 250-350 °C and 20-30 min retention time. Carbonization operates at a at temperature of 500 – 600 °C and 10 min retention time compared to the high pyrolysis process which operates at temperatures > 800 °C and 5 min retention time (Vakalis et al. 2016) . Carbonization and pyrolysis processes have been used for treating the HFW after pretreatment, which reduces the water content from 80% to 10% (Fig. 9).

Landfill treatment (LT): Landfill is the oldest form of waste treatment involving FW, apart from animal feed. However, traditional landfill sites have caused serious public health issues in the past and have had detrimental environment impacts including air pollution, methane emissions, water pollution, leachate, and litter problems. Research from the World Bank shows that each tonne of organic waste produce 300-1000 kg of CO_2 when sent to landfill (Zaman, A & Reynolds 2015). Following increasing public health and environmental concerns, modern landfills have been designed and built into the shape of huge complex in-ground vessels in order to reduce adverse impacts with the environment (Transpacific 2014).

Currently there are six common technologies that are used for landfill treatment: open dump, conventional with flares, conventional with energy recovery, standard bioreactor, flushing bioreactor and semi-aerobic landfills (Manfredi & Christensen 2009). The first one has been banned in most countries due to the impact on the environment and toxicity concerns, while some of the other technologies are still in use worldwide. Landfill has become complex and costly. Fig. 10 shows the layout of a modern Sanitary Landfill. Even after a 100 year timeframe, landfills may continue to release gas and leachate that are still impacting on humans and eco-systems. Thus up to 50% of carbon and 99% of heavy metals from household waste may remain in the landfill site at the end of the 100 year time horizon, and the landfill gas and leachate collection system will have a reduction in efficiency over time (Manfredi & Christensen 2009).

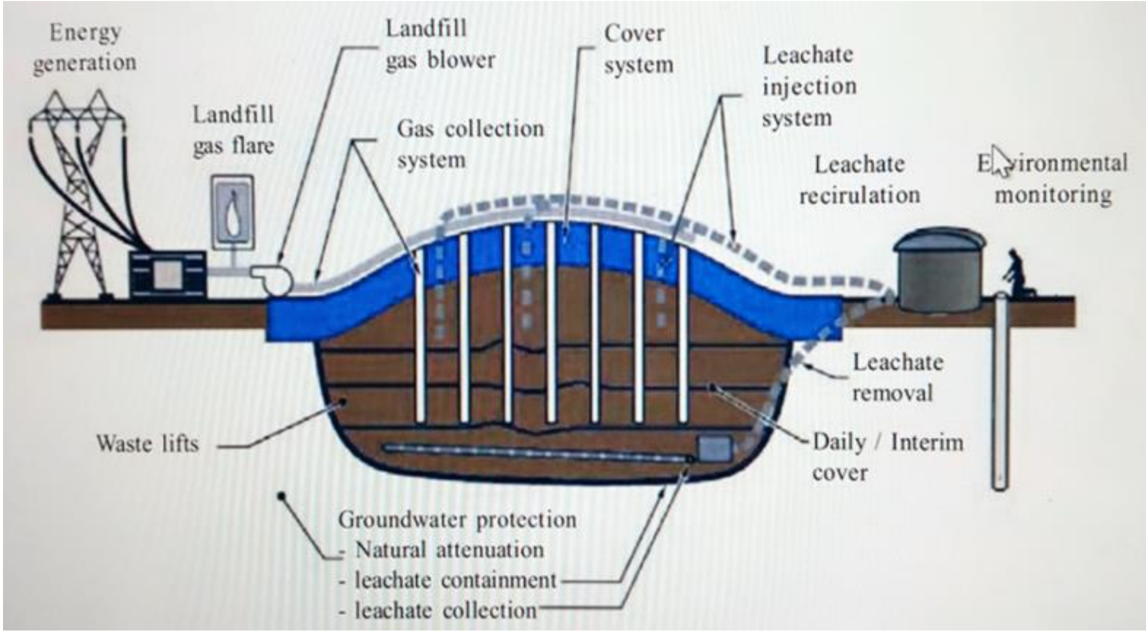


Fig. 10 Sanitary Landfill model drawing

Food waste processing: It is now common practice for a food waste processor (FWP) to be used prior to the treatment of HFW. The FWP, as first introduced in the USA, was usually installed under the kitchen sink (Iacovidou 2012). There are currently two types of FWPs. The first type uses an electrically driven mixer to macerated food waste in combination with water to flush the homogenate into sewer system. The second type is an advance on the first in that it dehydrates the macerated FW to produce either a compost material for potting mix or for transferal into a MSW bin (Fig. 11).

(a) (b) (c)

Fig. 11 FWPs **(**a) collected in tank for community, (b) under kitchen sink flue to sewage system, (c) de-water processor.

Since 2000 the use of FWPs located under kitchen sinks have been promoted extensively in the USA and in some European countries. However, since that time more data has become available, indicating that the use of FWPs had led to an increase in septic tank BOD from 20 to 65%, suspended solids from 40 to 90% and fats, oils and grease from 70 to 150% (USEPA 2000). The extensive use of FWPs also had a major effect on water consumption, sewerage systems and wastewater (Iacovidou 2012). In this regard, Australia is vulnerable to water shortage (Lundie & Peters 2005) and all efforts to reduce water consumption need to be considered, including in the processing of FW.

In the USA and in most industrialized countries, FWPs have been available for several decades. These have proved to be a very convenient way for residents to treat FW, especially for those who are living in apartments and small units within urban areas.

Discussion

Analysis and interpretation

In order to compare different FW treatment technologies, this review focused on the research articles which assessed a comparison between AD and other technologies such as composting, thermal, landfill and FWP. Some 19 studies, which covered over 169 scenarios, were selected and compared (Annex 1). Parameters which were included in this comparison included different methodologies, functional units, system boundary settings, resources input and product output, mass flow and waste composition., However, given the differences in Geographical, temporal scope, the technologies used, time horizons and the uncertainties, it has been very difficult to compare different studies (Astrup et al. 2014; Bernstad, Wenzel & Jansen 2015; Bernstad, Wenzel & la Cour Jansen 2016). Therefore, for this review, the comparison was made in digital form using grades. Five grades from 1 to 5 were used to represent the combination of environmental impacts, the economic and social benefits. They are: 1 = not acceptable, 2 = partly acceptable, 3 = neural, 4 = good, and 5 = excellent. The final combination result will calculate using the formula (1):

Final combination grad = $(\sum_{n=i} Ni) / \mathrm{n}$ (1)

N: grad of each assessment result

n: number of scenarios

i: number of references

Table 3 lists the results for each reference. The combination grades are 4.2, 2.8, 3, 2.3, and 1.4 respectively for AD, CC, HC, IT, and LF. The result shows that AD treatment system (4.2) is the favoured option compared to other systems of CC, HC, IT and LF; with the LF treatment system (1.4) being the worst option. These results also agree with that of Bernstad and la Cour Jansen (2012a) who reviewed 25 studies of 105 scenarios pre-2009.

Table 3 List of references and the results of assessments comparison with difference technologies.

Reference	Geography	Waste type	Scenarios number	Combination result with different technologies				
				AD	CC	HC	IT	LF
Ahamed et al. (2016)	Asian Singapore	FW	3	5			1	
Bernstad (2012)	Worldwide	30-40 % HFW	52	5	3	3	4	1
Bernstad, Davidsson and Bissmont (2016)	EU Sweden	HFW	3	3				
Bernstad and la Cour Jansen (2011)	EU	FW	5	5	2		4	
Bernstad and la Cour Jansen (2012a)	EU Sweden	FW	25	5	2		3	1
(Chi et al. 2015)	China	MSW	4	5	4		3	2
Chiu et al. (2015)	Asian Macau	HFW+ Sewage	5	5			1	
Dou (2015)	China	FW	qualitative	5	3		3	1
Hill (2010)	EU Denmark	HFW	2	4			2	
Khoo, Lim and Tan (2010)	Asian Singapore	FW	4	5	1	2	1	
Koroneos and Nanaki (2012)	EU Greece	FW + paper	6	5				1
Levis, JW et al. (2010)	USA and Canada	FW	3	5	3			
Manfredi et al. (2015)	EU	HFW	25	5	2		3	1
Nakakubo, Tokai and Ohno (2012)	Asian Japan	HFW + Sewage	12	5			1	
Righi et al. (2013)	EU Italy	Organic MSW	4	4	3			1
Takata et al. (2013)	Japan	FW	6	5	3			
Turner, Williams and Kemp (2016)	UK	HFW	4	1			2	4
Zhao and Deng (2014)	Asian HK	HFW	6	5	3	4		1
Zschokke, Kagi and Dinkel (2012)	USA	FW		5	4			1

Environment impact

Table 4 shows the main environmental impacts within major MSW management facilities with respect to specific factors (Giusti 2009; Manfredi et al. 2015). These impacts can be divided into three main categories: non-toxic impacts, toxic impacts and resource usage - and nine sub-categories which have been descripted previously.

Table 4 Main environmental impact of municipal solid waste management (reproduced from (Giusti 2009; Manfredi et al. 2015)

	Water	**Air**	**Soil**	**Climate**
Anaerobic Digestion	Minor impact	CO_2, N_2O	Minor impact	Neural emissions
Composting	Leachate	CO_2,CH_4, VOCs, dust, odour, bioaerosols	Minor impact	emissions of greenhouse gases
Incineration	Fall-out of atmospheric pollutants	SO_2, NOx, N_2O, HCl, HF, CO, CO_2, dioxins, furans, PAHs, VOCs, dour, noise	Fly ash, slags	Greenhouse gases
Landfill	Leachate (heavy metals, synthetic organic compounds)	CO_2,CH_4, odour, noise, VOCs	Heavy metals, synthetic organic compounds	Worst option for greenhouse gases emission
Recycling **Waste transportation**	Wastewater Spills	Dust, noise CO_2, SO_2, NOx, dust, odour, noise, spills	Landfilling of residues Spills	Minor emissions Significant contribution of CO_2

Anaerobic digestion does not just recover energy through biogas but also utilizes the residual as carbon storage. When the FW from high energy crops is used for AD on an industrial scale, it can result in a net avoidance of GHG-emissions that is several times higher than most other treatment technologies (Bernstad, Wenzel & Jansen 2015). Bernstad and la Cour Jansen (2012a) also stated that, even with an unclear framework, using difference methodologies and within various boundaries, as documented in 105 reviewed studies, there was clearly a range of environmental impacts between the different treatment technologies (Fig. 13). On the basis of the existing literature we can see that anaerobic digestion (AD) technology has the minimum impact in Global Warming Potential (GWP) compared to incineration treatment (IT), landfill (LF) and composting. This result is similar to the study by Turner, Williams and Kemp (2016). Zschokke, Kagi and Dinkel (2012) who also showed that even from the total Eco-indicator 99 point that AD has the minimum value compared to CC, IT and LF which are about 38%, 42%, 51% and 100%

respectively. Furthermore Zhao and Deng (2014) supported the concept that landfill of FW has the highest impact on global warming even with the energy recovery. The composting of FW had the highest impact on acidification and nutrient enrichment. Zhao et al. (2010) had also showed replacing landfill by incineration would not have improved the impact on the environment. However a combination treatment of digestion and composting can reduce -12.4 PE in human toxicity by water way, -12.2 PE in acidification, -5.7 PE in nutrient enrichment and -7.9 in global warming.

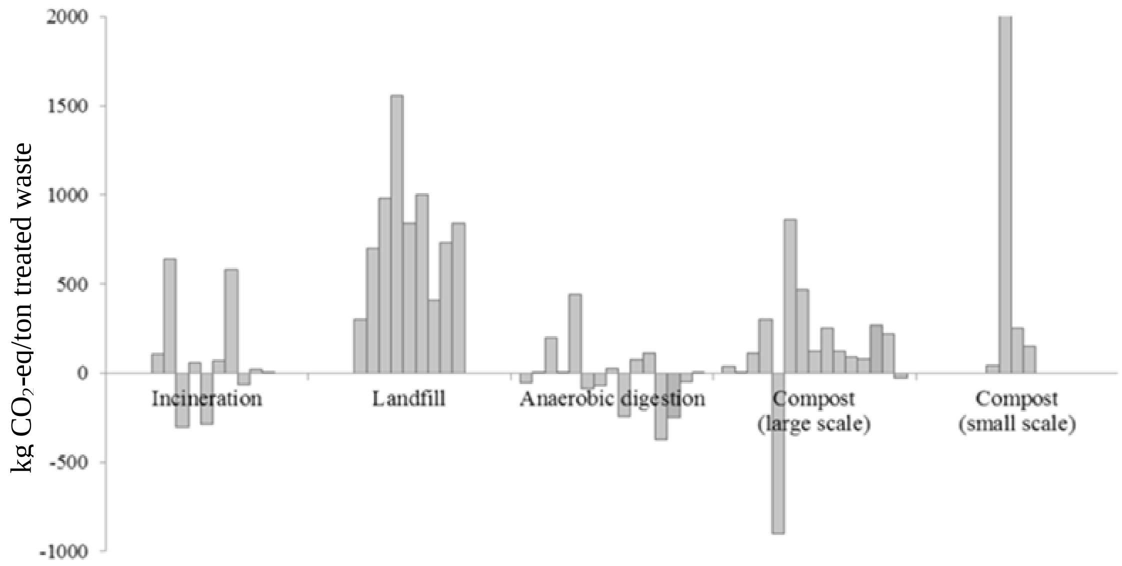


Fig. 2.13 Global Warming Potential (GWP) from 1 ton of food waste treated with different technologies (Bernstad & la Cour Jansen 2012a)

Composting represents a cost effective outlet for the producers of compostable wastes and a potential cheap source of organic matter and fertilizer for landowners. However, an important key to the success of a composting operation is a marketing or distribution program for compost products (Tweib, Rahman & Khalil 2012).

Home composting results in a compost with high pH (~ 9.12 - 9.62) and electrical conductivity (EC) (Arrigoni 2015). Experiments reported by Arrigoni also showed that moisture loss from small waste batches led to variations in temperature and leachate accumulation during the process. Manual mixing could potentially favour a higher particle specific surface area and, therefore, a higher rate of microbial decomposition and C loss in the form of CO_2, which would result in a lower organic matter content. During the composting and storage of digestant, loss of nitrogen may also occur (Bernstad, Wenzel & Jansen 2015).

Landfill contributes about 30% of the global anthropogenic emissions of methane to the atmosphere (Tweib, Rahman & Khalil 2012) and causes damage to vegetation, increases groundwater contamination and creates the possibility of fire and explosions. Furthermore, pathogenic agents, toxic substances and gases, together with bad odors spreading from landfill sites, pose risks for public health (Domingo 2008). Also, potential loss of land value has meant that landfill, as a means of disposing of FW, has become less popular worldwide.

In modern landfill sites, the impact from the construction of soil covers and impermeable liners, and other upstream inputs, are not accounted for in most LCAs. Bernstad, Wenzel and Jansen (2015) stated that, with landfill gas collection (LFG) technology, any collection ratio < 70% will still have a significant impact on GHG emissions. Pickin (2009) also emphasized that, for new landfills, running costs will be more than for those they replace, especially with "the externality gap between the interests of a private landfill operator and those of the owner of the waste supply". Therefore, "there are no true 'alternatives' to landfill, but rather only ways of slowing down the rate of landfill inputs". It is therefore considered to be the worst option in waste management (Manfredi et al. 2015).

Furthermore, on a 100 year time frame, the emissions date of GWP100 (Global Warming Potential over 100 years) is within the higher range. Therefore the IPCC uses a value of 72 for the GWP20 for methane but 21 for the GWP100. Leachate parameters, which are critical indicators for license conditions, such as nitrogen, total dissolved solids, pH or manganese level, are not always met by some of the companies responsible for landfill operations (Pickin 2009).

Thermal waste treatment technologies have been still not been fully accepted by governments and environmental scientists. Some arguments are that IT is a lock-in process. Because of the very high costs that have been incurred in investing in IT, it has been suggested that a more sustainable technology will not be developed. This will have a detrimental effect on the introduction more sustainable Metropolitan Solid Waste Management (MSWM) (Massarutto 2015). Thermal treatment for MSW has been promoted in most developed countries, especially for those with limited land for landfill. It has a signification advantage in reducing the time to process the waste. However, the high water content, which can be up to 80%, results in a decrease in energy efficiency, leading to an increase in gaseous acidification and an increase in the toxicity of emissions. Thermal treatment needs more energy and resources for the separation of feed stock and the pre-treatment of MFW, including drying to 10% of water content, before it can be used as fuel material for a thermal process. So it has less benefit than other organic materials such wood for thermal treatment (Vakalis et al. 2016). After a review and analysis of 136 references of thermal WtE technologies, (Astrup et al. 2014) concluded that comparing IT to recycling, landfill and commercial composting treatments, the recommendation rates are 4 to 25, 22 to 4, and 3 to 4, respectively. It also shows that from a sustainability point of view, IT technology is better than landfill and close to commercial composting treatment - but it is still lest favorable than recycling.

With FWP, the solids, oils and fats of components will be susceptible to autoxidation causing deterioration of the substrate and restricting the sewage flow.

In most studies, the human and ecological toxicity associated with collection, pre-, post- treatment and transportation, together with occupation health and safety issues, working conditions and local environmental impacts, that are associated with odour and noise, have been less considered. Nevertheless, they can significantly influence the treatment options at the local level.

Economic and social analysis

Economic analysis has also been done by analyzing the cost-benefits of a particular treatment system and its material flow and represents an important part of achieving sustainable MSW management.

Environmental impact is difficult to measure in dollar terms. The damage costs of greenhouse gases, for example, are of uncertain magnitude and involve uncertain human impacts that occur over an uncertain timeframe. Also, effect-by-effect valuation is poor at capturing costs associated with risk. There are huge discrepancies when it comes to cost estimates of environmental impact from different sources such as from BDA's (BDA Group 2009) and Murdoch University that are $2,700/t and $4,300 to $11,600/t respectively for PM10 particulates. And the figure was up to $108,000/t to $221,000/t from the CSIRO calculation (Beer 2002). Some potential costs and benefits cannot be readily valued, and tend to be generally ignored. Pickin (2009) used the problems at Cranbourne landfill as example to show that "the compensation understood to be under negotiation could soak up all of BDA's estimated landfill amenity costs for the whole of Australia for years or decades".

Bernstad (2012) assessed 218 thermal energy plants and found that only 2-3% of investment had yielded returns. Hellweg et al. (2005) combined an 'environmental cost-efficiency indicator' with LCA to analyse and compare the systems of IT, LF and MBT. He found that the IT had the lowest environmental impact compared to LF and MBT, but it is based on a higher financial cost.

Table 5 Economic comparisons between systems

Tech-system	Economic
AD	Highest benefit 40% - 80% efficiency (in biogas) (Bernstad, Davidsson & Bissmont 2016)
CC	"System which include free or unconstrained garden waste collection series tend to be more costly than those which target food waste only" (Eunomia research & consulting 2007)
IT	23% efficiency (in heat) (Bernstad, Davidsson & Bissmont 2016)
LF	Any biogas collection rate under 70% will cost financial loss (Bernstad)
FWP	Increase investment in capital or upgrade the facility and sewage system

For a composting plant there are three issues that need to be considered: construction costs and materials, user exposure to composting materials and leachate collection and disposal. During the composting process, volatile organic compounds VOCs, NH_3 and H_2S will be emitted by microorganism activity and CH_4 due to poor air circulation and a smaller proportion of alkanes, alkenes and cycloalkanes. Also, organic dust carrying various fungi may cause pulmonary inflammation (acute inflammation, hypersensitive neumonitis), occupational asthma, and chronic bronchitis, along with other general health problems such as gastrointestinal disturbances, fevers, infections and irritations of eyes, ears and skin (Domingo 2008).

Also, "market demand is a key factor to make the best use of the available resources and technologies, and provide economic feasibility for resource constraint governments." (Ahamed et al. 2016)

A significant amount of research has confirmed that the separated collection and treatment of HFW in MSW management will significantly improve the environmental impacts, with associated economic and social advantages (Bernstad & la Cour Jansen 2012b; Chi et al. 2015; Chu, Heaven & Gredmaier 2015; Dong et al. 2013; Edwards et al. 2016; Levis, JWB, M A; Themelis, N J; Ulloa, P 2010; Mart ńez-Blanco et al. 2010; Matsuda 2012; Rigamonti, Grosso & Giugliano 2009; Yoshida, Gable & Park 2012). Furthermore, Righi et al. (2013) stated that the impacts of transportation in the collection process and the disposal of residual after waste treatment have environmental, economic and social implications.

Conclusions and recommendations

HFW treatment technologies and relevant management systems do not just involve environmental concerns but are also deeply connected to economic and social issues. Therefore, to pursue the goal of sustainable waste management with respect to both materials and energy recovery, it is necessary to obtain public awareness, active commitment and participation from citizens. With this in mind, when considering the strategy in HFW management, decision-makers should avoid having too narrow a focus on Global Warming (GW) and also address other, more specific, aspects such as resource recovery and toxic emissions as well as economic performance, social acceptance, local involvement, technical robustness, etc.

The concept of circular economics (CE), Fig.14, has been increasingly gaining acceptance and is being applied to the process of converting resources to consumable goods. It is an alternative to the traditional line-directional approach where consumption and disposal are seen as the end point of resource utilization. The statement of “waste does not exist” is holistic and restorative and may be represented generically by the ‘value circle’ schematic (Ellen MacArthur Foundation and McKinsey & Company 2014). CE may change “the structure of a system” (Meadows 2004). However, this may be limited within an industrial economy (Ellen MacArthur Foundation and McKinsey & Company 2014), especially with respect to FW management systems (Clift, Doig & Finnveden 2000). Therefore, when applied to a specific problem (i.e. ‘Micro’ Circular Economics, MCE) – that potentially involves circular material flows – such as the management of HFW, the framework of CE has become ‘less relevant’. The MCE concept focuses on the activities of individuals (e.g. at the household level), which will bridge the relationship between policy and individual within/under economics, the surrounding environment and changing society. This will lead to further research on the local level with respect to HFW management within the concept of MCE showed as Fig. 15.

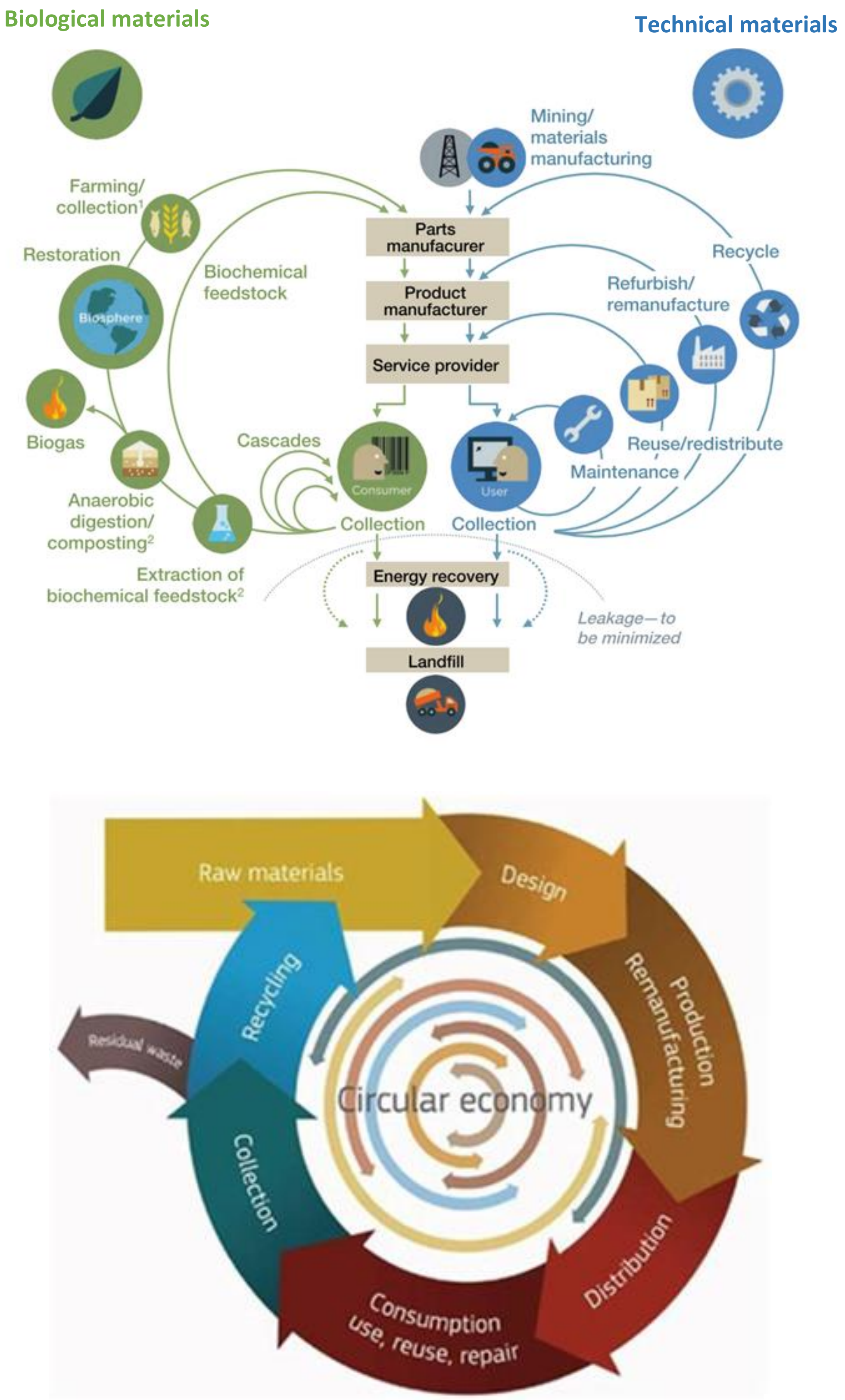


Fig. 14 The concept of Circular Economics (CE) (Ellen MacArthur Foundation and McKinsey & Company 2014; Gourguignon 2014)

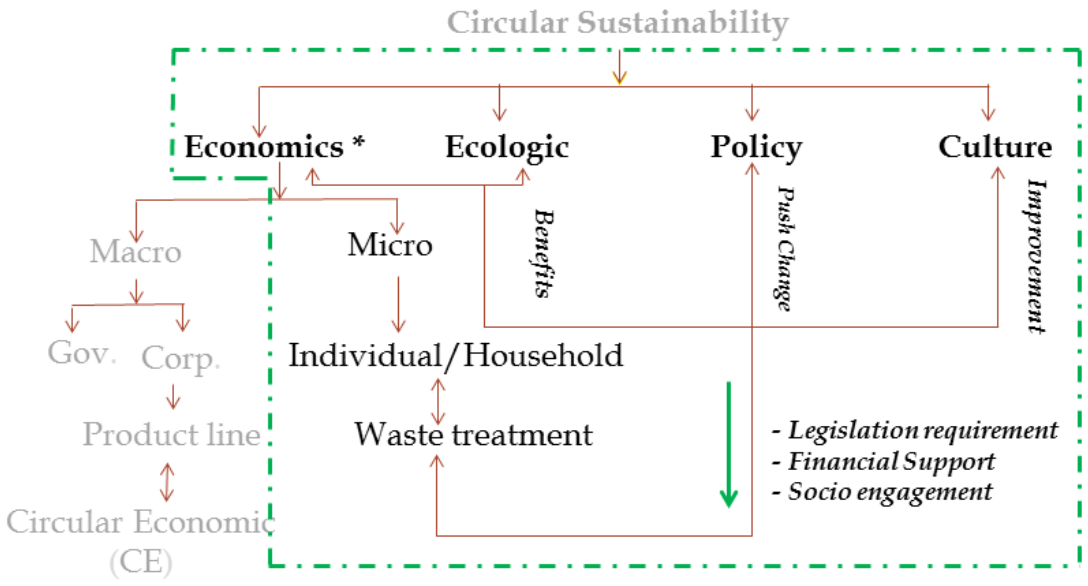


Fig. 15 The concept frameworks of MCE

With respect to MCE, consistent with the Medium-Term Strategy of the United Nation Environment Programme, the decentralized solution becomes an important option for FW treatment in modern urban planning and development (United Nations General Assembly 2016). This is especially true in conjunction with the trend towards renewable energy, such as solar and wind power. These are still in non-continuous and non-flexile supply modes which currently are not able to satisfy the residential base power demands in a regular way. Therefore, the energy recovered from food waste generated from our daily lives could contribute to renewable energy production and could become even more significant into the future.

Internationally, existing technologies in FWT have a number of limitations that will continue to restrict the sustainable development in HFW management, Fig 16.

Therefore, on-site modern small scale AD technology will need to be developed to reducing the impacts and costs arising from collection, sorting and transportation and, at the same time, turning the waste into energy and fertilizer - on site. This promises to close the loop of production from the end of food chain and finally to achieve “zero waste” at the micro scale (Fig.17).

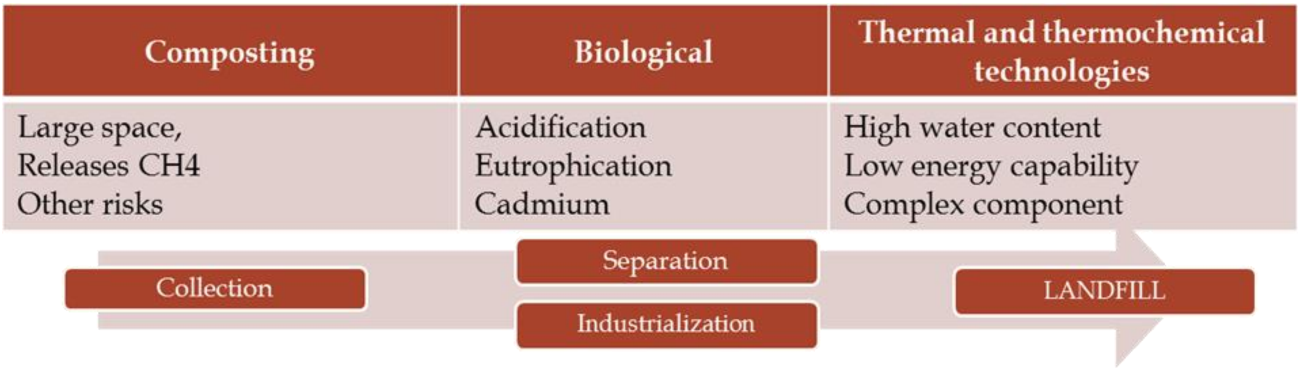


Fig.16 Limitations of existing technologies in FWT internationally (Pham 2015) (Vandermeersch, T et al. 2014)

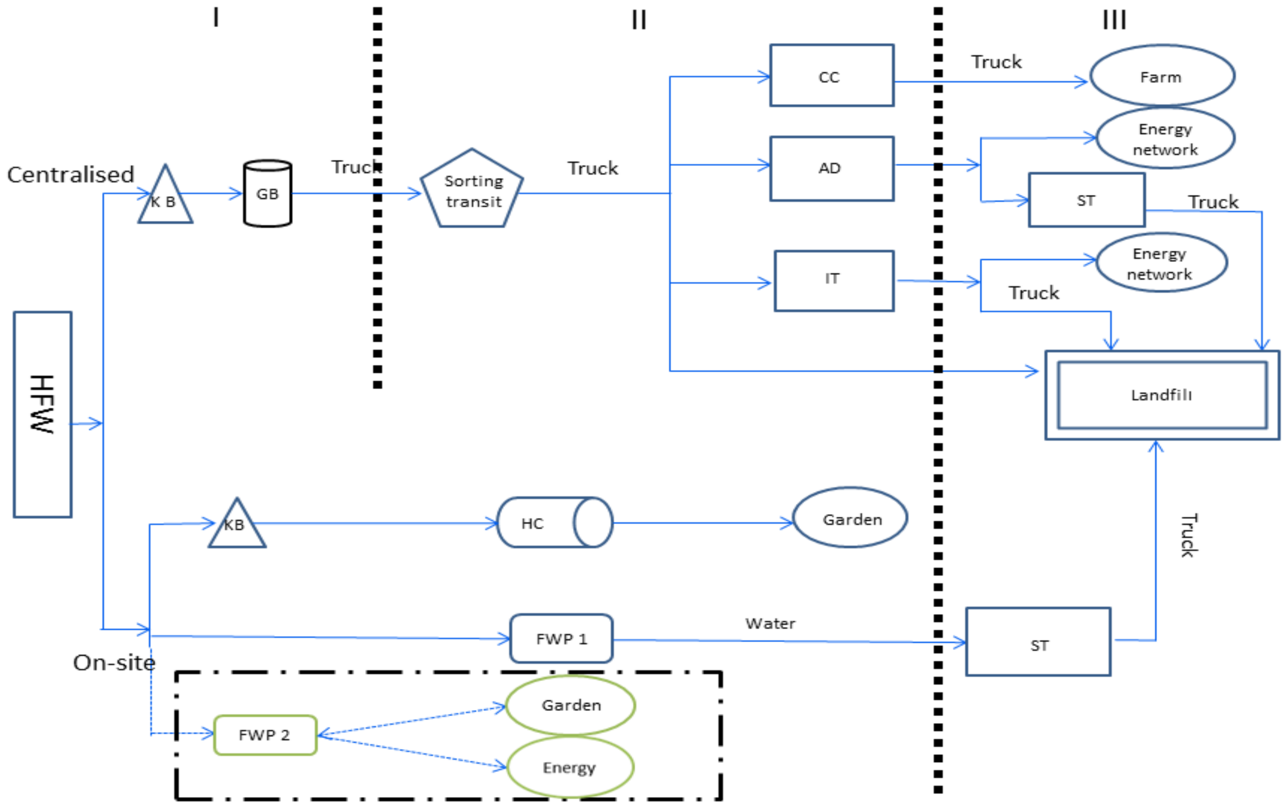


Fig. 17 New HFW management system map

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