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EWP Treatment Technologies Technical Paper

Report for Essex Waste Partnership

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Glossary

Abbreviation	Definition
ABP	Animal By Products
ABPR	Animal By Products Regulations
ABSL	Advanced Biofuel Solution Ltd
AD	Anaerobic Digestion
APC	Air Pollution Control
AQMA	Air Quality Management Area
AQMAU	Air Quality Modelling & Assessment Unit
ATT	Advanced Thermal Treatment
BAT	Best Available Technique
BioSNG	Bio-Substitute Natural Gas
BREF	Best Available Techniques Reference Document
C&I	Commercial & Industrial
C/N	Carbon/Nitrogen
CCS	Carbon Capture and Storage
CEMS	Continuous Emissions Monitoring Systems
CHP	Combined Heat and Power
CHRSs	Compost Heat Recovery Systems
DfT	Department for Transport
DM	Dry Matter
DMR	Dry Mixed Recycling
DRS	Deposit Return Scheme
EfW	Energy from Waste
EIA	Environmental Impact Assessment
EPR	Extended Producer Responsibility
EWP	Essex Waste Partnership
FiTs	Feed in Tariffs
GHG	Greenhouse Gas
HDPE	High-Density Polyethylene
IAA	Inter Authority Agreement
IBA	Incinerator Bottom Ash

Abbreviation	Definition
IBAA	Incinerator Bottom Ash Aggregate
IED	Industrial Emissions Directive
IVC	In-Vessel Composting
JMWMS	Joint Municipal Waste Management Strategy
LPA	Local Planning Authority
MBT	Mechanical Biological Treatment
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
NCV	Net Calorific Value
NIR	Near Infrared
OAWC	Open Air Windrow Composting
OCC	Old Corrugated Cardboard
OECD	Organisation for Economic Co-operation and Development
OFMSW	Organic Fraction of Municipal Solid Waste
PET	Polyethylene Terephthalate
PVC	Polyvinyl Chloride
RCHW	Recycling Centre for Household Waste
RDF	Refuse Derived Fuel
RHI	Renewable Heat Incentive
ROCs	Renewable Obligation Certificates
RTFCs	Renewable Transport Fuel Certificates
RWS	Resources and Waste Strategy
SAF	Sustainable Aviation Fuel
SPZ	Source Protection Zone
SRF	Solid Recovered Fuel
TPA	Tonnes Per Annum
TRI	Thermochem Recovery International
TS	Total Solids
TTT	Thermal Treatment Technologies
UK	United Kingdom
USA	United States of America
VS	Volatile Solids

Abbreviation	Definition
WCA	Waste Collection Authority
WDA	Waste Disposal Authority
WEEE	Waste Electrical and Electronic Equipment

1 Introduction

Essex County Council and the 12 Constituent Councils, collectively the Essex Waste Partnership (EWP) are undertaking a revision of the current Joint Municipal Waste Management Strategy (Joint Strategy), adopted in 2008 for the period 2007 to 2032. In accordance with the Waste and Emissions Trading Act 2003 (section 32), EWP is obliged to keep strategic policies under review and consult on revision to these, as appropriate. EWP has appointed Ricardo to undertake a refresh of the Joint Strategy to ensure that it better reflects current needs, taking into account future policy direction, waste quantities and composition and suitable treatment technologies for the waste streams to be managed.

Ricardo is undertaking analysis and modelling of the total waste streams currently collected, processed and treated that are within the EWP's jurisdiction i.e. local authority collected waste which includes materials arising through kerbside collection schemes, bulky waste collections, recycling centres for household waste (RCHW), street cleansing services and other smaller waste streams. To support the refreshed Joint Strategy, the analysis will include a forward look of waste composition and the quantities expected to be managed by EWP over the next 25+ plus years and during the lifetime of the new Joint Strategy. This serves a number of purposes, providing estimates of the likely quantities to be treated and by nature of the materials generated, what treatment technologies would be suited to the materials to be managed. This Treatment Technologies Technical Paper provides information on a range of treatment technologies for residual waste, dry recyclable materials and organic waste (food and garden wastes) to enable EWP to consider future treatment options. These options will be set in context with EWP's current performance and the emerging Vision for the new Joint Strategy and how this may affect future performance. It will also take account of external factors from the national policy landscape set by the UK Government's Resources and Waste Strategy, Environment Act, Net Zero Strategy and targets for waste reduction, reuse, recycling, landfill diversion and decarbonisation of waste activities. Together EWP will consider how these combined aspects will shape the evaluation criteria to be used when appraising the options for future collection services and treatment technologies. **This technical paper is therefore intended to provide essential background information for Workshop 4 to be delivered on 29th November 2021.**

2 Treatment Technology Review

EWP wish to understand what options are available for the treatment and disposal of waste streams produced by residents and businesses in the County area. Ricardo has undertaken a review of available treatment technologies to manage the following waste streams:

- Residual waste
- Mixed recycling streams
- Separated recycling streams
- Garden waste
- Food waste
- Mixed organic waste

This section provides a summary of the technology review. The long-list of technologies reviewed is provided in Table 2-1 below and full descriptions of each technology are provided in Appendices A1 to A3.

The technology long-list has been categorised into three broad groups:

- **Thermal treatment** – principally for the treatment of residual waste.
- **Mechanical materials recovery** – for the treatment of dry recycling streams, organic waste and residual waste.
- **Biological treatment** – for the treatment of garden waste, food waste, mixed organic waste and residual waste.

Table 2-1 Technology Long-List

Thermal Treatment	Mechanical Materials Recovery	Biological Treatment
Combustion: Moving Grate	Clean MRF: Single Stream	Aerobic: Open Air Windrow Composting
Combustion: Fluidised Bed	Clean MRF: Two-Stream	Aerobic: Enclosed Housed Composting Halls
Combustion: Oscillating Kiln	MBT: Anaerobic Digestion	Aerobic: In-Vessel Composting
ATT: Gasification	MBT: Composting	Anaerobic: Wet-AD
ATT: Pyrolysis	MBT: Autoclave	Anaerobic: Dry-AD
	MBT: Enzyme	

2.1 Thermal Treatment

2.1.1 Combustion

Combustion (also referred to as incineration) encompasses those processes where waste feedstock undergoes complete oxidation (combustion) in a furnace with excess oxygen, releasing heat into the gaseous exhaust and solid combustion products. In this category, three combustion technologies have been considered:

- Moving grate
- Fluidised bed
- Oscillating (or Rotary) kiln

In any waste combustion process the products are a hot flue gas which passes through a boiler to recover heat and then through a flue gas treatment system to remove pollutants, residual ash containing the incombustible fraction of the waste and a hazardous residue from the flue gas treatment system which contains the captured pollutants and chemicals used to treat the flue gas. The majority of the ash output can usually be treated and used in construction.

2.1.1.1 Technology Description

Moving grate refers to the action of the furnace grate, which moves the waste feedstock through the combustion area to facilitate complete combustion. In fluidised bed combustion, pre-treated waste is combusted within a reactor chamber containing very hot sand, which is fluidised by an air stream, thus promoting rapid heat transfer between particles. In an oscillating kiln, waste is loaded into a hopper and mechanically pushed into the top of a tapering cylinder or kiln. To pass the waste through the kiln and control the rate of combustion, the kiln oscillates from side to side, passing the waste between paddles set into the internal walls of the kiln.

2.1.1.2 Energy Recovery Method

In all three technologies, heat in the exhaust gases is used to heat water in a boiler and produce steam, which is then expanded through a steam turbine to generate electricity. Heat can also be recovered from the turbine for process use or to supply a district heating network.

2.1.1.3 Technical Considerations

Combustion (EfW)	Moving Grate	Fluidised Bed	Oscillating Kiln
Typical application & feedstock characteristics	Mixed waste feedstocks: MSW, C&I waste, RDF, SRF. Net Calorific Value of typically between 7 to 15 MJ/kg, moisture up to 50% (by mass)	Homogenous feedstock such as biomass, sewage sludge, RDF. Shredded waste particle size of 5 –	Mixed waste feedstocks: MSW, C&I waste, RDF, SRF, hazardous waste. Suitable for hazardous waste: high

Combustion (EfW)	Moving Grate	Fluidised Bed	Oscillating Kiln
		15cm with metal removed.	temperatures above 1,100ºC
Process outputs	Hot flue gases, energy (power and/or heat), bottom ash, fly ash, air pollution control residue, ferrous metal.	Hot flue gases, energy (power and/or heat), bottom ash, fly ash, air pollution control residue, ferrous metal.	Hot flue gases, energy (power and/or heat), bottom ash, fly ash, air pollution control residue, ferrous metal.
Scale and capacity	50,000 to approximately 350,000 tpa for each process line; multi-lines up to 1m tpa.	UK plant of approx. 500,000tpa	Best suited to small scale applications e.g. 60,000 tpa. Smaller footprint than moving grate / fluidised bed.
Technology Readiness Level	Proven system through successful operation	Proven system through successful operation	Proven system through successful operation
Environmental Impacts	Flue gas emissions containing CO_2 and very low levels of other pollutants (below regulatory limits)	Flue gas emissions containing CO_2 and very low levels of other pollutants (below regulatory limits)	Flue gas emissions containing CO_2 and very low levels of other pollutants (below regulatory limits)
Suitability for use by EWP	Tried & tested, flexible technology suited to residual waste	Suitable for pre-sorted RDF from residual waste	Suitable for a very wide range of waste but generally only suitable at smaller scale
Limitations	Small scale plants (<50,000 tpa) may not be viable.	Requires pre-sorting of metal and pre-shredding of waste. Small scale plants (<50,000tpa) may not be viable.	Larger scale plants (>150,000tpa) may not be viable.

2.1.2 Advanced Thermal Treatment

Advanced Thermal Treatment (ATT) is an umbrella term applied to a wide range of technologies, all of which involve the conversion of waste into a combination of gas, liquid and solid products which can be upgraded and used for various purposes. The most common forms of ATT technologies are gasification and pyrolysis. Gasification is usually focused on the conversion of waste into syngas, while pyrolysis may prioritise either syngas, synthetic oil or solid char. The various products retain much of the energy of the original waste, unlike combustion where the energy is fully released as heat.

2.1.2.1 Description

Pyrolysis is the thermal breakdown of waste in the absence of oxygen. Waste is heated to high temperatures (>400°C) without the addition of oxygen.

Gasification is the thermal breakdown/partial oxidation of waste under a controlled oxygen atmosphere, producing syngas, which primarily consists of carbon monoxide (CO) and hydrogen (H_2) (the oxygen content is lower than necessary for full combustion).

Some gasification processes (including plasma assisted processes) operate at very high temperature to melt the ash and other residues, with potential to use in construction.

2.1.2.2 Energy Recovery Method

Syngas can be used for a variety of purposes. It can be simply combusted in a boiler or cleaned and upgraded for use in a gas engine. It can also be upgraded and converted to fuels and chemicals. Liquid products can be similarly converted to fuels and chemicals. However, cleaning the syngas and liquid products is a considerable technical challenge and a complex process. For those processes looking to produce a high purity syngas, the more refined the input waste the lower the technical risk and more chance of a successful project.

2.1.2.3 Technical Considerations

Advanced Thermal Treatment	Gasification	Pyrolysis
Typical application & feedstock characteristics	Pre-treated MSW, C&I waste, hazardous waste (preferably highly refined when producing fuels and chemicals)	Pre-treated MSW, C&I waste, hazardous waste (preferably highly refined when producing fuels and chemicals)
Process outputs	Syngas, char/ash. Syngas can be refined and used for power and heat generation, or upgraded to fuels and chemicals	Syngas, oils & waxes, solid (char, carbon black) Syngas and oil can be refined and used for power and heat generation, or upgraded to fuels and chemicals
Scale and capacity	Highly variable	Highly variable
Technology Readiness Level	Variable. Limited commercial experience on MSW derived feedstock in the UK and restricted to combustion of syngas with power generation	Variable, but no examples operating on MSW in the UK
Environmental Impacts	Similar to combustion where syngas used for energy recovery. Minimal air emissions possible when process configured to produce fuels/chemicals	Similar to combustion where syngas used for energy recovery (but typically syngas production is a by-product, so emissions are reduced). Minimal air emissions possible when process configured to produce fuels/chemicals. Flue gas emissions (from combustion of syngas) including CO_2
Suitability for use by EWP	Limited successful commercial deployment on residual waste in the UK.	Not yet fully demonstrated at commercial scale in the UK for residual wastes.
Limitations	Higher technical and commercial risk than combustion	Higher technical and commercial risk than combustion

2.2 Mechanical Treatment

2.2.1 Material Recovery Facilities (MRFs)

MRFs use a combination of processing equipment including screens, separators and conveyors to recover recyclable material streams from single stream waste materials. Types of equipment commonly used in MRFs include:

- material preparation e.g. bag splitters and feed hoppers.
- material transportation e.g. conveyors and walking floors.
- material separation e.g. overband magnets, wind shifters, infra-red optical separators, ballistic separators, disc and other screens.
- material bulking e.g. baling or stockpiling for transportation.

MRFs can be used to process residual MSW (commonly termed a "dirty MRF", described in section 2.2.2) or, more commonly, dry mixed recyclables (DMR). DMR is usually collected from residential properties and commercial organisations producing residential-like streams, and transported to the MRF for processing. There are several different approaches to the collection and processing of DMR, the most common of which include:

- single stream – processing a single co-mingled feedstock
- two-stream – processing two streams of material segregated at source
- multi-stream – processing multiple streams of material segregated at source.

In addition, some facilities can process a range of feedstocks via multiple entry points into the facility, and thus can process both two-stream and fully co-mingled materials.

2.2.1.1 Technical Considerations

Materials Recovery Facility	Single-Stream	Two-Stream	Multi-stream
Typical application & feedstock characteristics	Mixed paper, cardboard and containers, which may or may not include glass	One stream containing paper and cardboard, and the other containing mixed containers (which may include glass), which are then fed into different input points in the MRF	More than two streams, segregated at source by the producer, collected via a specialist collection vehicle and delivered to the facility as separate materials.
Process outputs	Recyclables, rejected materials	Recyclables, rejected materials	Recyclables, rejected materials
Scale and capacity	40,000 – 250,000 tpa (can be scaled to meet most requirements)	40,000 – 250,000 tpa (can be scaled to meet most requirements)	40,000 – 250,000 tpa (can be scaled to meet most requirements)
Technology Readiness Level	Proven system through successful operation of various configurations	Proven system through successful operation of various configurations	Proven system through successful operation of various configurations
Financial Implications	The capital cost of a MRF increases as the level of automation increases (i.e., in a high-tech MRF) but operational costs are higher for low-tech MRFs as picking staff are	The capital cost of a MRF increases as the level of automation increases (i.e., in a high-tech MRF) but operational costs are higher for low-tech MRFs as picking staff are	A multi-stream collection model will require bespoke vehicles to carry out collections which can store a number of separate waste streams.

Materials Recovery Facility	Single-Stream	Two-Stream	Multi-stream
	required to manually segregate materials.	required to manually segregate materials.	Depending on the final design a multi-stream MRF will often be cheaper as less sorting equipment is required to separate the recyclable materials. A large transfer station will be required to store the separate streams.
Environmental Impacts	Release of contaminated materials if not well managed	Release of contaminated materials if not well managed	Release of contaminated materials if not well managed.
Suitability for use by EWP	Tried & tested, flexible technology suited to DMR	Tried & tested, flexible technology suited to DMR	Tried & tested, flexible technology suited to DMR
Limitations	Level of recovery dependent on quality of input material and the configuration of the processing equipment (affects the accuracy of sorting)	Level of recovery dependent on quality of input material and the configuration of the processing equipment (affects the accuracy of sorting)	Quality dependent on residents and individuals accurately separating recyclables. Requires updating collection fleet with specialist, multi-compartment vehicles. Requires a large floor area to receive and bulk up separate recyclable streams prior to removal from site.

2.2.2 Dirty MRF (including MBT)

Dirty MRF is a term used for the processing of residual MSW or other non-DMR streams through a mechanical sorting process. Outputs from a dirty MRF differ depending on the desired outputs of the operator, but usually include heavy (inert) rejects, a fine organic rich fraction, ferrous and non-ferrous metals, and RDF.

The amount of equipment used in a dirty-MRF can vary widely depending on the tonnage to be processed and the required quality of the output product. A dirty-MRF will generally consist of an amount of equipment using similar technology and layout to a DMR MRF. This is likely to include shredding, screening, magnets and eddy current separators to separate out the fine content (largely organic and inert such as sand and stones) and recover metals to leave a residual RDF fraction.

A more advanced plant is likely to employ more advanced technology such as near infra-red (NIR) sorting which is capable of identifying and ejecting a wide range of materials including paper and plastic. The NIR sorters can be used to perform different functions. Some plants may choose to try and recover plastics for recycling, targeting it and ejecting it from the waste stream. Other plants may use the NIR sorters to maximise recovery of plastics and other high energy content materials into the RDF stream, discarding inert or low energy content items.

The dirty-MRF is not a full waste disposal system, there are a number of products and residues which require disposal. RDF will typically be sent for thermal treatment of some kind. Organic fines will require disposal, either to landfill or via biological treatment as discussed in section 2.2.3. Residual, non-combustible materials will require disposal to either thermal treatment or landfill.

2.2.3 Mechanical Biological Treatment (MBT)

2.2.3.1 Introduction

Dirty MRFs are often used in combination with biological treatment processes which is collectively known as mechanical biological treatment (MBT). The biological steps would typically be anaerobic digestion and/or composting. Residual waste is mechanically sorted and any material capable of being recycled is extracted (metals and sometimes some plastics). Other output streams from the plant include:

- Organic fines, screened out of the input waste and generally containing a high organic fraction as well as fine inert materials such as sand, glass, ceramics and stone.
- Refuse Derived Fuel (RDF), comprised of combustible materials which are too contaminated to be recycled including paper, plastic, textiles, wood and other materials.
- Residual fraction, comprised on non-combustible or composite items which are not suitable for recycling or energy recovery.

There are several methodologies for the treatment of the non-recyclable outputs from an MBT plant including anaerobic digestion, composting and energy recovery. MBTs could also incorporate other processes such as autoclaving and enzyme treatments as pre-treatments to further biological treatment..

2.2.3.2 Biological treatments

The organic fines fraction could be treated biologically using anaerobic digestion (AD) or composting processes. In AD, the fines are mixed with water and the heavy, inert fraction is removed. The remaining organic sludge is pumped into tanks where is it held for a period (commonly 21 – 28 days, but will vary depending on the specific technology) in the absence of oxygen. These anaerobic conditions allow bacteria to form which break down the organic component and produce methane alongside other compounds, collectively known as biogas. This biogas may be used to fuel an engine to generate electricity, may be upgraded and injected into the gas grid, or alternatively liquified for use as transport fuel.

The residual fraction from AD is a digestate. Digestate derived from mixed waste (as typically received by an MBT plant) cannot meet the appropriate quality standard to allow it to be applied to land as a fertiliser which limits its use considerably. It may be suitable for applications such as landfill capping or land remediation, subject to the appropriate environmental permits being in place.

Composting involves the stockpiling of organic fines either on an external concrete slab, or in a specially designed building. The material is aerated either by turning it over periodically or via the injection of air through a specially designed floor. This encourages the growth of aerobic bacteria, which break down the material releasing only CO2. In some cases the material may be dried which will reduce the tonnage for disposal and may make it suitable for energy recovery. As with the AD digestate compost derived from mixed waste cannot be used in as a fertiliser and so is limited to bespoke applications such as land remediation.

Further details of biological treatment processes are provided in section 2.3 and Appendix A3.

2.2.3.3 Energy Recovery Method

The RDF produced from the residual waste which can be combusted to generate heat and electricity in a thermal treatment plant. RDF is generally favoured by the operators of thermal treatment facilities as it is a consistent, homogenous feedstock with known characteristics (such as moisture content, energy content, particle size etc.). Much of the RDF produced in the UK is exported to mainland Europe for disposal via thermal treatment, although this has dropped considerably in recent years following the introduction of RDF import taxes by several key importing nations.

2.2.3.4 Landfill

The use of landfill for the disposal of waste is considered the least preferable option in the waste hierarchy, and it should not be in consideration as a main means for treating MSW arising from residents and businesses in the county. However, landfill does still have its place for the disposal of certain waste streams after all the options for extraction of value from those streams (such as reuse, recycling or energy recovery) have been exhausted. As a result, the use of landfill for disposal of small, residual fractions from the MBT process may be required, but every effort should be made to ensure these fractions are minimised and contain only inert materials which cannot be disposed of by any other means.

Furthermore, the policy direction under the UK Government Net Zero strategy will restrict the use of landfilling as a disposal solution for residual waste for certain materials found in the waste stream, such as biodegradable waste.

2.2.3.5 Other MBT processes

MBT can incorporate other processes. One of these is the use of autoclaves, high pressure rotating vessels which effectively “cook” the waste at high pressure and temperature. This sterilises the material, breaks the organic fraction down into a consistent “fibre” product, and cleans recyclables such as metals and plastics. The autoclave process also initiates a hydrolysis process in the organic fraction which can lead to elevated gas yield when used in an AD process. However autoclave technology is still rare in waste treatment due to high energy consumption and unreliability.

Another new approach which is being used is enzyme reactors. This involves loading the organic material into a large rotating drum and adding water and an enzyme mixture which partially breaks down the organic fraction, allowing it to be separated from the other materials and accelerating the AD process. This is new technology and has not yet been widely adopted, with a single plant operating in the UK

2.2.3.6 Comparison of MBT approaches

Mechanical Biological Treatment	MRF + AD*	MRF + Composting**	Autoclave + MRF	Enzyme +MRF
Typical application & feedstock characteristics	MBT – MSW AD – organic fraction (OF) of MSW (for wet AD, OFMSW needs extensive preparation)	MBT – MSW Composting – MSW (biodrying), OFMSW, digestate	Pre-treatment for residual MSW prior to AD	Pre-treatment for residual MSW prior to AD
Process outputs	Recyclables, RDF/SRF, rejected materials, digestate, biogas/biomethane	Recyclables, RDF/SRF, rejected materials, OFMSW, stabilised wastes for landfilling or land remediation	Recyclables, biodegradable waste for subsequent AD or other biological processes.	Recyclables, biodegradable waste for subsequent AD or other biological processes.
Scale and capacity	Typically from around 50,000 tpa to 300,000 tpa, but could be more depending on size of mechanical plant and AD tanks and	Typically from around 50,000 tpa to 300,000 tpa, but could be more depending on size of mechanical plant and composting halls.	Batch process – several can be used in sequence (using heat recovered from one batch in the next batch). Capacity is dependent on the	Batch process – several can be used in sequence (using heat recovered from one batch in the next batch) Capacity is dependent on the

Mechanical Biological Treatment	MRF + AD*	MRF + Composting**	Autoclave + MRF	Enzyme +MRF
	associated infrastructure.		size of the autoclave vessel and the number of autoclaves – can be scaled up as required.	size of the enzyme reactor vessel and the number of reactors – can be scaled up as required. Existing UK plant up to 80,000tpa.
Technology Readiness Level	Established technology for MSW, however performance issues have been identified at a number of sites.	Established technology for MSW, however performance issues have been identified at a number of sites.	Full-scale plants have been developed and operated in the UK and Ireland using source segregated wastes and residual MSW feedstocks, but with limited commercial success.	A single full-scale plant is currently in operation in the UK using MSW feedstock. Performance is unknown but the plant commissioning was delayed.
Financial Implications	Capital costs are dependent on the technology provider and infrastructure to process the feedstock. Lack of defined disposal route for the resulting compost product increases operational costs.	Capital costs are dependent on the technology provider and infrastructure to process the feedstock. Lack of defined disposal route for the resulting compost product increases operational costs.	High capital cost and operational costs due to high energy requirement. This may be offset somewhat by enhanced biogas yield if used in tandem with AD.	Capital costs are dependent on the technology provider and infrastructure to process the feedstock. Relatively unknown process in the UK leads to uncertainty around costs.
Environmental Impacts	The combustion of digestate / biogas will release biogenic carbon as CO_2 (and any contaminating plastic carbon not effectively removed). Digestate when processing mixed waste is often highly contaminated and cannot be used as a fertiliser.	The combustion of digestate / biogas will release biogenic carbon as CO_2 (and any contaminating plastic carbon not effectively removed). Process is naturally odorous so good odour control system required.	The combustion of post-autoclave organic fibre (or biogas derived from that) will release biogenic carbon as CO_2 (and any contaminating plastic carbon not effectively removed). Process is naturally odorous so good odour control system required.	The combustion of digestate / biogas will release biogenic carbon as CO_2 (and any contaminating plastic carbon not effectively removed). Process is naturally odorous so good odour control system required.

Mechanical Biological Treatment	MRF + AD*	MRF + Composting**	Autoclave + MRF	Enzyme +MRF
	Process is naturally odorous so good odour control system required.			
Suitability for use by EWP	Offers an alternative to thermal treatment for residual MSW, however issues remain with regard to disposal of digestate and a third party thermal processor or landfill will still be required for the offtake of RDF.	Offers an alternative to thermal treatment for residual MSW, however issues remain with regard to disposal of compost and a third party thermal processor or landfill will still be required for the offtake of RDF. Issues have been experienced in scaling up the technology to work with residual waste feedstock.	Not been successfully operated at full-scale, particularly using an MSW feedstock.	One plant operated at full scale in UK (Orsted Renescience) with limited track record.
Limitations	Wet AD requires significant pre-treatment of OFMSW to prevent heavy inert material accumulating in AD tanks. Digestate cannot meet requirements of PAS110 standard due to mixed waste source, and so cannot be used as a fertiliser on agricultural land or parks/gardens. Thermal treatment will still be required for offtake of RDF, and potentially landfill for other residues.	Composting typically requires a larger land footprint. Compost cannot meet requirements of PAS100 standard due to mixed waste source, and so cannot be used as a fertiliser on agricultural land or parks/gardens. Thermal treatment will still be required for offtake of RDF, and potentially landfill for other residues.	High energy requirement for steam raising. Technology not widely proven using MSW feedstocks at a large scale. Can cause textiles to wrap into a heavy mass which is hard to handle. Organic compost like output cannot meet requirements of PAS100/ PAS110 standard due to mixed waste source, and so cannot be used as a fertiliser on agricultural land or parks/gardens. Disposal of residues will be required, likely to be landfill or	Relatively unknown and unproven technology. Significant pre-treatment of OFMSW likely to prevent silting up of digesters. Organic compost like output cannot meet requirements of PAS100/ PAS110 standard due to mixed waste source, and so cannot be used as a fertiliser on agricultural land or parks/gardens. Disposal of residues will be required, likely to be landfill or thermal treatment.

Mechanical Biological Treatment	MRF + AD*	MRF + Composting**	Autoclave + MRF	Enzyme +MRF
			thermal treatment..	

**See Section 2.3.2 for more detail on AD*

***See Section 2.3.1 for more detail on composting*

2.3 Biological Treatment

2.3.1 Aerobic Composting

2.3.1.1 Description

Composting is the biological treatment of waste by aerobic microorganisms in the presence of air. This is essentially a low temperature bio-combustion process where biogenic organic material is degraded by the microorganisms and oxidised to CO_2 and H_2O.

The main composting treatment types are:

- Open Air Windrow Composting (OAWC) - a simple open-air process undertaken outside on concrete pads.
- Contained Composting – composting undertaken within a building (Enclosed Housed Composting Halls) or in a vessel (In-Vessel Composting (IVC) where the emissions can be collected and treated before discharging to the atmosphere.

2.3.1.2 Energy Recovery Method

Aerobic composting yields a large quantity of heat (thermal energy), which is normally lost to the surrounding environment. Efforts to recover this heat using compost heat recovery systems (CHRSs) have been sporadic and the focus has been on producing a useful organic matter to use as a soil amendment.

2.3.1.3 Technical Considerations

Composting	Open Air Windrow Composting	Enclosed Housed Composting Halls	In-Vessel Composting
Typical application & feedstock characteristics	Source segregated household garden waste, parks waste and farm wastes that do not contain Animal By-Product (ABP) materials. Also used to biologically treat soils contaminated with organic pollutants such as hydrocarbons, and to stabilise wastewater, sewage sludges and anaerobic digestate sludges	Green waste, co-mingled green and food waste, whole MSW and the organic fraction of residual MSW, waste sludges and contaminated soil	Source segregated organic waste, such as food and green waste collected from households and businesses
Process outputs	“Stable” compost (low biodegradability) for use as soil conditioner,	ABPR compliant stabilised compost for use as soil conditioner, volatilised ammonia (recovered from acid	Sanitised compost for further treatment, leachate

Composting	Open Air Windrow Composting	Enclosed Housed Composting Halls	In-Vessel Composting
	or landfill, rejects from screening	scrubbers) can be used as fertiliser	
Scale and capacity	Can be scaled to requirements (micro – large)	Can be scaled to requirements	It is typically undertaken at scales of more than 5,000 tpa and can be found at sites treating 250,000 tpa
Technology Readiness Level	Proven for treating source segregated non ABP commercial and household green garden waste	Proven process when associated with MBT processes, for pre-treatment of MSW and/or stabilisation of organic fraction	Robust and proven process for treating source segregated household and commercial organic waste, green garden waste and food, containing ABP materials. Has also been used to pre-treat MSW prior to MBT.
Financial Implications	Typically low cost	More expensive than OAWC due to building and abatement costs	More capital-intensive due to technology and process requirements
Environmental Impacts	Untreated emissions to air, including ammonia (can have odour implications). Recycling to land of compost generated from residual MSW is possible but requires more regulatory approvals, as it cannot attain end of waste status.	Treated emissions to air, possibly containing low levels of contaminants. Recycling to land of compost generated from residual MSW is possible but requires more regulatory approvals, as it cannot attain end of waste status.	Treated emissions to air, possibly containing low levels of contaminants. Leachate generated which needs to be captured.
Timescale	8 – 12 weeks	2 weeks (biodrying), 6 weeks (stabilisation)	2 weeks (initial sanitisation)
Suitability for use by EWP	Tried and tested for source segregated non ABP commercial and household green garden waste	Suitable for a range of wastes, including whole MSW, with control of odour and other emissions to air	Suitable for co-treating food waste and green garden waste, with control of odour and other emissions to air
Limitations	Large scale processing has large land footprint requirement. Can be significantly impacted by adverse weather. Not suitable to treat mixed food and green waste	More expensive than OAWC	Capital-intensive. IVC treated waste is not stabilised from the short treatment time and usually requires further composting and maturation via OAWC or enclosed housed composting

Composting	Open Air Windrow Composting	Enclosed Housed Composting Halls	In-Vessel Composting
			hall. Leachate capture is required

2.3.2 Anaerobic Digestion

2.3.2.1 Description

Anaerobic digestion (AD) is a biological process through which organic material is decomposed without the presence of oxygen (and other electron acceptors such as nitrate, nitrite and sulphate) by micro-organisms and within an enclosed system to generate biogas (a mixture of methane and carbon dioxide).

The AD process can be undertaken with the waste either in a solid form with a relatively high dry matter content 'dry AD' or as a liquid slurry of relatively low dry matter content 'wet AD' condition.

2.3.2.2 Energy Recovery Method

Anaerobic digestion generates biogas (a mixture of CH_4 and CO_2) which may be combusted to produce heat and electrical energy, or alternatively the CH_4 separated out as biomethane and used as a fuel, e.g., by injecting into the national gas grid or as a transport fuel. Biogas can also potentially be used as a chemical feedstock.

2.3.2.3 Technical Considerations

Anaerobic Digestion	Wet-AD	Dry-AD
Typical application & feedstock characteristics	Source segregated organic waste, predominantly food wastes with low contamination (or pre-treated to remove contamination), OFMSW	Green waste mixed with food waste, tolerates presence of non-biodegradable contaminants – functions best with a blend of materials and particle sizes
Process outputs	Digestate, biogas, biomethane, rejects, leachate	Digestate, biogas, rejects (such as metals, plastics, ceramics)
Scale and capacity	Can be scaled to most requirements (one stage or multistage)	Can be scaled to most requirements (batch or plug-flow)
Technology Readiness Level	Proven in the UK - most AD technology in the UK uses the wet process	Less common in the UK than wet AD
Financial Implications	Extensive feedstock pre-treatment required, such as de-packaging units. Capital costs are dependent on the technology provider and infrastructure to process the feedstock.	Less pre-treatment required, but post-digestion treatment may be needed. Capital costs are dependent on the technology provider and infrastructure to process the feedstock.
Environmental Impacts	The combustion of digestate / biogas will release biogenic carbon as CO_2 (and any contaminating plastic carbon not effectively removed). Digestate is not stabilised so	The combustion of digestate / biogas will release biogenic carbon as CO_2 (and any contaminating plastic carbon not effectively removed). Digestate is not stabilised so

Anaerobic Digestion	Wet-AD	Dry-AD
	further treatment is required for most uses. If landfilled the digestate may generate landfill gas.	further treatment is required for most uses. If landfilled the digestate may generate landfill gas.
Suitability for use by EWP	Most common AD process in the UK for source segregated food waste	Suitable for mixed organic wastes with higher dry solids content and/or higher contamination
Limitations	Pre-treatment has experienced significant problems in generating a suitable material for wet AD that is free of contaminants such as grit and plastic which can be damaging to the AD plant.	Post-digestion treatment may be required to remove contamination such as metals, plastics and ceramics and to stabilise the digestate.

3 Planning and permitting considerations

Securing planning permission and an environmental permit is vital to the development and operation of any waste treatment facility. Several key factors are considered during the planning and permitting process including national and local planning policies, site location, land area requirements and environmental constraints. These factors should be considered early on as part of a business case and initial feasibility work to select the most suitable site for development and avoid issues arising during the planning process.

3.1 Site selection and local impacts

To increase the chance of a successful planning application, the chosen site and technology should be consistent with the National Planning Policy for Waste and the Planning Authority’s adopted or emerging Local Plan. The planning application together with the permit must include an assessment of health impacts and place limits on emissions in accordance with legislation and technical compliance standards such as the Best Available Techniques (BAT) Reference Document (BREF) for waste incineration[1] and the associated Commission Implementing Decision (EU) 2019/2010[2]. As well as health impacts, the impacts of aspects including odour, noise, visual impact and traffic on relevant sensitive receptors should be assessed within the planning and permit applications. When choosing a location for a facility, site-specific factors such as flood risk and proximity to Air Quality Management Areas (AQMAs) and groundwater Source Protection Zones (SPZs) should also be considered. It is common practice to co-locate waste developments on adjacent sites to minimise the overall impact of waste management in a given area.

3.2 Land area requirements

The land area required for a waste development differs depending upon the type of technology, design of the facility, local constraints, storage requirements and annual throughput capacity. The sizing of the site needs to consider capacity for at least the following:

- waste reception
- processing or pre-treatment of waste (where required)

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[1] https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC118637_WI_Bref_2019_published_0.pdf

[2] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2019.312.01.0055.01.ENG&toc=OJ%3AL%3A2019%3A312%3ATOC

- feedstock storage
- primary treatment plant
- plant for cleaning or processing of outputs
- storage of products or waste residues
- other ancillary plant or equipment.

3.2.1.1 Space Requirements of Different Plant Types

	Land requirement
Combustion plants with energy recovery:	
▪ Small scale (up to 100,000 tpa)	▪ 10,000 – 20,000 m^2
▪ Medium scale (100,000 - 300,000tpa)	▪ 20,000 – 35,000 m^2
▪ Large scale (>300,000tpa)	▪ >35,000m^2
▪	
AD plants:	
▪ Average	▪ 25,000 m^2
▪ Small-scale AD plants treating farm-based wastes	▪ 4,000 m^2
▪ Larger facilities treating the organic fraction of MSW	▪ 20,000 – 40,000 m^2
MRFs:	
▪ Less than 100,000 tpa	▪ 11,000 m^2
▪ Up to 300,000 tpa	▪ 10,000 – 20,000 m^2
MBT:	
▪ MBT using AD	▪ 30,000 – 40,000 m^2
▪ MBT using forced aeration composting	▪ 50,000 – 100,000 m^2

For both single and multi-line combustion plants with energy recovery, the overall land area required, comprising all assets within the site perimeter, can vary significantly depending upon each site's geographical setting and the ancillary plant or operations at the site. ATT technologies (such as pyrolysis and gasification) have broadly similar requirements to equivalent capacity combustion plants, but the building and stack height can often be lower. However, ATTs do require pre-treatment of waste to provide a feedstock of suitable quality, i.e., RDF or SRF, and this may be undertaken at an external site or on-site prior to thermal treatment requiring additional land area. The overall land area required for an MRF site varies depending upon whether additional storage areas are required for segregated material post-treatment.

3.3 Planning process

Once a suitable site has been selected, the next stage is to prepare the planning application. A programme for planning should be estimated as part of the business case and initial feasibility work. A flowchart of the planning process is given in Figure 3-1 below.

Figure 3-1 Planning Process Flowchart

Source: https://www.planningportal.co.uk/images/plan_flow_chart_eng.gif

The programme for preparing and determining a planning application can vary significantly and is generally dependent upon the complexity of the proposal including the type of waste treatment technology being implemented, scale of operation and whether there are any contentious issues. The legislation governing the planning process and the regulating authority that makes the decision is dependent upon the type of waste treatment and scale of operation. For EfW, this is dependent upon the generating capacity of the facility. EfW plants with a generating capacity of 50 MW and less are subject to the Town and Country Planning Act 1990 and those greater than 50 MW are subject to the Planning Act 2008. The applicable planning process can impact the development cost and should be factored into the planning programme. Once the application is submitted there are generally three timescales that the Local Planning Authority (LPA) should keep to:

- Minor / small applications (e.g. small householder applications) = 8 weeks
- Major applications (this tends to include all waste applications and other large developments) = 13 weeks
- Applications with an Environmental Impact Statement – where an EIA is required to be submitted with an application i.e. the development is deemed likely to cause significant environmental effects – the timescale is 16 weeks for a decision following submission of the application and EIA.

3.4 Environmental permitting process

The operation of a waste facility requires an environmental permit or exemption in accordance with the Environmental Permitting (England and Wales) Regulations 2016. In England, the permit will usually be regulated by the Environment Agency and will set out the limits on waste type and tonnage, storage and handling of raw materials and wastes, emissions from the process and the management procedures required to be in place. The permitting process can take 6 to 12 months or longer depending upon the complexity of an application. Due to its current backlog of applications awaiting determination, the Environment Agency is taking approximately 6 months to allocate an application to a determining officer. Once allocated, the application will undergo duly making and determination, which is normally expected to take 4-6 months, but this can be longer for more complex applications. Additionally, there are long queues for assessment by the Air Quality Modelling & Assessment Unit (AQMAU), which may introduce further delays to the process for applications including air quality and noise assessments. An installation also needs to go through a commissioning phase to validate that it can operate under the agreed conditions and meets the pre-operational conditions set out in the permit before becoming permanently operational.

4 Conclusion

This Treatment Technologies Technical Paper provides information on a range of treatment technologies for residual waste, dry recyclable materials and organic waste (food and garden wastes) to enable EWP to consider future treatment options. The technologies investigated essentially form a ‘long-list’ of treatments that may be suitable to treat EWP’s waste streams. As part of the new Joint Strategy development, a set of evaluation criteria will be agreed upon at a workshop to be held on 29th November 2021. in order to assess the technologies on the long-list. The next step is to assess the technologies on the long-list and narrow this down using the evaluation criteria to form a short-list of options that will be subjected to further appraisal. Evaluating the options will be set in context with EWP’s current performance and the emerging Vision for the new Joint Strategy and how this may affect future performance and take account national policy and targets for waste reduction, reuse, recycling, landfill diversion and decarbonisation of waste activities. This technical paper provides background information for EWP consideration prior to the planned workshop.

Appendices

A1 Appendix 1 - Thermal Treatment Technology Descriptions

A1.1 Introduction

Thermal treatment technologies (TTT) cover a range of approaches to treating waste, with the common element being the use of high temperatures as a means to destruct or convert the waste to a different form. The majority of waste thermal treatment involves combustion whereby waste feedstock undergoes complete oxidation in a furnace with excess oxygen, releasing heat into the gaseous exhaust and producing solid combustion products (incinerator bottom ash, or IBA and fly ash). Energy recovery is achieved by using the heat in the exhaust gases to produce steam, which is then expanded through a steam turbine to generate electricity. Heat can also be recovered and exported for space heating and process heating (e.g via a district heating network).

Alternatives to combustion come in the form of Advanced Thermal Treatment (ATT) technologies. The most common of these are pyrolysis and gasification, where the waste feedstock is exposed to high temperatures in complete or partial absence of oxygen respectively. ATT processes may produce various outputs depending on the design and configuration of the equipment including liquid fuels, carbon rich char and synthesis gas (syngas). The feedstock material, depending on the temperature range adopted and local conditions, undergoes a process of decomposition where most of the chemical bonds are restructured allowing various elements of the material to be extracted in different forms.

ATT is suitable for a variety of emerging applications such as for the chemical recycling of plastic waste whereby plastics can be broken down into their constituent chemical elements for re-use or waste to liquid fuels suitable for vehicle or aviation applications.

Waste combustion processes are well proven and widely used around the world, representing a low technology risk. ATT does not have the same track record for processing general residual waste but, unlike combustion, allows for the production of a range of fuels and chemicals. Increased investment into ATT processes is being seen, driven by the desire to produce products such as transport fuels and chemicals from waste.

This technology guide is split into three broad categories of TTT:

- Combustion (often referred to as Incineration).
- Advanced Thermal Treatment.
- Derivatives of ATT.

Each main category of TTT features several variants which are described in the relevant sub-sections.

A1.2 Combustion

A1.2.1 Introduction

Waste combustion technology is well established and proven worldwide. Many technology providers offer a wide variety of different furnace configurations which are tailored to the waste type and composition received. Combustion provides complete sanitary destruction of the waste, including plastics and paper that will be present in mixed waste feedstocks. A wide variety of waste types can be combusted producing heat which can be used to generate electricity via a steam turbine. The residual heat may be used to heat homes and businesses as part of a district heating system. In addition, some process residues are produced including incinerator bottom ash (IBA) and air pollution control residues (APC residues).

A combustion plant will be designed to process waste which has an energy content falling within a certain band, measured in mega-joules per kg (MJ/kg). For most wastes including MSW and C&I streams the energy content of the waste is sufficient to maintain the combustion process. When wastes with lower calorific values require treatment the combustion process may require the addition of supplementary fuel to maintain a sufficient heat level, but this is not typical for MSW and similar wastes. If waste is processed which has a higher energy content than the plant is designed for there is a risk that too much thermal energy could be released which may damage the plant. As a result, if the energy content is higher than originally designed for, the throughput of the plant may need to be reduced.

As a result, an operator of a combustion plant should be mindful of the waste streams being brought to the plant, and any changes in legislation or public behaviour which may alter the composition of the waste and consequently the energy content of the material.

The inert fraction which remains following the destruction of the combustible material is known as IBA. IBA contains the non-combustible ash fraction of the waste along with various inert materials including metals, stone, glass, ceramics and potentially a small proportion of un-burned carbon. It is now common in the UK for IBA to be sent for further processing in order to extract recyclable materials. Ferrous metal and non-ferrous metal can be separated from the IBA and recycled as a post burn metal. The non-ferrous fraction often contains small amounts of precious metals (for example from WEEE which was in the waste stream) and some specialist processors will separate these metals further.

The remaining IBA can be recycled into a recycled aggregate product. The process for this includes a maturation period for 6 - 8 weeks, then it is then crushed, screened and graded to produce an aggregate which complies with recognised British Standards for construction grade material. The Environment Agency has issued a regulatory position statement (RPS247) clarifying its position on the use of IBA derived aggregates titled *“Using unbound incinerator bottom ash aggregate (IBAA) in construction activities”*. This describes the conditions which must be met by users of IBA aggregate to allow the material to be used in construction without the requirement for an environmental permit. The majority (around 85%) of IBA from European and Japanese moving grate combustion plants is recycled. It should be noted however that recycling of IBA is not currently included in national recycling figures.

Flue gas treatment residues, also commonly referred to as air pollution control (APC) residues, comprise of the light ashes and dust particles which are carried up with the hot exhaust gas stream and spent reagents used in the gas cleaning process, and are captured by the flue gas treatment system. APC residues are hazardous and must be managed appropriately, commonly via a hazardous landfill. APC residues may be recycled into products such as concrete blocks using processes including carbonation and cementation, though at present only around 20% of hazardous APC residues are currently recycled in the UK[3] due to limited processing capacity.

All combustion plants will produce emissions from the process which are released to atmosphere, which without proper control and management may prove harmful to health. A well designed and correctly operated combustion plant can avoid negative health and environmental impacts[4]. Combustion plants fall under the remit of the Industrial Emissions Directive (Directive 2010/75/EU of the European Parliament) which sets out Best Available Techniques (BAT) to minimise environmental risks[5] as defined by the EU directive for waste incineration. There are many detailed recommendations listed in the conclusions, but key aspects of emissions control are:

- Maintaining a flue gas residence time of at least 850°C for a minimum of 2 seconds to destroy pollutants, including dioxins precursors. Auxiliary fuel (typically natural gas or diesel) should be available to maintain this condition at start up or shut down or if furnace conditions become unstable. Urea or ammonia is usually injected into the furnace to remove oxides of nitrogen (NO_x), though NOx abatement may also be carried out in a separate reactor after the flue gas treatment process.
- Rapid cooling of flue gases post combustion is necessary to avoid dioxin formation followed by flue gas treatment with lime or sodium bicarbonate reagent to remove acid gases such as hydrogen chloride (HCl) or sulphur dioxide (SO_2), and activated carbon is used to absorb heavy metals and any dioxins that are produced.

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[3] Tolvik, 2019.

[4] United Kingdom Health Protection Agency. (2009). Municipal waste incinerator emissions to air: impact on health

[5] Best available techniques (BAT) conclusions, under Directive 2010/75/EU of the European Parliament and of the Council, for waste incineration, November 2019

All modern combustion plants will be equipped with air pollution control systems which use filtration and the addition of reagents to minimise the presence of harmful substances in the exhaust air stream. Continuous emissions monitoring systems (CEMS) are also used to monitor the composition of the gases being released to atmosphere and ensure compliance with the plant environmental permit.

In general, the key advantages of a combustion process is that the process can generate relatively large amounts of electricity which is used to power the plant and exported back to the national grid. Thermal energy is also available in the form of low-grade steam and/or hot water which may be used in local district heating systems if available. The technology is flexible enough to receive a wide range of waste feedstocks and will provide complete, sanitary destruction of the waste. The resulting IBA and APC residue streams may undergo further processing to recover recyclables and to make elements suitable for re-use. The process is compact, requiring less land than non-thermal technologies.

The principal drawback of combustion is the release of CO_2 into the atmosphere. The level of fossil carbon released is a direct result of the waste composition. It is likely that carbon capture may be needed at the stack or fossil carbon content is required to be substantially reduced in the waste feedstock in order for combustion plants to be compliant with future environmental legislation. Public perception of combustion is negative, and as a result opposition to the development of new plants is high and gaining planning permission can be time consuming. Finally, combustion plants tend to be designed for long-term operation (>25 years) due to the high cost. There are a number of changes to legislation and public perception/behaviour due to increased focus on the environment which may change the composition of waste significantly over the coming 25 years. As a result, the combustion plant operation may be affected by a change in NCV for example if not specifically designed for it.

A summary of the key characteristics of a combustion plant is provided in Table A 1.

Table A 1: Summary of combustion plant characteristics

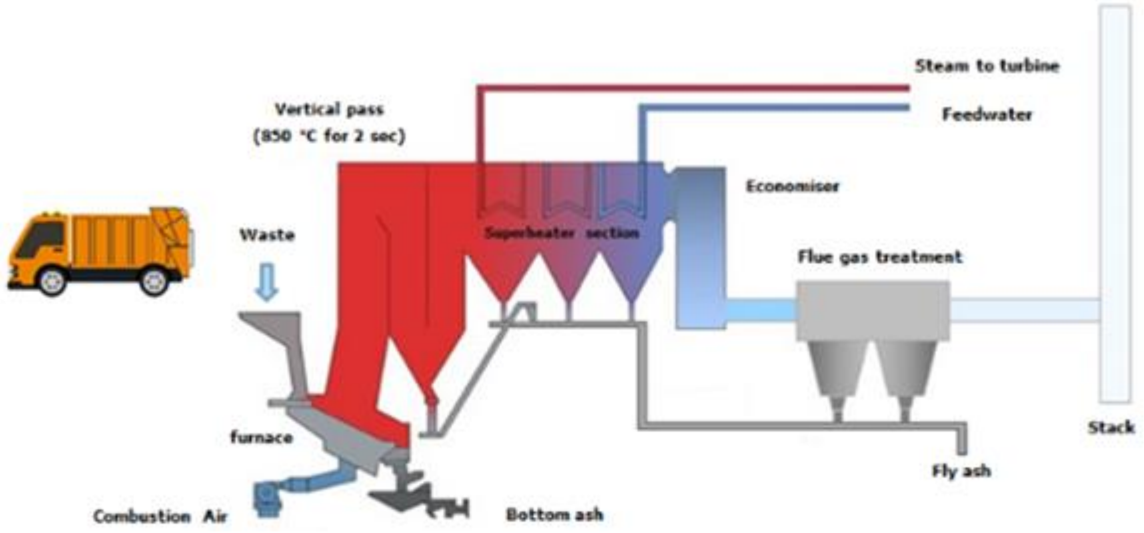
Aspect	Summary
Type of energy conversion	Waste is fully oxidised in the presence of excess oxygen to recover the energy content of the feedstock. The hot flue gases have little or no chemical energy content left following full combustion. Energy conversion of the hot flue gases into electrical power or heat is achieved through a high-pressure steam boiler.
Typical application	Typical application is combustion of raw Municipal Solid Waste (MSW) but can also process refuse derived fuels (RDF) and solid recovered fuels (SRF). Has high flexibility to handle changes to input regarding heating value, ash content and moisture.
Feedstock characteristics	Conventional combustion will treat waste with a wide range of Net Calorific Value (NCV) and moisture content. Minimal pre-processing of the waste is required but shredding or crushing of larger objects prior to being fed into the waste chute is advisable to reduce the potential for blockages to occur. Some specific grate technologies may require greater pre-treatment for the process to function effectively.
Scale and capacity	Suited to a wide variety of scales from circa 50,000 tonnes per annum (tpa) up to 320,000 tpa for each process line. Multi-line plants may have capacities of up to 1m tpa plus.
Process outputs	Hot flue gases from the combustion zone pass into a steam boiler resulting in energy recovery. The process produces electricity for its own use and grid supply via a steam turbine and heat for district heating and/or industrial process use.
By product recycling	IBA which may be processed to recover recyclables including metals and aggregate. APC residues may be recycled into products such as concrete blocks.

Aspect	Summary
Emissions	Hot combustion gas stream, controlled and monitored to ensure compliance with the plant environmental permit and Industrial Emissions Directive BAT with regard to emissions.
Advantages	▪ Combustion is well proven and is flexible in dealing with a highly variable feedstock such as MSW without the requirement for pre-treatment. ▪ Technology is familiar, well understood and relatively simple to maintain. ▪ Large scale electricity generation is possible. ▪ Low-grade residual heat may be utilised for local district heating schemes. ▪ Further treatment of IBA and APC residue streams allows further recycling and diversion from landfill to be achieved.
Limitations	▪ Combustion will release carbon dioxide (CO_2) to the atmosphere which is a greenhouse gas. ▪ Public perception of combustion is poor which can lead to lengthy planning and permitting approval processes. ▪ Combustion plants often require a tall exhaust stack and relatively tall process building to accommodate the boiler and flue gas treatment equipment ▪ Overall electrical efficiency through a steam cycle is limited due to the corrosive nature of unsorted waste. Pre-treatment of the waste to remove corrosive compounds (such as chlorine) may limit this, but a key advantage of moving grate is the ability to accept waste streams with no pre-treatment required.

A1.2.2 Process description

The general principle of operation of a combustion plant is illustrated in Figure A 1. Waste is taken from a storage bunker by a crane and dropped into a feed chute. Waste at the bottom of the chute is pushed into the furnace. Combustion air is injected beneath the grate, drying and combusting the waste. Waste moves along the grate as it burns, with additional combustion air injected above the grate to ensure complete combustion. The resulting inert material know as bottom ash is extracted from end of the grate. The hot combustion gases are used to generate steam in a boiler. This superheated steam is used to generate electricity via a steam turbine generator. The combustion gases exiting the boiler pass through flue gas treatment equipment to remove particulates from, neutralise acid gases and capture other pollutants prior to release to the atmosphere.

Figure A 1 Combustion plant process diagram



There are a number of combustion processes commercially available for the treatment of waste, the most common being:

- Moving grate.
- Fluidised bed.
- Oscillating kiln.

Each of these configurations is summarised below.

A1.2.3 Moving grate

The moving grate furnace is illustrated in Figure A 2. The basic principle of a moving grate furnace is the use of a number of inclined grate bars which move backwards and forwards, pushing the waste down the grate. Waste which is loaded into the plant via a hopper and chute is mechanically pushed onto the moving grate. Combustion air is injected from the bottom of the moving grate drying and combusting the waste. The action of the grate bars moving backwards and forwards transfers the waste along the grate and as combustion progresses the combustible fraction of the waste burns, leaving an inert IBA fraction which falls from the end of the grate and is extracted.

Complete combustion is achieved by injecting secondary air above the grate. The flue gases must experience a temperature of at least 850°C for a minimum of 2 seconds following the last injection of air, as required by the Industrial Emissions Directive (IED)[6].

Auxiliary fuel (e.g., diesel) is required for start-up and shutdown procedures to achieve the minimum temperature conditions for waste combustion to commence.

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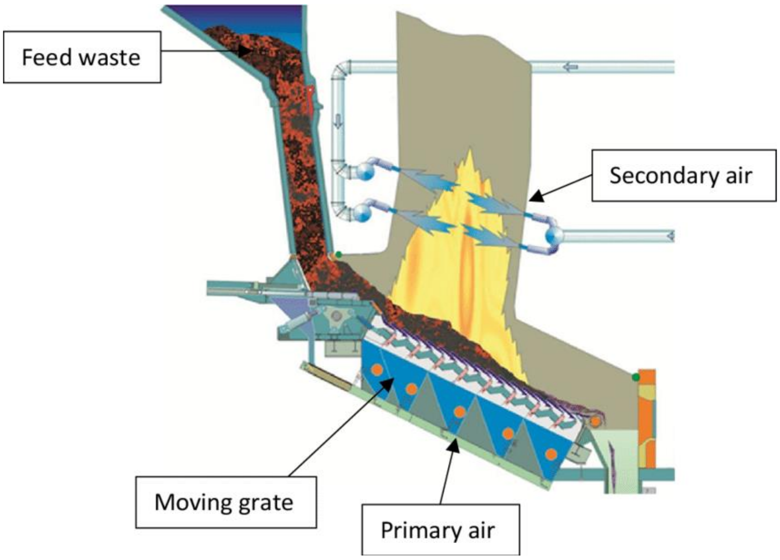
[6] The EU Withdrawal Act 2018 maintains established environmental principles and ensures that existing EU environmental law will continue to have effect in UK law, including the IED. Link here.

Figure A 2 Moving grate combustion chamber[7]



The main advantage of a moving grate system is the fact that it can receive a wide variety of feedstock materials without a requirement for pre-treatment (other than breaking down very large particles). It is reliable and widely used around the world. The main drawback is that it is not so suitable for scaling down to smaller plant capacities less than around 100,000 tpa.

A1.2.4 Fluidised bed

A fluidised bed reactor uses hot air and a carrier medium such as sand to agitate the waste, enabling better heat transfer to the material and consequently effective combustion. Pre-treated waste is transferred to the reactor chamber via a hopper and chute. The reactor chamber contains hot sand which is fluidised by an air stream from the wind-box below. The fluidised sand allows rapid and efficiency transfer of heat to the waste feedstock enabling combustion to occur. The residual inert fraction remaining drops through the sand and out of the furnace and is removed from the process as IBA. The IED requirement of minimum 2 seconds at 850°C is achieved in the secondary combustion zone. Energy is transferred to a boiler system in the same way as a grate fired facility. The fluidised bed process is illustrated in Figure A 3Figure A 3 Bubbling fluidised bed reactor chamber

Figure A 3 Bubbling fluidised bed reactor chamber

Figure A 3 Bubbling fluidised bed reactor chamber

Figure A 3 Bubbling fluidised bed reactor chamber

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There are many subsets of this technology including bubbling bed and circulating fluidised beds.

Within the bubbling bed variant, the sand bed is contained within the combustion chamber whereas with the circulating bed a much higher fluidising velocity is used, entraining the sand in the gas flow before being separated out using a cyclone and returned to the bottom of the process However, in all cases pre-treatment of the feedstock is required to ensure particle size is small enough to be fluidised within the carrier medium in order for effective combustion to occur.

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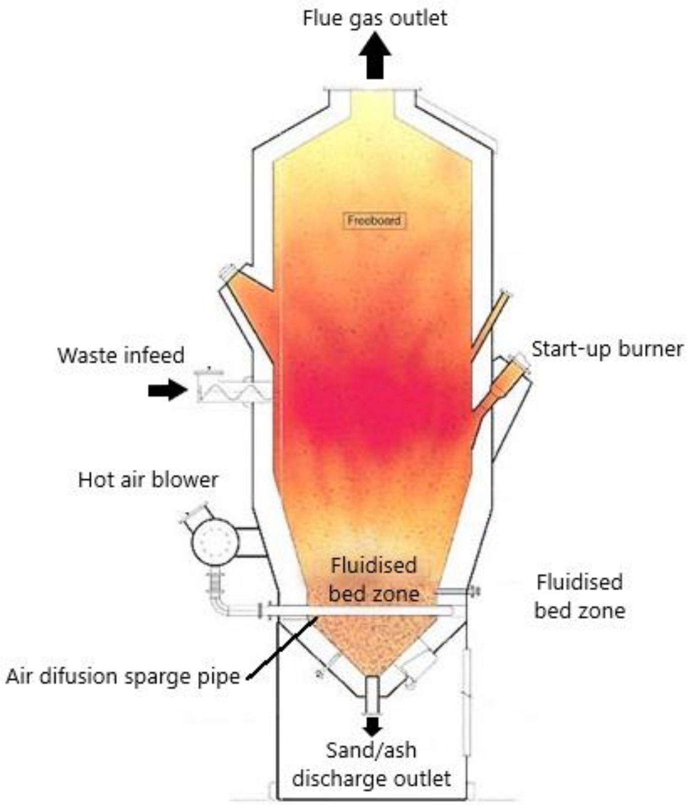
[7] Zjup, Wdse & Bourtsalas, Athanasios & Huang, Qunxing & Zhang, Hanwei & Themelis, Nickolas. (2020). Energy recovery in China from solid wastes by the moving grate and circulating fluidized bed technologies https://rdcu.be/b3jg1. 2. 27-36.

Figure A 3 Bubbling fluidised bed reactor chamber



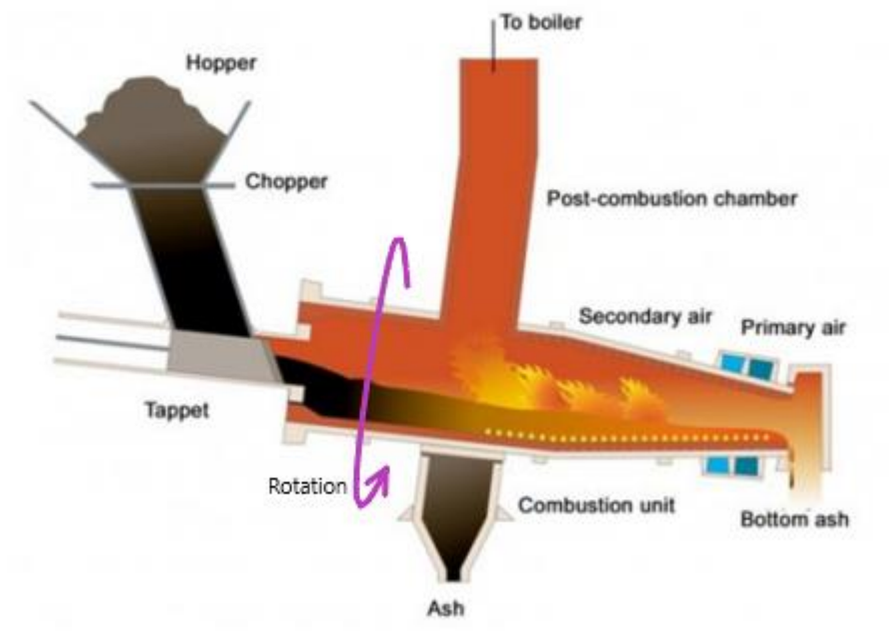
Fluidised bed reactors can generally cope with feedstocks of higher moisture content that other designs, and a wider range of NCV. They occupy a relatively small footprint, and the homogenous input feedstock and combustion approach results in more stable combustion temperatures leading to stable and consistent steam generation. The key drawback is the requirement to pre-treat the waste prior to introducing to the furnace in order to maximise efficiency of the plant, which carries additional capital and operational costs. The technology is less well known in the UK, but has been used with success in other regions around the world.

A1.2.5 Oscillating kiln

Waste is loaded into an input hopper drops down a chute to the furnace. It is then mechanically pushed into the top of a slightly inclined tapering cylinder or kiln. To move the waste through the kiln and control the rate of combustion, the kiln oscillates from side to side, passing the waste between paddles set into the internal walls of the kiln. The inert fraction remaining after the destruction of the combustible elements of the waste falls out of the end of the kiln and is removed from the plant as IBA.

The oscillating kiln process is illustrated in Figure A 4.

Figure A 4 Schematic of an oscillating kiln combustion process



The oscillating kiln process is generally suitable for treating smaller volumes of waste which make it well suited to specialist, low volume waste streams or regions with low waste availability. The technology is expensive however, and so when used particularly to process lower volumes the cost per tonne is likely to be higher than other combustion technologies.

A1.3 Advanced Thermal Treatment

A1.3.1 Introduction

ATT is a blanket term used to refer to technologies that use high temperatures to destruct the waste, but with limited oxygen to prevent complete combustion. As a result, the feedstocks do not burn, but instead are converted to a combination of gaseous, liquid and solid streams (depending on the composition of the feedstock and the type of process) which can be captured, purified and used in a variety of applications. The most common forms of ATT technologies are gasification and pyrolysis. Gasification involves the introduction of a small, controlled volume of air or oxygen to convert waste into syngas. External heat is not generally required as a proportion of the feedstock combusts to provide the heat needed to drive the reactions. Pyrolysis is a thermal process which takes place entirely in the absence of oxygen of which the primary objective is often the generation of a synthetic oil or hydrocarbon mixture, producing syngas as a by-product. Unlike gasification, pyrolysis requires an external heat source.

ATT technologies are commonly reliant on the pre-treatment of the feedstock to produce a homogenous, consistent material with a fine particle size to enable it to be fed into the process, although some systems are capable of processing raw MSW. The scale of pre-treatment depends on the feedstock being utilised. Waste wood for example may require a simple shred and metal removal, whereas mixed residual waste streams will require a much more comprehensive sort to make them suitable for ATT.

There are a number of ATT technologies, also often referred to as advanced conversion technologies, in development and use around the world. Whilst the technology can work well in certain applications, the use of ATT to treat residual MSW has proved challenging with limited commercial, large scale success achieved over the past 25 years. The exception to this is Japan and South Korea where high temperature gasification and melting systems are relatively commonplace and have been used to treat waste and vitrify (and therefore minimise the volume) the bottom ash to comply with local legislation. These systems tend to prioritise waste destruction over energy recovery. These systems differ from

ATT technologies that have been developed in Europe as their design and higher operating temperatures mean they are not as sensitive to waste composition nor require extensive pre-treatment. ATT technologies discussed further in this section are of the type commonly used in Europe.

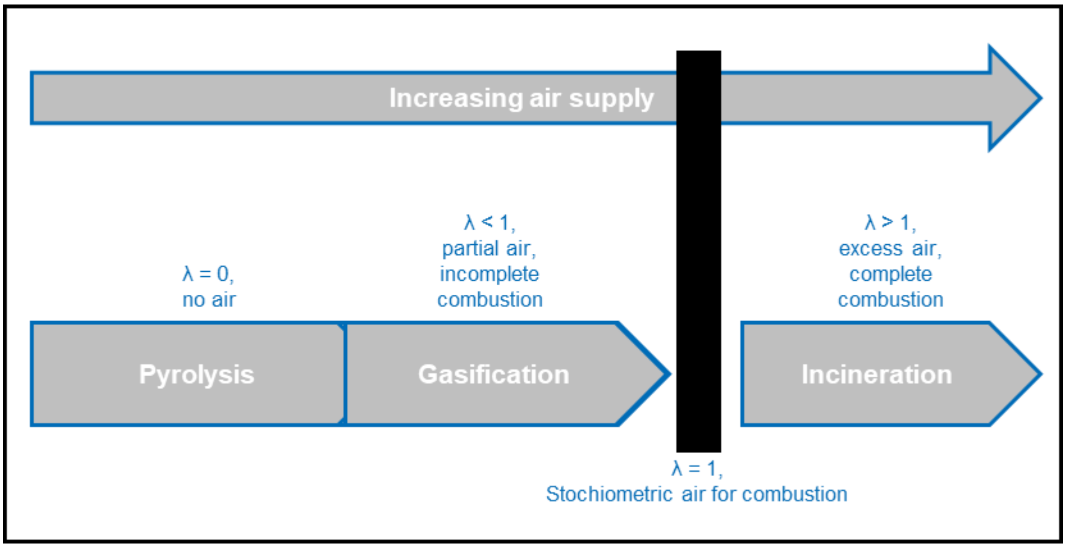
Increasingly more novel and higher value uses are being sought for pre-treated MSW (i.e. RDF and/or SRF), such as the production of synthetic liquid fuels (although this technology is in its relative infancy). These more novel approaches are likely to continue as operators seek to extract maximum value and apply the principles of the circular economy to their business models. The net zero agenda may also incentivise the production of alternative chemical or fuel products from waste, offsetting derivation of similar products from fossil fuel sources. In addition, government backed incentives or technology development grants are helping to drive the development of these technologies.

The major difference between ATT technologies and 'conventional' incineration is summarised below.

- **Combustion** (incineration with waste as the feedstock) is a complete oxidation process ensured by the provision of excess oxygen than the stoichiometric requirement. The temperature in the combustion chamber is typically >850°C.
- **Pyrolysis** is the thermal breakdown of waste in the absence of oxygen. Waste is heated to high temperatures (>400°C) in the absence of oxygen. The products are a combination of char, pyrolysis oil and syngas (pyrolysis gas). These products can be used for a variety of purposes including conversion to biofuels, as a chemical building block or combustion in a reciprocating gas engine.
- **Gasification** is the thermal breakdown/partial oxidation of waste under a controlled oxygen atmosphere (the oxygen content is lower than necessary for full combustion) that produces syngas (primarily consisting of CO and H_2).. Potential syngas uses are the same as for pyrolysis when they are captured and cleaned within the design process. Two-stage gasification process varies in that rather than capturing the generated syngas, the gas is immediately combusted with the addition of air in a second continuous process step.

Figure A 5 illustrates the importance of the supply of air to drive the reaction in each methodology. In alternative conversion systems, an intermediate product is generated, and the combustion process is carried out later (unless the target material is a precursor for chemicals or liquid fuels, in which case no combustion occurs).

Figure A 5 Principal of thermal treatment with air supply



ATT processes may produce a range of output products depending on the design and configuration of the system. The principal products most commonly associated with ATT processes include:

- Syngas – The syngas is a mixture of different components. The desired constituents of the gas, to be chemically reactive, need to have a high percentage of Carbon Monoxide (CO), Hydrogen

(H2) and Methane (CH4). The composition of the gas strongly depends on the feedstock adopted and the operating conditions of the process.

- Oils and Waxes – A liquid mixture of hydrocarbons that can be further refined and adopted in petrochemical processes. As with the syngas, the oil compositions are strongly dependent upon the feedstock and the technology adopted.
- Solid (Char, Biochar, Carbon Black) – From the bottom section of the high temperature chamber a solid material can be extracted. Many gasification processes produce limited char as it is mostly consumed in the process. Depending on the feedstock and the process conditions this can be either a product (i.e. Char, Biochar or Carbon Black) or a waste by-product of the operations (Ash).

A summary of the key characteristics of ATT technologies is provided in Table A 2.

Table A 2 Summary of ATT plant characteristics

Aspect	Summary
Type of energy conversion	Waste is heated with a limited amount of oxygen, converting material to a combination of gaseous, liquid and solid streams (depending on the composition of the feedstock and the type of process) which can be captured, purified and used in a variety of applications
Typical application	Used to treat a variety of feedstocks to produce synthetic gas or liquid fuels which may be used in lieu of fossil fuels in a range of applications.
Feedstock characteristics	Feedstocks will usually require an element of pre-treatment to homogenise the waste and maximise the efficiency of the process.
Scale and capacity	Similar scales can be achieved to combustion plants, generally involving the use of multiple processing units co-located at the same site.
Process outputs	Syngas and/or oil which may be used in place of traditional fossil fuels. Hot flue gases from the combustion zone may pass through a heat exchanger in order to recover heat suitable for district heating and/or industrial process use.
By product recycling	Char, Biochar and/or Carbon Black. The full potential of these materials is still the subject of research and development and is dependent on the feedstock characteristics, but it is suggested there may be a number of uses including as a soil improver or as an adsorbent material suitable for carbon sequestration but where MSW is the feedstock this may be subject to regulatory constraints.
Emissions	Highly variable depending on technology. For processes focused on power generation there will be a hot combustion gas stream, controlled and monitored to ensure compliance with the plant environmental permit and Industrial Emissions Directive BAT with regard to emissions.
Advantages	▪ Typically lower CO2 emissions to atmosphere (although burning of the syngas or oil will release CO2). ▪ Technology is generally perceived to be “greener” than combustion. ▪ Production of gaseous or liquid fuels increases the flexibility of the technology, allowing the products to be used for transport fuels or other applications. ▪ For processes that refine and cleans the intermediate products (syngas, oils) and are not classed as incineration under the Environmental Permitting regulations, the planning and permitting processes may be simplified. ▪
Limitations	▪ Technology is still largely unproven in the processing of MSW (with respect to those processes cleaning and refining syngas to higher value products).

	▪ Pre-treatment of MSW generally required which increases the capital and operational cost of the plant.

Reliability and bankability are still major issues with ATT technologies for the treatment of MSW. Whilst several variants of the technologies are being actively promoted by development companies there is little evidence to suggest they have achieved the track record and performance levels required to treat high volumes of residual MSW.

The commercial outlook for all ATT technologies in the UK without the backing of government enabled incentives is challenging. Several gasification plants that have been proposed or built in the UK have not reached operations, including the 50MW Air Products plasma gasification scheme in Teesside and the Energos gasification plant constructed for Derbyshire and Derby councils.

A1.3.2 Variants of ATT technologies

A1.3.2.1 Chemical recycling of plastic

Chemical recycling uses a variation of pyrolysis to heat a variety of waste plastics and break down the molecular structure in order to allow the component oil to be recovered for potential re-use. One of the leading developers of the technology is Plastic Energy[8]: a UK based company with over 10 years of experience in large scale pyrolysis plants, designed for the chemical recycling of plastics. The technology adopted by the company is currently covered by intellectual property rights but is based on the conversion of plastics into Tacoil® which is a combination of hydrocarbons adopted by the refining industry to either produce new plastics or fuels.

At the moment, Plastic Energy has two operating plants (Seville and Almeria) at industrial scale which are the largest pyrolysis plants in Europe with an overall capacity of 30-40 k tonnes per year of plastic.

The technology has been recently supported by several major oil and gas and energy companies including Exxonmobil, SABIC, INEOS and Total. In addition at the moment several major retailers such as TESCO are supporting the adoption of Plastic Energy technology to recycle flexible and foiled packaging.

The technology presents some limitations in terms of feedstock:

- Minimal level of contamination should be present in the feedstock.
- Certain types of plastic like Type 3 (PVC) and Type 7 (any other plastics) cannot be accepted by the process.
- The technology requires an extensive pre-treatment in order to adjust its physical and chemical characteristics prior to conversion.

A1.3.2.2 Gasification to produce aviation fuel

Thermochem Recovery International (TRI) is an American manufacturer providing gasification technologies for RDF, MSW and sewage sludge. The company has proven their technological capabilities in their 200 barrel per day test plant in Oklahoma, USA with over 10,000 hours of operational data. TRI is collaborating in the UK with Velocys to build the first Sustainable Aviation Fuel (SAF) plant to support British Airways. The site, based in Immingham, is designed to produce over 20 million of gallons of jet fuel and naphtha from MSW. The project, named “Altalto”, has been recently supported by the Department of Transport (DfT) in the Green Skies Initiative with an initial grant of £4.2M.

A1.3.2.3 Plasma Gasification

Plasma gasification is the term that applies to a range of technologies that involve the use of a plasma torch or arc. Plasma is an electrically conductive gas, such as nitrogen or argon, which is heated by an electrical current to very high temperatures. The reaction takes place within a chamber connected to a

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[8] https://plasticenergy.com/

plasma torch, which is refractory lined to withstand the high temperatures produced. The plasma gasification process is illustrated in Figure A 6.

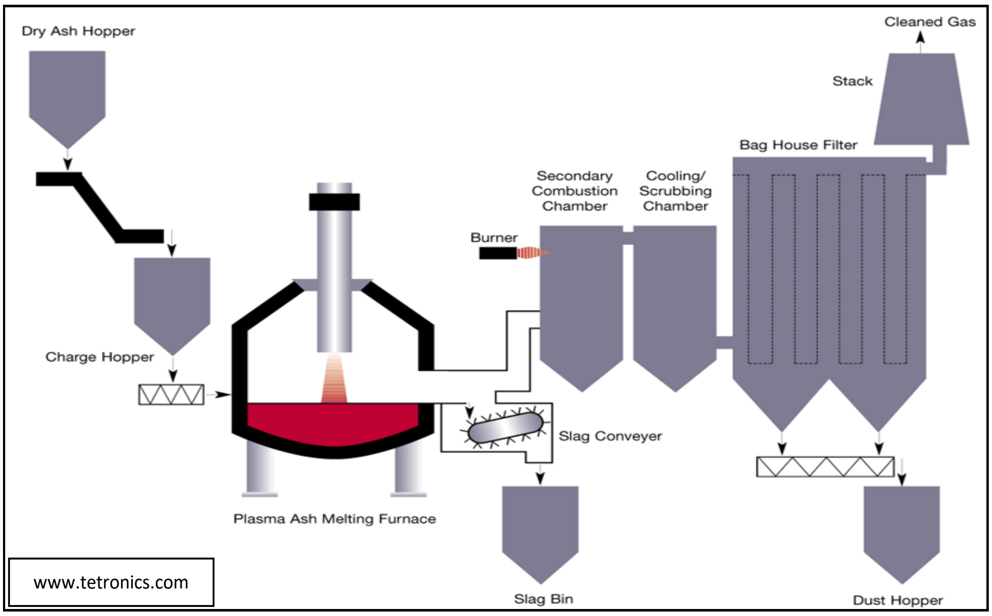
The plasma torch can be applied directly to the feedstock, or to the syngas produced by a proceeding gasification process. Plasma gasification operates at temperatures as high as 7,000°C, resulting in rapid chemical reactions to break down the feedstock into gases. Inorganic materials are melted into a liquid slag, which is cooled into a solid.

The higher temperatures ensure that the syngas produced by a plasma process is cleaner than conventional combustion, as the higher temperatures allow for the breakdown of tars. Whilst the syngas can be used for energy utilisation, the plasma process itself has high electricity consumption.

The feedstocks for this process are MSW, C&I, hazardous wastes and ashes. The process is less sensitive to particle size than gasification, and capacity ranges from 0.5-100 tonnes per hour.

Plasma gasification is a complex and expensive process. The technology has not yet been deployed commercially in the UK, and significant energy input is required. The syngas cleaning process is complex, and the required quality of the syngas output has not yet been fully demonstrated in a commercial plant.

Figure A 6 Plasma gasification process



Source: Tetronics

Currently the major technology developer for plasma gasification technology in the UK is Advanced Biofuel Solution Ltd (ABSL). The company has designed the world’s first plant to convert household waste into bio-substitute natural gas (BioSNG). The plant is currently under construction in Swindon, UK. The plant will convert 8,000 tonnes of waste into 22GWh of gas each year. The project is scheduled to enter ‘hot commissioning’ in October 2021.

The technology also offers a Carbon Capture and Storage (CCS) system, integrated in the overall plant, in order to minimise the carbon footprints associated with the operations.

A2 Appendix 2 Mechanical Materials Recovery Descriptions

A2.1 Introduction

Implicit in the treatment of several waste streams are mechanical processing operations. These are principally physical mixing, shredding, crushing and macerating, drying, and separation processes. These may be applied before, as part of, or after other treatments as indicated in the discussion of the thermal and biological treatments above. For example, the screening of compost after composting, de-packaging of food waste in preparation for AD treatment, and the processing of residual MSW in an MBT which generates an organic fraction destined for composting or anaerobic digestion.

There is a wide variety of mechanical treatment processing equipment which may be combined into large sequential processing units. Such processes are increasingly employing more sophisticated approaches such as artificial intelligence to recognise and select different materials when separating mixed wastes. Where a waste is collected as a source segregated material the mechanical processing may take place at the reprocessing/recycling plant. This would avoid the need for such mechanical processing albeit at the additional complication of having multiple source-separated collections.

For mixed wastes, i.e. commingled wastes, such as residual waste or co-collected dry mixed recyclables (DMR), the mechanical treatment may be under the control of a waste authority and some of the outputs sent to reprocessing plants.

A commonly applied complex mechanical treatment plant is often applied for processing dry mixed recyclables (commonly referred to as a Materials Recovery Facility). The main types of equipment used in Material Recovery Facilities (MRFs) are those for:

- material preparation;
- material transportation; and
- material separation.

A2.1.1 Material preparation equipment

The key pieces of equipment for material preparation include bag splitters and feed hoppers. Bag splitters are used to open bagged material which enters the MRF (if required depending on the collection approach). Bag splitters usually consist of a hopper with a conveyor system at the bottom; this feeds the material towards a rotating drum which opens and empties the bags without damaging the contents of the bags. As well as opening bags, the bag splitter acts as a metering system for the infeed into the plant, to ensure a continuous smooth flow of material.

Feed hoppers work in a similar way, providing a metred flow of material without the bag opening element. These are used where material is delivered loose.

A2.1.2 Material transportation equipment

The key piece of equipment for material transportation are conveyors. There are a variety of different type of conveyors, such as:

- **in-floor or walking floor conveyors** - used to load material into the MRF or in an automated baling system;
- **inclined conveyors** - used to elevate material into sorting equipment; and
- **picking belts** - used at sorting stations to enable operatives to sort material in a safe and efficient manner.

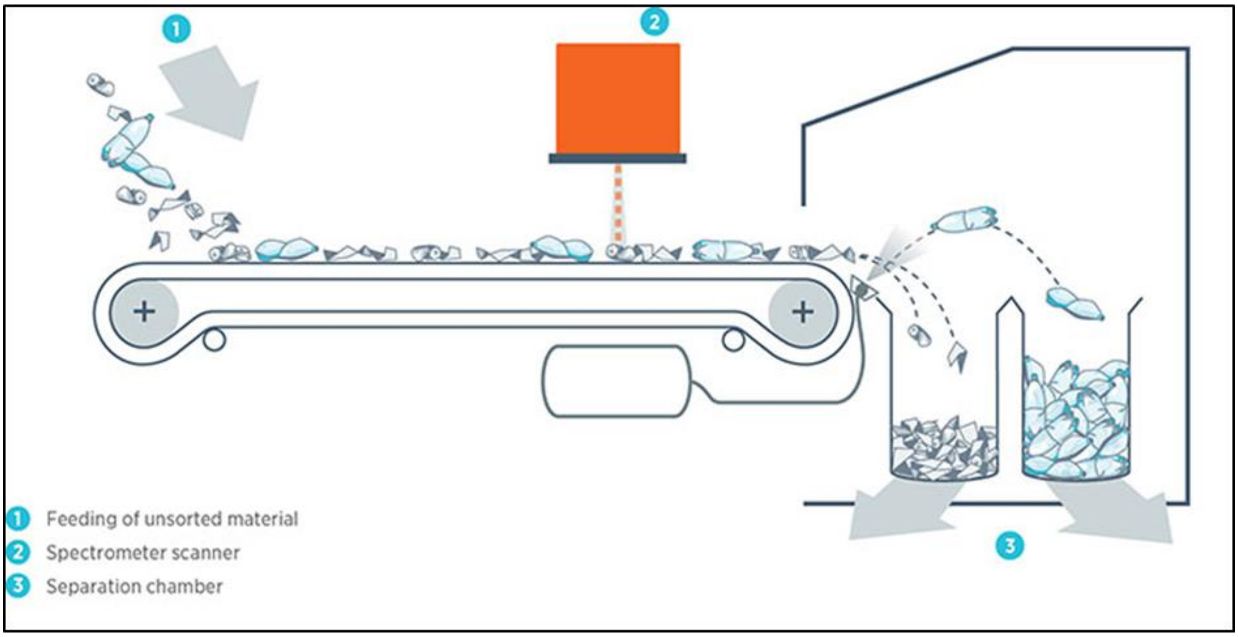
Every effort should be made during design to prevent equipment being installed in pits due to height restrictions. Pits represent both a maintenance challenge and health and safety risk associated with confined spaces.

A2.1.3 Material separation equipment

There is a wide variety of technologies utilised for material separation. These different pieces of equipment have the same ultimate purpose, which is to utilise the differing properties of material types to separate materials from the incoming stream. The main equipment groups for material separation are:

- **air classifiers** – utilise differences in size and density of various materials within the input stream, allowing lighter elements such as plastic film to be separated from denser materials within the input stream using compressed air jets.
- **magnetic separation** – including over-band magnets and eddy current separators which enable ferrous and non-ferrous metals to be separated respectively.
- **size classifiers** – allow materials to be separated based on their size, e.g., trommel screen which has fixed aperture size(s) to allow material below a certain size to be segregated from a mixed input feed.
- **shape classifiers** – disc screens consist of several rows of discs, which spin in the direction of material flow. Two-dimensional materials, such as newspaper and cardboard, move up an incline of rotating discus, while containers are bounded and roll down or through the screen; and
- **optical sorters** – use spectroscopy to scan the contents of a moving conveyor belt to identify the material targeted (often used to segregate plastic but can be used for other streams such as paper or glass). Plastic can be segregated into different polymers (PET, HDPE etc) as well as by colour using near infrared (NIR) and visible light respectively. Each polymer type absorbs specific wavelengths when exposed to NIR and transmits others, thus each polymer type has its own characteristic response which can then be detected by sensors. Once the targeted polymer type has been identified the optical sorting unit can then calculate the position and speed of the target item, and typically uses a jet of compressed air to blow the material from the waste stream into a dedicated hopper, allowing its separation. An example of this is shown in Figure A 7 .

Figure A 7 Optical sorter segregating plastic from a mixed stream[9]



Material presentation is key to successful sorting or separation. It is important to ensure that material is distributed evenly on the belt with no overlap, so that all material is clearly visible, and allows equipment to operate effectively, to minimise any contamination in the segregated streams.

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[9] https://www.tomra.com/en/solutions-and-products/sorting-solutions/recycling/recycling-technology/

The range of technologies used in a MRF vary in terms of their performance. For example, to enable the segregation of several polymers and potentially colours, several optical sorting units would be required. Similarly, for sorting many grades of paper and card, several screens may be used to segregate different characteristics of material, and subsequently manual picking operations or optical sorters can be used to separate different grades of paper from a more consistent input stream.

In addition to the technology, manual picking/separation is used (even with high tech MRFs) to either positively pick recyclables or negatively pick contamination to improve final purity as part of a quality control process. Invariably there will also be a manual pre-sort process at the front end of the MRF to remove extraneous items that may be detrimental to the plant operation such as large metal items and non-target items such as large film, textiles, large metal items and heavy cardboard tubes.

There is a significant variation in the process configurations used for MRFs, depending on several factors including:

- Input materials: quantity, composition, and presentation i.e., bagged or loose.
- Space available for processing.
- Grades of material to be separated.
- Degree of automation.

A2.2 Material Recovery Facility (MRF)

A2.2.1 Introduction

Material Recovery Facilities (MRFs) come in various configurations which are dependent upon several factors; the most important of these is the composition of the input material to be processed. Other variables include the level of automation, types of technology utilised and the flexibility of the process(es) to adapt to market changes in the output requirements.

With the range of potential configurations, it is difficult to define a ‘typical’ process. Broadly speaking, MRFs can be split into two categories depending on their level of automation, i.e., ‘low-tech’ and ‘high-tech’. At its simplest a ‘low-tech’ process can simply be a raised conveyor on which the materials pass and are hand sorted, while a ‘high-tech’ facility can consist of a semi or fully automated system and utilise various unit operations which exploit the differences in the properties of the recyclables to separate them.

There are benefits to each type of process in terms of capital costs, flexibility, processing capacity and throughput. The capital cost of a MRF will increase as the level of automation increases, but operational costs will be higher for MRFs with less automation as picking staff are required to manually segregate materials. However, high-tech MRFs still require some manual picking staff who fulfil a quality control role on the segregated streams, picking any items of contamination within the segregated streams before the material is deposited within storage bunkers.

MRFs which recover recyclables from source segregated dry mixed recycling (DMR) (often termed ‘clean MRFs’), may process feedstock in a number of different formats. Commonly they are grouped as follows:

- single stream, i.e., mixed paper, cardboard and containers, which may or may not include glass; and
- two-stream, i.e., one stream containing paper and cardboard, and the other containing mixed containers, which are then fed into different locations in the MRF.

In addition, some facilities can process a range of feedstocks via multiple entry points into the facility, and thus can process both two-stream and fully co-mingled recyclables.

Typically, clean MRFs recover more than 90% of the feedstock as recyclables, which is then sold to re-processors. However, this is dependent upon the quality of the input material, as large quantities of contamination (non-recyclable materials) and non-target materials (i.e., those not collected by the kerbside recycling scheme) or material which has become non-target due to its management, (e.g., wet paper) can have a significant impact on the yield of output materials segregated from the feedstock and also the quality of each output stream. There will always be some material which is rejected, for example material such as some types of plastics which cannot be easily recycled and are therefore typically sent to landfill, energy from waste or another facility which produces RDF. In addition to this, quality is also impacted by the configuration of the processing equipment and the degree of accuracy of sorting it can achieve.

A2.2.2 Co-mingled MRF

A2.2.2.1 Introduction

A co-mingled MRF is one designed to receive a single stream of mixed material and process it to recover the component elements for re-use, recycling, energy recovery or other disposal routes. Depending on the tonnage of waste received the MRF may include several parallel processing lines in order to cope with the volume, but they will usually follow identical process steps as all lines are processing the same feedstock.

The term “co-mingled MRF” will usually refer to a plant processing dry-mixed recyclables (DMR), which is likely to include as a minimum:

- Paper and card
- Metals
- Plastics

Depending on the design of the plant and the requirements of the client the MRF may also accept glass co-mingled, although this can cause issues with wear and tear around the MRF and impact the quality of some of the output materials.

Outputs from the MRF will differ from plant to plant depending on the design of the MRF and the output requirements but will typically include:

- Newspaper and pamphlets (News and pams)
- Old corrugated cardboard (OCC)
- Mixed paper
- Ferrous metal
- Non-ferrous metal
- PET
- HDPE
- Mixed plastic
- Heavy fines (glass, stone, ceramic etc.)
- Light fines (small pieces of paper, cardboard and plastic)

The majority of the MRF outputs will have a high purity and will be sent to a third party for recycling back into new products. The heavy fines fraction contains a high proportion of inert material and so may be suitable for use as a low-grade aggregate subject to meeting the required quality standard. The light fine fraction contains a high proportion (potentially 100%) of combustible material and so is suitable for disposal as a refuse derived fuel for energy recovery or alternatively landfill.

MRFs can typically recover more than 90% of the feedstock as recyclables, which are then sold to re-processors. This is however dependent upon the quality of the input material as large quantities of contamination (non-recyclable materials), non-target materials (not collected by the kerbside recycling scheme) and materials that become non-target due to their management (e.g., wet paper) can have a significant impact on the yield of outputs materials segregated from the feedstock and the quality of each output stream. In addition to this, quality is also impacted by the configuration of the processing equipment and the degree of accuracy of sorting it can achieve.

Streams segregated in MRFs are then passed on to re-processors with an income received from some streams, whilst for other streams a gate fee must be paid by the MRF operator. Quality of the segregated streams is of key importance to maximise the income received from the sale of recyclables.

The activities undertaken by re-processors vary significantly, with some offering closed loop solutions (e.g., glass going for re-melt to produce new glass bottles), or open loop recycling, often termed 'downcycling', (e.g., glass being crushed to produce an aggregate).

Table A 3 Summary of key characteristics of a co-mingled MRFs

Aspect	Summary
Type of mechanical treatment	Dry, mechanical processing utilising screens, separators, conveyors and other mechanical elements to separate mixed recyclables out into high-purity, single material streams.
Typical application	Sorting of comingled dry mixed recyclables (DMR).
Feedstock characteristics	DMR is typically collected from residents and businesses by local authorities or waste management companies. Material is commonly collected in refuse collection vehicles which compact the material to increase the payload.
Scale and capacity	Co-mingled MRFs operated in the UK typically range in capacity from circa 40,000 to 250,000 tpa of comingled dry recyclables.
Process outputs	Outputs will vary depending on the design of the plant and the requirements of the operator. Typical outputs include: ▪ Paper ▪ Cardboard ▪ Ferrous metal ▪ Non-ferrous metal ▪ Plastics
By-product recycling	Typical by-products are a heavy residual fraction and a light residual fraction. If glass is included within the feedstock then the heavy fraction will make up a larger proportion of the plant outputs. The glass-rich heavy fraction may be sent to specialist reprocessors who are capable of recovering the glass from the residues to recycle it into a cullet product suitable for recycling. There are not many glass recycling plants capable of receiving MRF glass with high levels of contamination, but there is one located in Essex. If glass recovery is not possible the heavy fraction may be cleaned up further and disposed of as a low-grade aggregate product. The light residual fraction may be sent for energy recovery as RDF.
Advantages	▪ Facilitates simplified collection regime using a single vehicle and collection round. ▪ No requirement for residents and businesses to have separate boxes and bins. ▪ Single reception hall area for the storage of incoming feedstock with no segregation requirements or separate loading needed.
Limitations	▪ Output material quality may be lower due to comingled nature of incoming stream.

Aspect	Summary
	▪ Output material quality can also be lower as there is no manual interaction with DMR collected at the kerbside – it is all loaded into the vehicle.

A2.2.2.2 Process flow

There is a wide range of technology available to process DMR. As a result, it is hard to provide a single detailed analysis for a production plant as they all differ in terms of cost, complexity and output quality. Most modern MRFs will follow a broadly similar process flow.

DMR is loaded into a loading hopper with a metering drum to provide a consistent feed of material into the plant. If DMR is received in bags then a bag splitter or shredder may be used to open bags and free up the material. The material will pass through a pre-sort step in which large items of contamination are removed by hand to prevent them causing an issue during the mechanical process stages.

The DMR is then transferred to an initial screening phase which will often size sort the material and separate 2D materials (paper and card) from 3D materials (plastic and metal containers). A fines streams, usually around 50mm or less, is separated at this point. The fines are passed beneath an overband magnet which removes ferrous metal and density separation to split heavy from light material, before being collected for further treatment (commonly a composting treatment).

The 2D and 3D streams will usually pass through a range of further equipment which depending on the configuration of the plant may include:

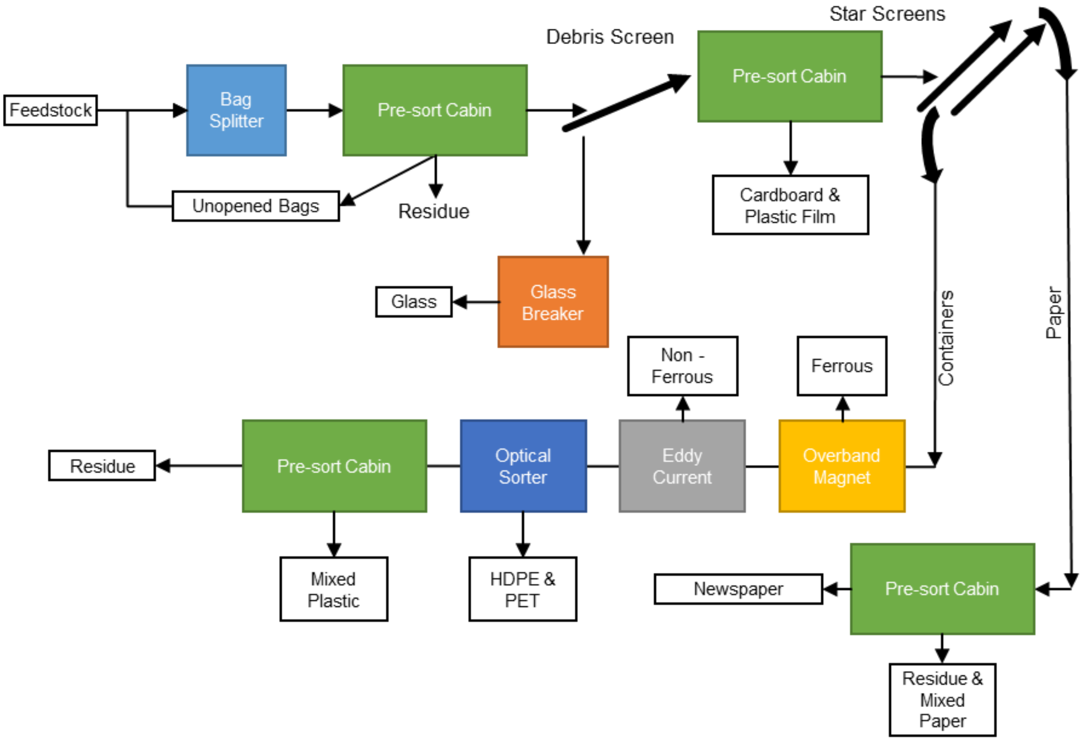
- Overband magnet to remove ferrous metal.
- Eddy current separator to remove non-ferrous metal.
- Density separator to remove light material such as paper and plastic from the waste stream.
- Optical separator, typically using near-infra red light, which may be used to separate paper from cardboard, or to target contamination such as plastic film.

Once separated the individual material streams are then commonly passed through a quality control step. This usually comprises of manual picking to remove non-target materials, though emerging technologies such as artificial intelligence and robotics are starting to become utilised.

The output streams are then bulked up in bunkers or bays, before being baled for export from site.

An example flow diagram for a generic co-mingled MRF is provided in Figure A 8.

Figure A 8 MRF processing bagged comingled dry recyclables[10]



A2.2.3 Two-stream MRF

A2.2.3.1 Introduction

A two-stream MRF is a facility which receives two source segregated input streams and passes them through two separate processing lines. This approach can lead to improved efficiency and output quality as dissimilar materials can be kept separate from each other. The two streams most commonly consist of fibre, containing paper and cardboard, and containers, comprising metals and plastics. If glass is accepted, it will be included in the containers line.

A two stream MRF will be equipped with two separate infeed hoppers for the two streams, and two separate lines configured for the material received. Some common equipment may still be shared such as fines processing equipment and balers.

This approach removes the requirement for a process step to separate 2D material (paper and card) from 3D (containers) which can often cause cross contamination. For example plastic bottles or metal cans may become compressed during collection and being flattened, causing them to present as 2D material.

Another source of potential contamination is glass, particularly in the paper fraction. Paper mills have a very low tolerance for glass shards in the paper as it can interfere with the pulping and pressing process, and so are likely to reject any loads with traces of glass in them. The inclusion of glass in the container line only (or removal from the MRF input at all) will remove the risk of glass being present in the paper recovered from the MRF, reducing the chance of non-compliant paper products being sent to paper mills.

A summary of key characteristics of a two-stream MRF is provided in Table A 4.

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[10] Source: Owen, N (2008) The effect of increased kerbside provision and MRF development on recycling rates in a rural community. Cardiff University. Graphic drawn by Ricardo.

Table A 4 Summary of key characteristics of a two-stream MRF

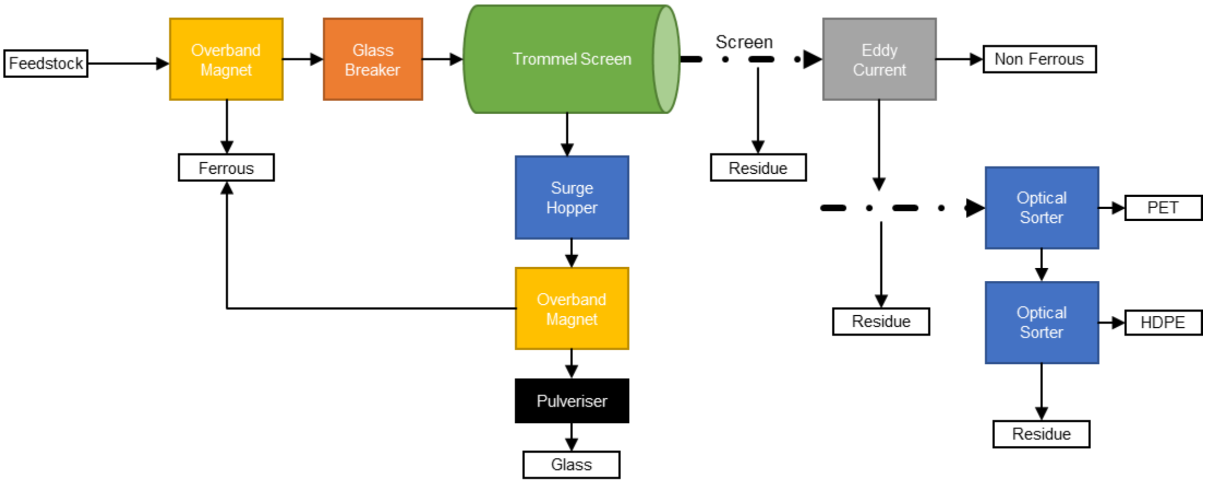
Aspect	Summary
Type of mechanical treatment	Dry, mechanical processing utilising screens, separators, conveyors and other mechanical elements to separate mixed recyclables out into high-purity, single material streams.
Typical application	Sorting of two source segregated DMR streams, commonly fibre (paper and card) and containers (metals and plastics).
Feedstock characteristics	DMR is typically collected from residents and businesses by local authorities or waste management companies. Material may be collected in split-loader refuse collection vehicles which compact the material to increase the payload, or by two separate collection vehicles.
Scale and capacity	Two-stream MRFs operated in the UK typically range in capacity from circa 40,000 to 250,000 tpa.
Process outputs	Outputs will vary depending on the design of the plant and the requirements of the operator. Typical outputs include: ▪ Paper ▪ Cardboard ▪ Ferrous metal ▪ Non-ferrous metal ▪ Plastics
By-product recycling	Typical by-products are a heavy residual fraction and a light residual fraction. If glass is included within the feedstock then the heavy fraction will make up a larger proportion of the plant outputs. The glass-rich heavy fraction may be sent to specialist reprocessors who are capable of recovering the glass from the residues to recycle it into a cullet product suitable for recycling. There are not many glass recycling plants capable of receiving MRF glass with high levels of contamination, but there is one located in Essex. If glass recovery is not possible the heavy fraction may be cleaned up further and disposed of as a low-grade aggregate product. The light residual fraction may be sent for energy recovery as RDF.
Advantages	▪ Better quality of output materials is possible due to the two distinct streams being segregated at source.
Limitations	▪ Requirement for waste collection operator to collect two separate streams which may require upgraded or separate vehicles. ▪ Residents/businesses will require two separate bins to store material which can be an issue in areas where space is at a premium, for example blocks of flats.

A2.2.3.2 Process flow

The process flow is broadly similar to that described in section0, with the exception that the 2D/3D separation step is not required as the two streams collected are already separated. The same equipment items and process steps will then be followed to extract recyclables.

An example flow diagram for the container line of a generic two-stream MRF receiving glass is provided in Figure A 9.

Figure A 9 Dual-stream MRF processing loose mixed container stream only[11]



A2.2.4 Multi-stream MRF

A2.2.4.1 Introduction

A multi-stream MRF is the term given to a collection of sorting and material handling equipment designed to process source-segregated materials, that is a waste stream separated into its component parts by the householder and collected in specialist vehicles which feature multiple compartments to keep the materials separate. Again this style of collection is generally used for DMR, although food waste and waste electrical equipment (WEEE) may also be collected using this methodology and at the same time as the DMR.

At the end of the collection round the vehicle returns to a transfer station where it discharges each compartment into a separate bay, maintaining the segregation between the different component materials. These bays will be used to bulk up the material and then are often loaded into a bulker trailer for transportation directly to a suitable re-processor for recycling.

The quantity and nature of processing equipment required will depend on the collection regime and requirements of the offtakers of the output products. It is possible for all materials to be source segregated and deposited in separate bays at the transfer station, removing the requirement for any sorting equipment at all. More commonly two or three streams may be collected together to reduce the number of containers required to be kept by the householder. These are likely to be:

- Mixed metals
- Mixed plastics
- Metals and plastics
- Paper and cardboard

In this case the transfer station may be equipped with several separate small-scale sorting lines, for example and magnet and eddy-current separator to separate ferrous and non-ferrous metals, optical sorters, manual picking or disc screens to separate paper from cardboard etc.

One of the key advantages of multi-stream collections is that the incoming material quality tends to be higher than that received in single stream collections. Likely reasons for that are greater engagement by the public, i.e. people have to “think” about which bin they are putting items into, and that the collection operatives tend to carry out a quality check as they are transferring the contents of the bins to the vehicle, manually removing contaminants.

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[11] Source: Owen, N (2008) The effect of increased kerbside provision and MRF development on recycling rates in a rural community. Cardiff University. Graphic drawn by Ricardo.

Down sides include the reliance on householders to correctly sort their recyclables, the requirement for a number of separate bins or containers to be held by the householder, and the space requirement to bulk up multiple streams of recyclables. This can be a particular issue in areas of high-density housing such as blocks of flats or terraced streets.

A summary of key characteristics of a two-stream MRF is provided in Table A 5.

Table A 5 Summary of key characteristics of a multi-stream MRF

Aspect	Summary
Type of mechanical treatment	Dry, mechanical processing utilising screens, separators, conveyors and other mechanical elements to separate mixed recyclables out into high-purity, single material streams.
Typical application	Sorting of two source segregated DMR streams, commonly fibre (paper and card) and containers (metals and plastics).
Feedstock characteristics	DMR is typically collected from residents and businesses by local authorities or waste management companies. Material may be collected in split-loader refuse collection vehicles which compact the material to increase the payload, or by two separate collection vehicles.
Scale and capacity	Two-stream MRFs operated in the UK typically range in capacity from circa 40,000 to 250,000 tpa.
Process outputs	Outputs will vary depending on the design of the plant and the requirements of the operator. Typical outputs include: ▪ Paper ▪ Cardboard ▪ Ferrous metal ▪ Non-ferrous metal ▪ Plastics
By-product recycling	Typical by-products are a heavy residual fraction and a light residual fraction. Glass tends to be collected separately and as a result tends to be of a high quality suitable for further processing into glass cullet for recycling. The light residual fraction may be sent for energy recovery as RDF
Advantages	▪ Higher quality of delivered material due to collection staff carrying out quality control. ▪ Better quality outputs as a result of processing like-materials together. ▪ High-quality glass fraction suitable for reprocessing into cullet and recycling.
Limitations	▪ Specialist collection vehicles required. ▪ Reliance on residents to comply with segregation requirements. ▪ Requirement for residents to keep multiple bins or containers which may cause issues in areas of high density accommodation. ▪ Large transfer station required in order to bulk up incoming material loose and process elements of it as required.

A2.2.4.2 Process flow

The process steps followed in a multi-stream MRF will be dependent on the blends of materials collected. If all materials are collected separately then there may be no requirement for any process equipment. Alternatively if a range of off-takers are arranged who have their own equipment for separating materials (for example a scrap metal merchant who can separate ferrous from non-ferrous metals) then again there may be no requirement for processing at the transfer station.

Generally, some processing will be required to produce higher value output streams. This may include:

- A magnet and eddy current separator to separate ferrous from non-ferrous metal.
- Optical sorters to separate plastics from other materials (such as metals if co-mingled), or to separate different polymer types such as PET, HDPE etc.

Manual picking to separate paper types, or paper from cardboard.

A2.3 “Dirty MRF” for residual waste

A2.3.1 Introduction

Dirty MRF is a term used for the processing of residual MSW or other non-DMR streams through a mechanical sorting process. Outputs from a dirty MRF differ depending on what the operator is trying to do, but usually include heavy (inert) rejects, a fine organic rich fraction, ferrous and non-ferrous metals, and RDF.

The amount of equipment used in a dirty-MRF can vary widely depending on the tonnage to be processed and the required quality of the output product. A dirty-MRF will generally consist of an amount of equipment using similar technology and layout to a DMR MRF. This is likely to include shredding, screening, magnets and eddy current separators to separate out the fine content (largely organic and inert such as sand and stones) and recover metals to leave a residual RDF fraction.

A more advanced plant is likely to employ more advanced technology such as near infra-red (NIR) sorting which is capable of identifying and ejecting a wide range of materials including paper and plastic. The NIR sorters can be used to perform different functions. Some plants may choose to try and recover plastics for recycling, targeting it and ejecting it from the waste stream. Other plants may use the NIR sorters to maximise recovery of plastics and other high energy content materials into the RDF stream, discarding inert or low energy content items.

Plants may also use NIR sorters to ensure the end user specification is achieved. For example many energy from waste (EfW) users may impose a limit on the chlorine content of the RDF. In MSW PVC plastic is the most common component which will give rise to chlorine production when combusted, and so NIR sorters can be used to target and extract PVC plastics, reducing the likely chlorine content of the resultant RDF/SRF.

Dirty-MRFs do have some drawbacks. An organic and heavy inert fraction are produced which will need to be disposed of. Some facilities compost the organic fraction, or use it as a feedstock for AD, but this can be costly and create a requirement for more processing area (unless a third party is utilised). The homogenous nature of MSW means that any output products recovered for recycling are typically highly contaminated and odorous due to the organic content of the waste sticking to other components of the waste. This reduces the value of those products on the market. Mechanical processing of MSW is a dirty process, and as such screens are liable to block up and conveyor belts and other components will become contaminated with organic waste. This increases the demand for plant cleaning and maintenance requirements. It also creates odour so a dirty MRF will require an effective air extraction and odour control system.

Table A 6 Summary of key characteristics of a dirty-MRF

Aspect	Summary
Type of mechanical treatment	Mechanical processing utilising screens, separators, conveyors and other mechanical elements to separate recyclables out and produce waste derived fractions which have some value as a feedstock to energy recovery technologies.
Typical application	Sorting of MSW to recover recyclable materials, an organic rich fraction suitable for biological treatment and an RDF suitable for energy recovery.
Feedstock characteristics	Residual or unsorted MSW.
Scale and capacity	Two-stream MRFs operated in the UK typically range in capacity from circa 40,000 to 300,000 tpa.
Process outputs	Outputs will vary depending on the design of the plant and the requirements of the operator. Typical outputs include: ▪ Ferrous metal ▪ Non-ferrous metal ▪ Plastics (although these are often too contaminated to be sold) ▪ Organic fines ▪ RDF
By-product recycling	By-products are generally larger, non-combustible items in the waste stream which are unsuitable for further treatment. These are usually sent to landfill or for incineration.
Advantages	▪ Ability to recover recyclables from residual waste, particularly valuable in areas where recycling schemes are hard to implement such as high-density housing areas. ▪ No harmful emissions to atmosphere.
Limitations	▪ Process is dirty and so experiences elevated levels of wear and tear and requires regular maintenance. ▪ Mechanical processing of raw MSW releases odour which can become a nuisance to neighbouring residents and businesses if not suitable controlled. ▪ Recycling rates are generally low (often circa 10-15%) and recyclables are dirty and odorous, making them hard to sell. ▪ It can be hard to find markets to process the organic fines output as it is highly contaminated and cannot comply with the requirements of the animal by-products regulations to be used as a compost. ▪ The RDF fraction will still require disposal via combustion or ATT, which carries associated environmental drawbacks.

A2.3.2 Process flow

Design of dirty-MRF plants will vary depending on the designer and the requirements of the operator. However the general processing principles are similar for all plants. Input waste is shredded to reduce the particle size, provide greater uniformity and to homogenise the input feedstock. Following this the waste is usually transferred to a screen with two screen sizes; a smaller 120 mm (or similar) hole size and a larger 300 mm (or similar) hole size. The smaller <120 mm material stream is typically passed over a vibrating screen with a hole size of 60-80 mm to separate the fine fraction from larger material. The fines are passed beneath an overband magnet which removes ferrous metal, before being collected for further treatment (commonly a composting treatment).

The 60-120mm stream passes through a range of further equipment:

- Overband magnet to remove ferrous metal.
- Eddy current separator to remove non-ferrous metal.
- Density separator to remove light material such as paper and plastic from the waste stream.
- Optical separator, typically using near-infra red light, which may be used for several duties. As illustrated in Figure A 10 the optical separator is targeting heavy combustible material such as wood, textiles/shoes, hard plastics etc. and transferring it to the SRF stream. An alternative use for the optical separator could be to remove non-target material such as large inert particles, or to target plastics to collect for recycling (such as PET and HDPE). The optical separators could also identify materials such as PVC which could increase the chlorine content of the SRF and divert it out of the fuel stream.

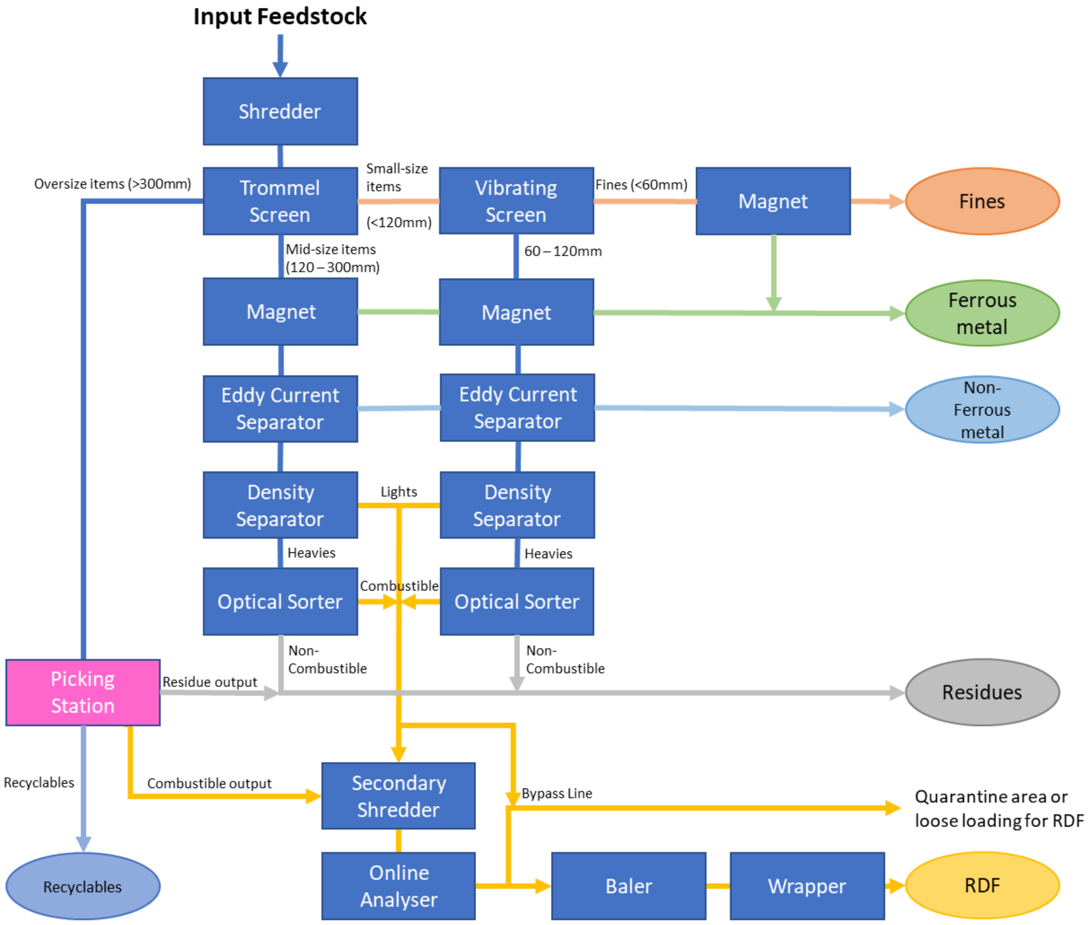
The mid-size fraction from the trommel (nominally 120 – 300mm) will pass through the same process steps as described above to remove the same outputs from the waste stream. The two streams may then be brought together for secondary shredding (if required by the RDF fuel specification). These shredders are usually hammer mills or similar which will reduce the particle size of the fuel to meet the specification requirements, often around 25mm. There may be several secondary shredders depending on the throughput of the plant and to provide redundancy in the event of breakdown or maintenance. The secondary shredder line will often have a bypass line to allow the operator to export a coarse grade RDF if required.

At a more advanced dirty-MRF an online scanner may be provided to analyse the RDF to establish material properties to ensure the fuel is within customer specification limits. This is often done by segregating a small sample from the main stream and spreading it on the belt to provide the analyser with clear vision of all components of the waste. The analyser commonly uses near-infra red light to identify the component parts of the waste stream. These materials will be cross-referenced against a database of material properties to provide an indication of energy content, chlorine content and other parameters. The analyser can even provide an estimate of moisture content based on the composition of the material.

If the analyser indicates that the material falls outside the specification a bypass line downstream of the analyser may divert that batch of SRF to a quarantine bay. From here it can be analysed further and either disposed of or blended back into the process with fresh feedstock to dilute the non-compliant elements of the fuel.

SRF which is compliant with the specification is then baled and wrapped prior to export from site.

Figure A 10 Indicative process flow diagram for a dirty-MRF producing RDF



A2.3.3 Secondary treatments

A2.3.3.1 Biological treatment

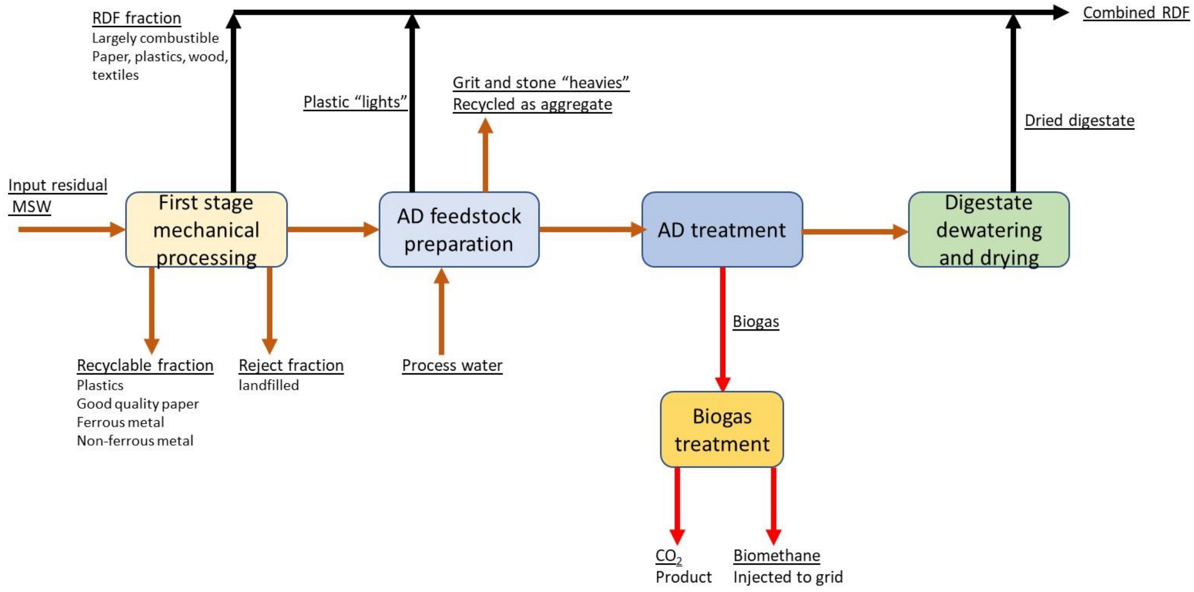
The residues from a typical first stage dirty MRF sorting scheme generates a residual waste stream that is concentrated in the biodegradable organic fractions of the waste. This organic rich stream (often referred to OFMSW – organic fraction of MSW) may be used as feed to an anaerobic digester as biological treatment stage or composted aerobically. These biological treatments are discussed below.

A2.3.3.1.1 Anaerobic Digestion

The organic fraction generated in a dirty-MRF process can be used as a feedstock for anaerobic digestion (AD). The organic fraction is usually highly contaminated with heavy elements such as glass, ceramic, sand and stone, as well as small pieces of plastic and paper/cardboard. As a result the organic fraction requires further comprehensive processing to remove non-organic contaminants and blend the material with water to form a slurry suitable for AD treatment.

Figure A 11 shows as an example a simple schematic for a dirty MRF designed to produce recyclables, RDF and an organic fraction from residual MSW for processing in an AD plant. In this example the biogas is upgraded to produce biomethane which is injected into the national grid and the digestate is dried and added to the RDF.

Figure A 11 Schematic of dirty MRF designed fir RDF production and AD treatment of OFMSW



A2.3.3.1.2 Composting

There are several options for composting the organic fraction from a dirty MRF. Composting is the aerobic biological treatment of the waste where there would be some removal of biodegradable organic carbon as biogenic CO_2 and loss of mass due to the destruction of some of the organic matter and evaporation.

Composting approaches include open windrow, in-vessel composting or the use of aerated maturation halls. The aim of composting is to reduce the biological activity in the waste. This can make it suitable for use in land remediation or landfill capping.

A2.3.3.2 Thermal treatment of RDF

Dirty-MRFs commonly produce RDF which is sent for energy recovery. The most common form of thermal treatment is combustion, but RDF is also a good feedstock for Advanced Thermal Treatment technologies which often require a more controlled specification for input feedstocks. The advantage of using RDF over raw MSW is that it is a more controlled feedstock which can be tailored to the end user's requirements via the removal of inert materials, organic material with a high moisture content and/or undesirable elements such as PVC plastic. Good quality RDF will attract a lower gate fee at a thermal treatment plant, reducing the disposal cost for the MRF operator.

A2.4 Other mechanical processes

A2.4.1 Introduction

Whilst MRF technologies are the most common mechanical treatment methodology, there are other approaches which blend mechanical action with other elements such as steam. Some of these are discussed below.

A2.4.2 Autoclave

An autoclave is essentially a pressure vessel which uses rotation, heat and pressure to break down the waste. Waste is loaded into the vessel and the door is closed to seal it. The vessel is then rotated to mix and break up the waste. Flights are commonly welded to the inner walls of the vessel to aid this. At the same time the vessel is heated. Some autoclaves may use a heated jacket to heat the body of the vessel and transfer heat to the contents, but for autoclaves processing waste it is more common to inject steam into the vessel to heat up the material, increase the pressure and introduce moisture to the mixture. Once up to pressure the autoclave is usually rotated for around 15 – 30 minutes during which time the waste effectively "cooks", breaking down the organic matter into a homogenous, fibrous flock, softening and crushing plastics and cleaning metals. At the end of the cycle the autoclave is emptied and the contents can be sorted using a MRF to recover recyclables, leaving the organic fibre as the primary output.

Autoclaving has several advantages. The material is held at a high temperature for a prolonged period which effectively sterilises the waste, making is safer to handle. Metals and rigid plastics come out clean with labels removed, although plastics can become discoloured. The autoclave will also fragment and partially hydrolyse the biogenic organic matter making this potentially easier to separate from other materials and enhance the biogas yield if anaerobically digested.

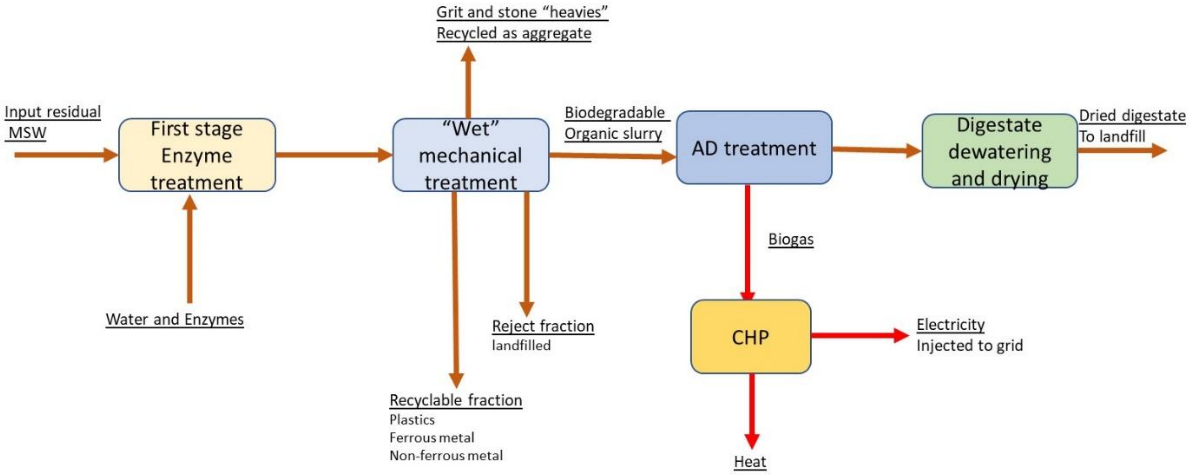
However the process is complex and requires ancillary systems such as a steam boiler in order to function. It is energy intensive, although cross-coupling two or more autoclaves to recover steam can improve the efficiency. Textiles in the feedstock will wrap around each other and form a large mass which is hard to handle in the MRF plant. Finally the organic fibre can be hard to dispose of if the feedstock is derived from mixed waste as it cannot be compliant with animal by-products regulations and therefore cannot be applied to land as a fertilizer.

A2.4.3 Enzyme treatment

A more recent development in waste treatment is using enzymes to partially hydrolyse the organic fraction making this also easier to separate and produce a ready feedstock for anaerobic digestion. Waste is loaded into a rotating drum to break up and homogenise the material. Water is added along with enzymes to initiate a biological reaction in the material. The enzyme addition usually includes celluloses which can hydrolyse cellulosic paper. The enzyme process is typically carried out at an elevated temperature of circa 50-60ºC and held there a few hours for the process to occur. The process can be quite efficient at extracting all the potential biodegradable waste, e.g. removing paper labels from glass and cans.

This process scheme is illustrated in Figure A 12. It should be noted that in this process the residual waste is wetted at the very start of the process scheme and all subsequent operations then take place with wet waste. Also in this example the biogas is used in a CHP to generate heat and electrical energy and the digestate is dried and sent to landfill. Other options for these outputs can be accommodated in this scheme.

Figure A 12 MBT configuration with an enzyme pre-treatment process for AD



Advantages of the enzyme reactor is in the preparation of the waste stream for AD and effective hydrolysation of organic materials without requiring pressure and steam as in an autoclave. However this is still a relatively unknown technology with only a few reference facilities in the UK. It is also likely to be hard to remove heavy inert material from the hydrolysed waste without losing organic material or carrying inert material forwards into the digesters.

A2.4.4 Ball mill

A ball mill is a pre-treatment step which can be used to homogenise the waste prior to mechanical sorting. Waste is loaded into a large rotating drum which has large steel balls inside it. The drum is rotated and the balls roll around in the waste, breaking it down and homogenising it. This method is often used to prepare MSW for AD as it breaks up the material, allowing recyclables to be removed by a sorting plant and pulverising the organic fraction (including paper and card) into a consistent organic stream for AD.

A3 Appendix 3 Biological Treatment Technology Descriptions

A3.1 Introduction

Biodegradable or organic waste is material that can be degraded by biologically via anaerobic or aerobic conditions. Depending on the environmental conditions of the process, by-products can include carbon dioxide, water, methane, biomass and mineral salts.

The biological treatment of organic waste is defined in the UK[12] as the decomposition and stabilisation of biodegradable wastes done under controlled conditions, resulting in sanitised materials that can be applied to land either for the benefit of agriculture, to improve the soil structure or nutrients in land. Possible effects of biological processes include the generation of significant amount of heat (in the case of aerobic digestion) and the production of methane rich biogas (in the case of anaerobic digestion).

The treatment options of biological waste can be a set of complex processes and activities and may be the basis of standalone processing of source separated wastes or the biological stage of mechanical biological treatment (MBT) processes. The biological treatment of waste can be divided into two main categories as illustrated in Figure A 13:

- Aerobic composting i.e., the processing of waste in the presence of air (oxygen); and
- Anaerobic digestion (AD) i.e., the processing of waste in the absence of air (oxygen).

This guide is particularly focused on the biological treatment of either the organic fraction of MSW or source segregated organic waste streams such as biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants.

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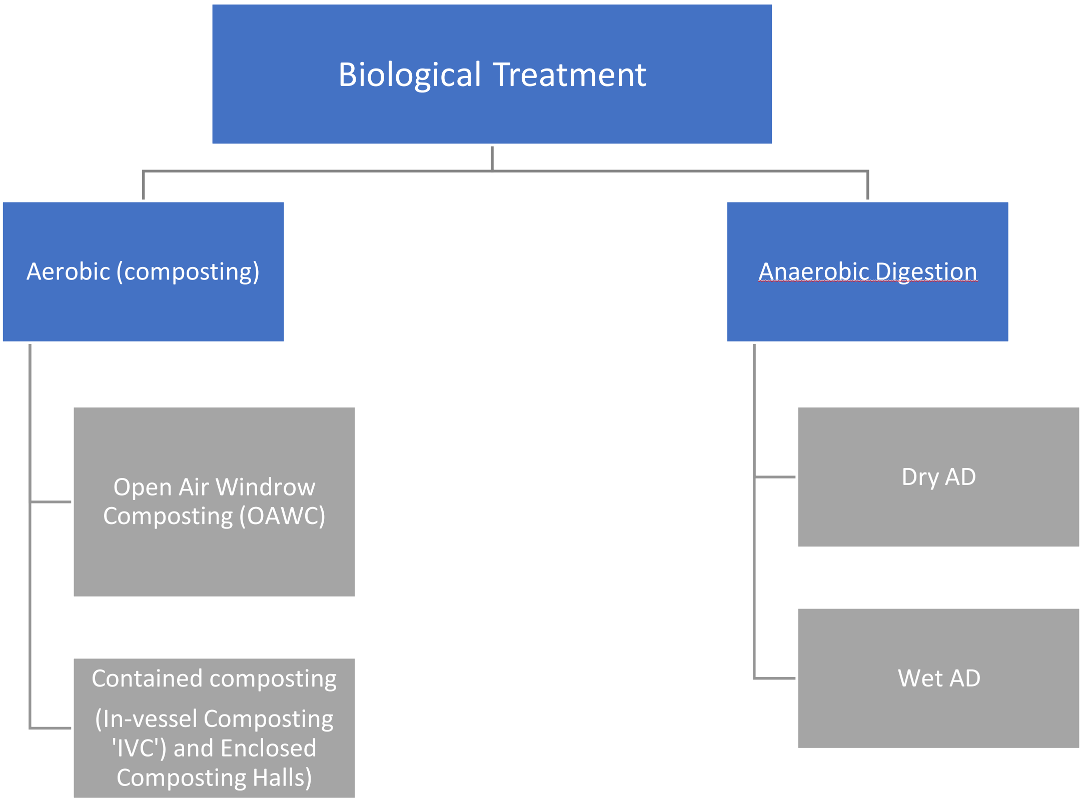
[12] *https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/898966/Appropriate_measures_for_the_biological_treatment_of_waste_-_consultation_document.pdf*

Figure A 13 Common biological treatment options for organic waste



A3.2 Aerobic Biological Treatment

A3.2.1 Introduction

Composting treatment technology capacity has increased significantly over the last 25 years as the separate collection of biodegradable waste has become the norm in response to diverting biodegradable municipal waste from landfill. This was by initial expansion of open-air windrow composting (OAWC) for the treatment of separately collected green waste. Composting technologies now also include in contained composting (including in vessel composting (IVC) and enclosed composting halls) where the composting conditions and environmental emissions are tightly controlled. Such technologies may be used for green waste, co-collected green/food waste and the organic fraction of residual MSW. Composting reduces the mass of waste, partly through decomposition of organic matter and moisture loss, and can, where the feedstock is certain source segregated organic wastes, produce a nutrient rich compost that can be recycled to land as soil conditioner and/or fertilizer and that has attained end-of waste status.

Composting is the biological treatment of waste by aerobic microorganisms in the presence of air. This is essentially a low temperature bio-combustion process where biogenic organic material is degraded by the microorganisms and oxidised to CO_2 and H_2O. This is an energy generating process as evidenced by the heat typically produced during composting which can reach as high as 70 to 80^oC and for which measures may have to be introduced to cool the composting waste as such high temperatures also kill off the microorganisms carrying out the composting.

Composting times vary considerably ranging from a few days to several weeks depending on the treatment objectives and type of composting process. It is typically associated with a loss of mass of the waste through decomposition of biodegradable organic matter and evaporation of moisture. Composting may be carried out in the open air on concrete platforms as open-air windrow composting or in enclosed vessels or buildings. Typically composting in enclosed vessels or buildings is more controlled than in open air composting, often with forced aeration and moisture adjustments of the waste.

As well as moisture and mass loss through decomposition, composting also results in significant air emissions including odours, ammonia and microorganisms. These emissions may be captured and mitigated in enclosed composting processes, whilst open air composting sites may need to be located in remote areas.

Composting is often applied to:

- Separately collected green waste and co-collected green and food waste where the compost product may be used as soil conditioner or in growing media. Here the temperatures reached would lead to sanitation of the waste to reduce the risk of seeds and pathogens. Such processes may result in the generation of waste reject streams such as when screening produces oversized material of undegraded wood and plastics. This material may then be combusted or landfilled.
- Mixed wastes and where the compost product may also under some circumstances be used in land reclamation.

There are other biological treatment technologies that are not widely applied at an industrial scale in the UK which are not discussed which include vermicomposting, insect farming and enzymatic treatment.

The aerobic biological treatment options of open systems (OAWC) and contained systems (IVC and enclosed composting halls) is described in further detail below.

A3.2.2 Open Air Windrow Composting (OAWC)

This is a simple open-air process undertaken outside on concrete pads and is most typically used to treat source segregated household garden waste, parks waste and farm wastes that do not contain Animal By-Product (ABP) materials. It is also used to biologically treat soils contaminated with organic pollutants such as hydrocarbons, and to stabilise wastewater and sewage sludges and anaerobic digested sludges (although ideally sludges and digestate composting should be carried out in housed composting halls).

Various feedstocks can be considered for composting, although some upfront treatment may be required to ensure that they are in the correct physical form and have sufficient nutrients to support the optimal growth of the .The feedstock ideally should contain structural bulking material to enable pathways for aeration to be formed. This bulking material may be already present in the received waste (such as twigs and branches in green waste) but may have to be provided for very wet or sludge type waste.

The process can be used on a micro (garden and community), medium (on farm composting or small centralised site) and large (industrial centralised site) scale.

A summary of some of the key characteristics of Open Air Windrow Composting is provided in Table A 7.

Table A 7 Summary of Open Air Windrow Composting key characteristics

Aspect	Summary
Type of energy conversion	Waste is partially decomposed in the presence of air to produce water, carbon, minerals, and nutrient-rich stabilized compost in presence of air. CO_2 is main offgas produced, but production of ammonia and other odours is possible.
Typical application	Typical application is treatment of segregated household garden waste, parks waste and farm wastes that do not contain Animal By-Product (ABP) materials. It can also be used to treat soils contaminated with organic pollutants such as hydrocarbons, and to stabilise wastewater and sewage sludges and anaerobic digested sludges

Aspect	Summary
Feedstock characteristics	Feedstocks accepted may be variable, as indicated above. Some preconditioning may however be required to ensure that the material has the correct characteristics for microbe metabolism. This includes[13]: - Feedstock quality (nutrients): The availability of carbon – through an understanding of the volatile solids (VS) content of the stream is important – ideally in range of 55%. The C/N ratio is another consideration, ratios can be between 20 and 45, more typical values of between 25 and 35 are however seen as optimal and ratios above this may then have insufficient N. Additional inputs of other nutrients such as phosphorus and trace elements such as calcium, sulphur etc. may be required. - Moisture content: can vary between 40 – 70 mass percent. - Particle size and structure: Bulk density is typically adjusted to be between 500 – 750 kg/m^3. Screening, shredding and addition of bulking agent may be added to ensure that sufficient air flow can occur. - pH: adjusted to be neutral i.e. to between 6 and 8.5
Scale and capacity	Suited to a wide variety of scales up to 75,000 tonnes per annum[14].
Process outputs	Humic material / compost that can be used in agriculture soil conditioning (i.e. fertiliser), land restoration, capping of historic landfill sites, landscaping, horticulture and as a peat free or peat reduced retail product.
By product recycling	The by products produced are: carbon dioxide, water (which will require treatment prior to discharge) and heat, limited by product recycling occurs.
Emissions	The following emissions need to be considered: - CO_2 - Ammonia - Bioaerosols
Advantages	- Simple, robust, low cost and proven for treating source segregated non ABP commercial and household organic waste. - Typically a low-cost option undertaken with a low level of process control. - Provides an alternative to landfilling of organic waste – which would have resulted in the production of methane (higher Green House Gas contribution) - Obtain a useful organic product that can be used to enhance soil quality
Limitations	The key restrictions are available land area for treatment and the use of the products and any sensitive receptors in the vicinity that may be exposed to emissions from the composting waste such as odours, ammonia and airborne microbial particles. In larger industrial-type schemes there may be a need for leachate capture and recirculation and/or treatment and discharge. However, it demands land for large scale processing, and it can be difficult to manage and control emissions such as odour, meaning that it is best undertaken away from urban areas or sensitive receptors. OAWC also generates significant ammonia emissions which are emitted to the air. Furthermore, adverse weather can hinder processing.

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[13] Environment Agency. (2009). Processes and Plant for Waste Composting and other Aerobic Treatment. R&D Technical Report P1-311/TR

[14] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/296711/LIT_8507_74a529.pdf

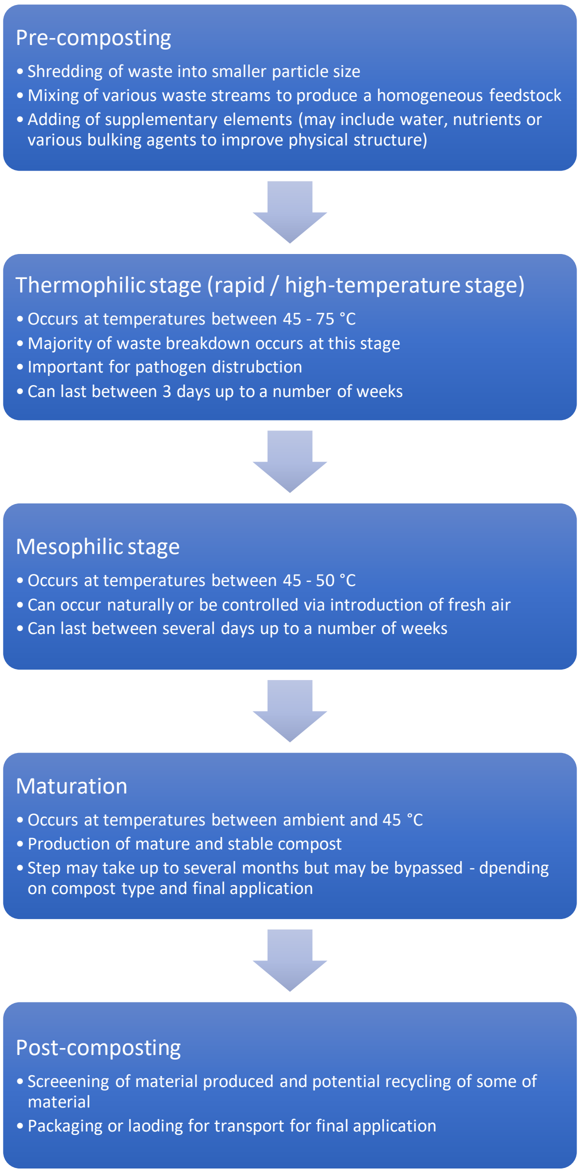
A3.2.2.1 Process Overview

The organic material being sourced for composting must first be treated to ensure that it meets the required feedstock requirements (as per Table A 7) This may include size adjustment (shredding and screening) as well as blending, with various nutrients or supplementary feedstocks. During the composting process the organic matters moves through a number of stages, where various microbes are predominant and active. Various reactions and activities are occurring in these stages, which are most notably indicated through a change in temperature. OAWC is often used as a maturation composting stage to further treat and fully stabilise waste that has already been partially treated in a housed composting hall or IVC. The process typically operates at temperatures between 50 to 70°C to ensure that the resultant compost is free from plant and animal pathogens and any viable weeds. Turning of windrows is typically undertaken to mix the composting waste.

OAWC typically requires specialised machinery including shredders, screens and compost turning equipment to make the process more efficient. Composting time is usually around 8 to 12 weeks during which most of the biodegradable organic matter is decomposed and the remaining material transformed into a “stable” compost, where stability refers to the material having low biodegradability.

On medium and large scale OAWC sites the received organic waste will be inspected for compliance against waste acceptance criteria and then shredded to produce a more consistent material that will break down more readily. The shredded organic waste may then be mixed with bulking agents such as larger woody items removed by screening of previous compost batches. The prepared feedstock will then be placed either into long, narrow windrows or blocks, typically using a loading shovel, telehandler or excavator, for composting. The windrows or blocks will be turned regularly to keep them aerated and ensure all material is exposed to the higher temperatures in the core. Finally, the compost will be screened to produce the required size grade and remove physical contaminants such as stones, plastics and metals. The figure below summarises the various stages of the composting process.

Figure A 14 Overview of Open Air Windrow Composting[15]



Pre-composting

- Shredding of waste into smaller particle size
- Mixing of various waste streams to produce a homogeneous feedstock
- Adding of supplementary elements (may include water, nutrients or various bulking agents to improve physical structure)

Thermophilic stage (rapid / high-temperature stage)

- Occurs at temperatures between 45 - 75 °C
- Majority of waste breakdown occurs at this stage
- Important for pathogen distrubction
- Can last between 3 days up to a number of weeks

Mesophilic stage

- Occurs at temperatures between 45 - 50 °C
- Can occur naturally or be controlled via introduction of fresh air
- Can last between several days up to a number of weeks

Maturation

- Occurs at temperatures between ambient and 45 °C
- Production of mature and stable compost
- Step may take up to several months but may be bypassed - dpending on compost type and final application

Post-composting

- Screeening of material produced and potential recycling of some of material
- Packaging or laoding for transport for final application

A3.2.3 Contained Composting

A3.2.3.1 Enclosed/Housed Composting Halls

Housed composting halls may comprise buildings where composting is undertaken with a greater level of control of the composting process than in OAWC. Composting may still occur in simple windrows set up in the building without additional process control. The main difference then being that emissions from the composting waste can be contained and treated before being emitted from the building.

Enclosed housed composting halls are often associated with MBT processes when MSW is being processed. Composting, depending on the MBT design, may be undertaken of the whole input residual MSW before any mechanical separation of recyclable material or on the organic fraction after removal of recyclable materials. Composting may have the objective to stabilise the waste for landfill by reducing the biodegradability of the waste or to maximise mass loss by evaporation of moisture and/or increase the calorific value of the output. Composting times would be typically about 6 weeks for this objective. The recycling to land of compost generated from residual MSW is possible but requires more regulatory

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[15] Environment Agency. (2009). Processes and Plant for Waste Composting and other Aerobic Treatment. R&D Technical Report P1-311/TR

approvals, as it cannot attain end of waste status. In some examples associated with MBT processes the composting is designed more to dry the waste (bio drying) in a short composting period of circa 2 weeks as a pre-treatment step to generating a dry high calorific fuel for treatment by a thermal process.

Composting may also be associated with MBT systems that have anaerobic digestion as a biological step where the digestate may then be composted to fully stabilise it. Some AD plants that have source segregated organics as a feedstock, may also compost the digestate.

Composting associated with an MBT may also be associated with mechanical processing after the composting process, e.g. to remove stones and grit for potential recycling as aggregate, and with stabilisation of digestate where some of the organic fraction is first subjected to anaerobic digestion.

A summary of some of the key characteristics of enclosed housed composting halls is provided in Table A 8.

Table A 8 Summary of Enclosed housed composting halls key characteristics

Aspect	Summary
Type of energy conversion	As with OAWC, waste is partially decomposed in the presence of air to produce water, carbon dioxide, minerals, and nutrient-rich stabilized compost in presence of air.
Typical application	Feedstocks may include green waste, co-mingled green and food waste, whole MSW and the organic fraction of residual MSW, waste sludges and contaminated soil. Products of IVC treatment may also be considered.
Feedstock characteristics	As with OAWC, some feedstock preconditioning may be required – refer to Table A 1
Scale and capacity	Suited to a wide variety of scales up to ~300,000 tonnes per annum as part of an MBT[16]
Process outputs	As with OAWC – refer to Table A 1, improved control of emissions and leachate can however be achieved.
By product recycling	Volatilised ammonia is recovered by acid scrubbers and can be used as a chemical fertiliser.
Emissions	Production of CO_2 and fugitive emissions from leakages of the facility.
Advantages	Similar to Open Air Windrow Composting, but with the following additional advantages: - The emissions from the composting pile can be collected and treated before discharge to the atmosphere. - Composting times to achieve a stable product are usually less than OAWC as the process is controlled and rates of composting greater. - The processing conditions can be suitably controlled such that the processing can achieve ABPR compliance.
Limitations	The composting hall technology is much more expensive than OAWC, for example there are the building costs and the air used in the process is typically treated to remove odours and ammonia before it is discharged into the atmosphere.

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[16] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/221039/pb13890-treatment-solid-waste.pdf

A3.2.3.2 Process Overview

The process steps followed for Housed composting halls is effectively the same as for OAWC. However, the process may be supplemented with the addition of moisture to control and optimise the moisture content of the composting waste, and with active aeration (either pushing air up through the waste or sucking air down through the waste) to enhance the microbial activity and the rate of composting.

Composting halls may also be used as a second stage composting process for material that has already been treated in an IVC which has been operated as a short sanitation step.

A3.2.3.2.1 In-vessel Composting

In vessel composting (IVC) systems utilise an enclosed container/s (vessel/s) to process organic wastes with monitoring and control of factors (temperature, moisture, aeration) relevant to efficient composting. There are many different vessels and formats used, however they can be broadly categorised into silos, agitated bays, tunnels, rotating drums and enclosed halls.

Most IVC systems have a mechanism to turn the organic material, whether continuously or periodically, and many involve forced aeration and water addition. Temperature measuring instruments, which may be located on air ducts leading out of the vessel, are used to inform whether optimum conditions are being achieved and maintained, and whether the rate of turning, air addition or water addition requires adjustment. In many IVC systems the process can be operated remotely using SCADA control systems.

Compared to open windrow composting, IVC systems have the benefits listed below.

- In the UK, kitchen food waste cannot be composted via open air windrow composting due to animal by-product requirements, but it can be input to IVC.
- Odorous air can be collected and treated prior to release.
- Vermin/pest issues are easier to prevent and control.
- Water loss through evaporation is reduced.
- Process conditions are easier to automate, monitor and control/optimise and that normally results in accelerated composting and decreased area footprint per tonne treated.

However, IVC technology is more complex and typically involves greater CAPEX and OPEX than open windrow composting. If green waste, or other non-putrescible plant-based waste, is to be composted then open windrow composting is often the better choice.

Conversion of organic material to compost can take as little as a week in small rotating drum IVC systems as they generally support a high active microbial biomass. However, compost produced will still need to mature for several weeks after being removed from the IVC.

A summary of some of the key characteristics of In Vessel Composting is provided in Table A 9.

Table A 9 Summary of key characteristics of in-vessel composting

Aspect	Summary
Type of energy conversion	As with OAWC, waste is partially decomposed in the presence of air to produce water, carbon dioxide, minerals, and nutrient-rich stabilized compost in presence of air.
Typical application	Feedstock can consist of source segregated organics, such as food and green waste collected from households and businesses, commercial and farm organic waste containing ABP materials.
Feedstock characteristics	The feedstock must consist of a mixture of different types of soft and hard organic wastes to enable pathways for aeration to be formed. For example, if the organic waste consisted of just soft materials it would not aerate and would turn anaerobic. As a result, food and garden waste is commonly ‘blended’ to provide

Aspect	Summary
	appropriate feedstock. As with OAWC, some feedstock preconditioning may be required.
Scale and capacity	It is typically undertaken at scales of more than 5,000 tpa and can be found at sites treating 250,000 tpa.[17]
Process outputs	As with OAWC – refer to Table A 1, improved control of emissions and leachate can however be achieved.
Emissions	Production of CO_2 and fugitive emissions from leakages of the facility.
By-product recycling	Volatilised ammonia is recovered by acid scrubbers and can be used as a chemical fertiliser. There are only a couple of examples globally of the low-grade heat from composting being captured and reused back on site.
Advantages	The following additional benefits, in addition to those of Enclosed housed composting halls are: ▪ Food waste (ABP) can be co-treated with green waste ▪ Enclosed vessels allow odour control and air treatment (via for example acid scrubbers to remove ammonia and biofilters) and means the process is less influenced by the weather ▪ The process typically requires less land
Limitations	▪ As with enclosed composting halls there is significant additional costs in construction and operation when compared to OAWC

A3.2.3.3 Process Overview

The organic waste is received at site, inspected for compliance against waste acceptance criteria and then shredded to produce a more consistent material that will break down more readily. The shredded organic waste is then be loaded into the vessel either via a mechanised loading system or through using loading shovels or similar equipment.

The vessels are then closed, and the process managed for several days (high temperature ‘sanitisation’ stage) before the material is removed. Typically, the IVC is focused on an initial short composting period of about 2 weeks, to sanitise the waste. The IVC treated waste is not stabilised from such a short treatment time and is usually put into a housed composting hall or OAWC for further composting and maturation.

The readily biodegradable organic material in the waste is rapidly broken down aerobically during this initial short composting period which generates heat that raises the temperature of the waste to kill pathogens leaving a sanitised waste which can then be further composted. IVCs may include forced aeration to increase the rate of degradation and avoid anoxic conditions. The modulation of the aeration rate may be used to remove heat and prevent the composting waste reaching too high a temperature, so it reaches the sanitation temperatures.

A3.3 Anaerobic Biological Treatment

A3.3.1 Introduction

Anaerobic digestion (AD) is a biological process through which organic material is decomposed without the presence of oxygen (and other electron acceptors such as nitrate, nitrite and sulphate) by micro-organisms and within an enclosed system to generate biogas (a mixture of methane and carbon dioxide)

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[17] Defra (2005) Advanced Biological Treatment of MSW

which can then be combusted as a renewable energy source (electricity and heat) or potentially used as a chemical feedstock.

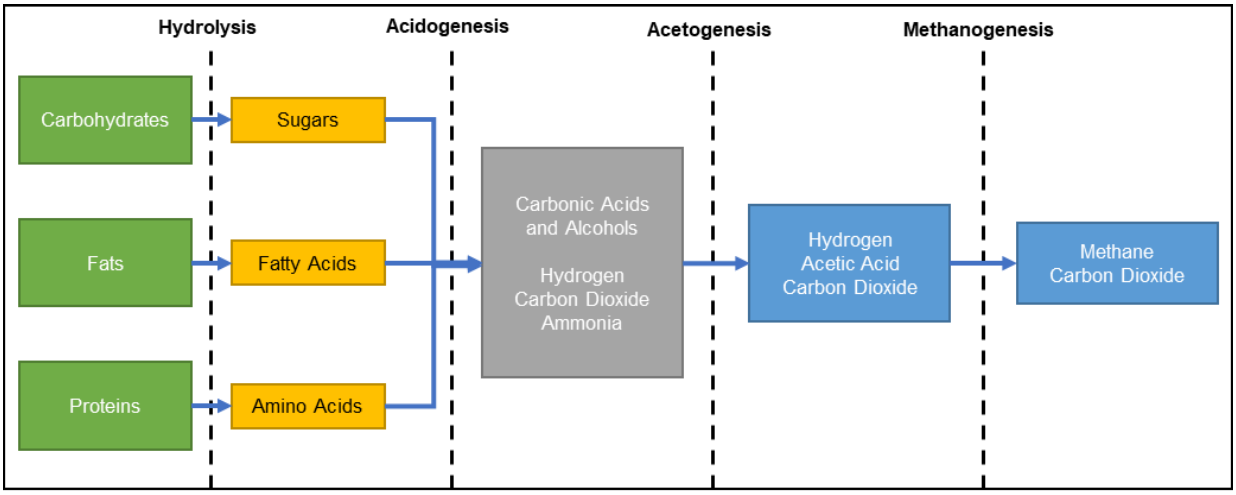
The AD process can be undertaken with the waste either in a solid form with a relatively high dry matter content ‘dry AD’ or as a liquid slurry of relatively low dry matter content ‘wet AD’ condition. Globally, and in the UK, the most common method of undertaking AD is via ‘Wet-AD’, where a low solids slurry substrate (typically 5% to 15% DM) is produced for digestion. Such processes can take place with inputs up to 20% DM, although that requires specific pumps, and is less common than processes with inputs in the 5% to 15% DM range.

Where water is added, the biogas potential of the AD infeed material is diluted, and the overall AD input is increased in volume. In turn, that requires larger tanks and process equipment, increased heat input and more processing and storing of outputs to accommodate the greater inputs and outputs. However, it can bring benefits in terms of ease of transfer and mixing of material, in increased automation and can allow the AD process to be undertaken on a consistent and continuous basis.

There are four key stages in microbial decomposition of organic material to biogas in AD (hydrolysis, acidogenesis, acetogenesis and methanogenesis). These are carried out by the different groups of microorganisms involved in the AD process, working together to carry out the whole transformation of the organic matter to biogas.

- Hydrolysis involves the breakdown of large biopolymers such as starch, cellulose, fats and proteins into small molecules such as sugars, fatty acids and amino acids, by fermenting bacteria.
- Acidogenesis involves the fermentation of the small molecules into smaller acids and alcohols (fermentation products), also by fermenting bacteria.
- Acetogenesis involves the further decomposition of the fermentation products to hydrogen gas, CO_2 and acetate by acetogenic bacteria.
- Methanogenesis is the final stage, involving the conversion of acetate, hydrogen and CO_2 to methane by methanogens.

Figure A 15 Biological and Chemical stages in AD



The degradation product of one group of micro-organisms provides the food for another group in a food chain. Successful AD requires the concerted integration of the microbial groups being balanced and working together as a consortium. AD processes can be sensitive to upsets if one group is out of synchronisation with the other groups. This can occur if there are sudden changes in operating conditions such as temperature or composition of feedstock. Operators of AD plants therefore need to ensure the conditions are suitable for all stages of the digestion process.

The UK has developed it’s biogas sector since the 1989 with the introduction of indirect subsidies for biogas production via the non-fossil fuel obligation. This incentive support was succeeded by different mechanisms (including Renewable Obligation Certificates (ROCs), Feed in Tariffs (FiTs), Renewable

Heat Incentive (RHI) and Renewable Transport Fuel Certificates (RTFCs)). By the end of 2019 the UK had 1,233 biogas plants (including biogas generated from landfill (460), agriculture (418), sewage (194) and biowaste (161). In 2019 the UK produced 20 TWh of biogas from which around 8 TWh of electricity was generated. This includes 99 biomethane plants which produced over 5 TWh of biomethane in 2019.[18]

A3.3.2 Wet Anaerobic Digestion

Wet AD is a common biological treatment for source segregated food waste, food waste management is a global environmental issue, with population growth and increasing urbanisation leading to a third of the food produced for consumption (~1.6 billion tonnes per year) being lost or wasted which accounts for ~8% of global anthropogenic GHG emissions[19]. A significant fraction of food derived waste is considered unavoidable; these include peelings, skins, bones and fats. If this unavoidable food waste can be collected and treated appropriately, it can mitigate the affect it will have on the environment. Food waste is very amenable for AD treatment as it is readily biodegradable and typically gives high yields of biogas.

The separate collection of kitchen food waste allows for a wider range of treatment options, including AD, which recovers 60% more energy than direct combustion[20]. Apart from kitchen food waste, commercial & industrial operations (for example, restaurants and food production) produce food/catering waste streams that can also be treated with AD.

Food waste, as a feedstock for AD, has many different characteristics, for example, as fruit and vegetable, meat and slaughterhouse processing wastes, packed and unpacked, monostreams or mixed materials, wet wastes or dry materials. Generally, these can all be treated via AD provided any packaging is removed and the input material is fed into the digester as an organic soup with minimal plastic contamination. The key is to have the right nutrients present to enable the AD process to be undertaken effectively.

In the UK mixed sources from kitchen food waste will generally produce about 120 m^3 of biogas per tonne of food waste. The average range of food waste types and their approximate potential for biogas production plus the energy that can be recovered via electricity production and the potential GHG reduction depending on its ultimate end use are presented in Table A 10.

Table A 10 Typical Food Waste Biogas Potentials

Food Waste Feedstock Source	Biogas Produced (m^3/wet tonne)	Electricity generated (MWhe /tonne)	GHG emissions reduction if used in transport (kg CO_2e)	GHG emissions reduction if used in electricity (kg CO_2e)	GHG emissions reduction if used in heat (kg CO_2e)
Potatoes (18%-20% total solids (TS))	100-120	0.27	1,946	1,899	1,976
Bread	400-500	1.09	2,506	2,315	2,631
Cheese	> 600	1.45	2,753	2,499	2,920
Vegetables	50-80	0.16	1,872	1,844	1,890

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[18] *EBA 2020 Statistical Report https://www.europeanbiogas.eu/eba-statistical-report-2020/*

[19] *Food wastage footprint & Climate Change (2011) http://www.fao.org/3/a-bb144e.pdf*

[20] *Valorgas (2014) Valorisation of food waste to biogas, Pg. 33 http://www.valorgas.soton.ac.uk/Pub_docs/VALORGAS_241334_Final_Publishable_Summary_140110.pdf*

Food Waste Feedstock Source	Biogas Produced (m^3/wet tonne)	Electricity generated (MWhe /tonne)	GHG emissions reduction if used in transport (kg CO_2e)	GHG emissions reduction if used in electricity (kg CO_2e)	GHG emissions reduction if used in heat (kg CO_2e)
Mixed food waste	75-140	0.26	1,942	1,896	1,972
Brewery Waste (20% TS)	60-100	0.19	1,896	1,862	1,919
Abattoir Waste	120-160	0.34	1,995	1,936	2,034
Assumed the food waste would have gone to an open landfill instead with no landfill gas recovery; when used for transport, diesel vehicles are used as a comparator; when used for electricity, the global electricity mix is used as a comparator; when used for heating, the EU fossil heat average is used as a comparator[21].					

Many other organic wastes such as liquid food wastes, farm crop wastes, paper, and green waste can be processed by AD treatment. The rate and yield of biogas production may vary. There is considerable interest in pre-processing feedstocks to increase their biodegradability e.g., by enzyme treatment and thermal hydrolysis such as autoclaving.

A summary of some of the key characteristics of Wet Anaerobic Digestion is provided in Table A 11.

Table A 11 Summary of wet AD key characteristics

Aspect	Summary
Type of energy conversion	Microbial breakdown of biodegradable material in the absence of oxygen to form carbon dioxide and methane.
Typical application	Suited to source separated waste with low degree of contamination and typically between 5%-15% DS. Pasteurisation required for ABP Category 3 feedstocks.
Feedstock characteristics	Other AD process factors include such as pH, feedstock loading rate, levels of metabolic products, such as ammonia and hydrogen sulphide, and absence of inhibitory compounds that might disrupt the microbial activities.
Scale and capacity	Largest in the UK is 300,000 tpa but the majority of facilities are sub 100,000 tpa.
Process outputs	The various process outputs are: ▪ Digestate which comprises the remaining undegraded material and is a nutrient rich (nitrogen, phosphate and potash) organic material ▪ Biogas (a mixture of methane and carbon dioxide)
By product recycling	The various by-products can be further utilised: ▪ Digestate can be utilised as a fertiliser or soil conditioner when derived from source-separated waste or in land reclamation applications when derived from organics separated from residual waste. ▪ Biogas can be combusted as a renewable energy source (electricity and heat) or potentially used as a chemical feedstock. It can also be further upgraded to produce biomethane which can be used as an alternative to natural gas.

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[21] *Global Food Waste Management: An implementation guide for cities, (2018) World Biogas Association and C40 Cities Food, Water & Waste Programme.*

Aspect	Summary
Emissions	Contributions the biogas industry have to the environment include the reduction of fossil fuel consumption by substitution with biogas, which mitigates global warming, providing a treatment route for waste and the reduction of nutrient losses. A biogas plant that generates energy (for example via CHP) displaces fossil fuel derived electricity and heat after taking into account system efficiency losses. A biogas plant that performs biomethane upgrading displaces the fossil fuel derived uses for heat use and transport networks. However, anaerobic digestion does itself lead to the production of several greenhouse gases, namely carbon dioxide, methane, and nitrous oxide, as well as emissions to air of other pollutants (ammonia, volatiles and combustion emissions if there is a CHP on site). As well as this, there is potential for emissions to water from spills and leachate.
Advantages	▪ Production of biogas that can be used for production of electricity or energy rather than the production of CO_2 ▪ Compared to traditional composting – reduction of odours ▪ Lower masses of digestate compared to residual organic compost
Limitations	Nutrient removal may not be as effective as composting, additional post-treatment may therefore be required.

A3.3.2.1 Process Overview

Preparation of feedstocks for AD may typically involve mechanical processing such as macerating and screening to remove materials such as plastic and grit. The material will then be mixed with water to a concentration of 5% to 15% DS to allow it to be pumped. AD processes are typically operated at a constant temperature and are hence often classified as either mesophilic (operating at temperatures of circa 30 to 40ºC) or thermophilic (operating at temperatures of circa 55 to 70ºC). The anaerobic biodegradation process does not involve oxygen and therefore is not a form of combustion and does not generate much heat. Therefore external heating is often required to maintain the operating temperatures, especially of thermophilic processes.

The wet AD process takes place in a controlled manner using a series of sealed tanks to break down the organic material and produce biogas. An AD facility will commonly involve tanks for a range of other purposes, including storage and preparation of feedstock and digestate, but the term anaerobic digester specifically refers to the tank or vessel in which the biological process takes place. Design and layout varies depending on the quantity of material and its composition, but will generally follow the same principles. The gas will be captured in the headspace of the tank or a separate gas holder, prior to burning or further processing. In some designs the material will then be pumped to a secondary digester for the second stage of decomposition, in others it will all take place in a single tank.

Additionally for ABPR compliance a pasteurisation step where heating to about 70ºC for at least an hour is required for mesophilic AD systems. Thermophilic AD systems can comply with ABPR requirements due to the extended exposure to higher temperatures during the actual processing. Thermophilic AD is often considered as having higher rates of biogas production than mesophilic, although this does depend on other factors such as the characteristics of the feedstocks.

Processing time varies depending on the biodegradability of the feedstocks and the overall design concept. Typically, an AD will operate with a residence time of ~30 days (~20 days minimum) during which the majority of the biogas producing potential of most feedstocks would be realised. Some feedstocks however may produce biogas more slowly and some AD plants may have residence times of as long as 60 to 70 days.

The digestate may be further processed by mechanical dewatering using centrifuges and/or filter presses to give a digestate cake. The removed water may be recycled in the process or require treatment prior to disposal. Digestate cake may be further dried and even compressed into briquettes for use as a solid fuel.

The biogas produced typically requires further processing to dry and clean up the biogas. It may then be used in combined heat and power engines to produce renewable heat and electricity, some of which may be used to run the plant and the excess exported. Alternatively, the biogas may be upgraded into biomethane which can be compressed as a fuel or injected into the national gas grid. Carbon dioxide produced from biogas upgrading to biomethane can also be marketed as a product output.

Hence as discussed AD is not a standalone process but forms part of an integrated scheme.

A3.3.2.2 Thermophilic and Mesophilic digestion

Thermophilic and mesophilic digestion also use microorganisms to digest organic material. Mesophilic digestion occurs at temperatures between 30 to 38 °C, where mesophiles are the primary microorganisms present. Thermophilic digestion occurs at temperatures between 49 – 60 °C, where thermophiles are the primary microorganisms present.

The advantages and disadvantages of thermophilic AD compared to mesophilic AD are summarised in Table A 12 below.

Table A 12 Advantages and disadvantages of thermophilic against mesophilic AD

Advantages	Disadvantages
Reduced hydraulic retention time, meaning a smaller anaerobic digester can be used (or more feedstock can be processed in the same size anaerobic digester)	The biological process can be less stable (for example, more sensitive to a change in feedstock type, quality or rate of input) with increased risk of issues that can suppress biogas yield or stop the biological process
Typically, higher biogas yields with increased rate of biogas production.	Increased energy use to heat the anaerobic digester

A3.3.3 Dry Anaerobic Digestion

Dry AD processes can be employed to treat a variety of feedstocks, but generally involves high dry matter feedstocks or a mixture of food waste with higher dry matter feedstocks such as green/garden waste (typically in excess of 20% up to 40% on a mass basis).

Feedstocks such as woody green waste provide structure, aiding percolate distribution and biogas escape, but do not fully degrade within a short-timescale dry-AD process and so post digestion aerobic composting processes are normally employed. This provides the advantage of being able to recover energy from feedstocks that may be less suitable for, or more problematic in, wet AD processes that would otherwise be composted without the benefit of energy generation.

Dry AD processes are normally simpler operations than wet AD processes and have the benefit of requiring very little water addition.

Dry AD is well suited to high DM feedstocks and can be undertaken without any significant pre-treatment contaminant removal or size reduction of particles to very low level, as often takes place in wet AD processes. The absence of large quantities of liquid digestate reduces the potential for environmental impact from digestate escape.

A summary of some of the key characteristics of Dry Anaerobic Digestion is provided in Table A 13.

Table A 13 Summary of Dry Anaerobic Digestion key characteristics

Aspect	Summary
Type of energy conversion	Microbial breakdown of biodegradable material in the absence of oxygen to form carbon dioxide and methane.

Aspect	Summary
Typical application	Suited to source separated waste but have higher tolerance of the presence of non-biodegradable contaminants such as plastics, grit and stones. Dry anaerobic digestion systems also allow the use of substrates with a high dry matter content.
Feedstock characteristics	Overall feedstock blend is typically in excess of 20% up to 40% on a mass basis.
Scale and capacity	Limited number of facilities in the UK, typically in combination with MBT or IVC.
Process outputs	The various process outputs are: ▪ Digestate which comprises the remaining undegraded material and is a nutrient rich (nitrogen, phosphate and potash) organic material ▪ Biogas (a mixture of methane and carbon dioxide)
By product recycling	The various by-products can be further utilised: ▪ Digestate can be utilised as a fertiliser or soil conditioner when derived from source-separated waste or in land reclamation applications when derived from organics separated from residual waste. ▪ Biogas can be combusted as a renewable energy source (electricity and heat) or potentially used as a chemical feedstock. It can also be further upgraded to produce biomethane which can be used as an alternative to natural gas.
Emissions	Similar to Wet AD
Advantages	Dry AD has both advantages and disadvantages in comparison to wet AD covered by **Error! Reference source not found.**
Limitations	Sourcing of sufficient substrate Sufficient space for plant construction Specific considerations (mechanical loading systems) for loading and unloading of digesters

A3.3.3.1 Process Overview

A3.3.3.1.1 Batch process

Dry AD, in its simplest form, involves placing waste within a sealed digester, digesting it, emptying it and inputting a new batch of feedstock. The process, therefore, takes place in batches rather than continuous or semi-continuous operation.

The digester is not normally mixed, and therefore it can be cuboidal, or other shape, rather than the typical cylindrical digester employed in wet AD processes. Tunnel designs with gas-tight front door access are common designs and can be constructed from steel or concrete. The walls and floors are often heated to ensure optimum conditions.

In such a system, the solid feedstocks can be loaded by mobile plant buckets (front end loader), overhead grabs suspended from travelling crane rails, or by belt or chain conveyor. Emptying the digester can involve opening the vessel to manually remove digested materials, although some material is left in place as microbiological seed material for the next batch of feedstock to be input.

Care needs to be taken when ramping-up the digester and emptying it to avoid explosive or asphyxiating environments. Purging with inert gas after filling and flushing air through prior to opening are methods commonly employed in that regard. Odour control biofilters are required to process expelled gases to prevent odour issues. However, that is commonly the case where food wastes are handled, stored and processed.

Significant amounts of water are not added to the process, as is common in wet AD processes. In some instances, leachate/percolate is collected from the base and recirculated to the top of the digester to aid in distributing moisture and microbiota throughout the digester.

Gas storage is normally remote from the digester, whereas in semi-continuous wet AD processes the gas storage can be either remote or integral to the digester. Gas clean-up, treatment and utilisation is no different between dry AD and wet AD processes.

The batch dry AD arrangements described above have both advantages and disadvantages when compared to wet AD processes (see Table A 14 below).

Table A 14 Comparison of Batch Dry AD vs Wet AD

Advantages of batch dry AD compared to wet AD	Disadvantages of batch dry AD compared to wet AD
No need for pre-treatment equipment to remove contaminants, size reduce to a high extent, add water (subject to DM content of feedstocks, wet AD may not need water addition) nor intensive mixing to form homogenous slurry.	Being a batch process, gas yield will fluctuate considerably. If that is an issue (for a large-scale operation it is likely to be), it can be partly overcome by having multiple digesters with time offset operation. However, that diminishes some of the benefits of dry AD, e.g. reduction in footprint area resulting from absence of water addition.
Low maintenance and low energy demand	
No need for mixed buffer tank to ensure prepared wet AD substrate is maintained mixed and available for regular controlled feed forward to digesters.	Being a batch process, if there was only one digester, there will be a period of weeks (typically 6 to 8 weeks) between feed input. As above, that can be at least partly overcome by use of multiple digesters with time offset feeding. However, when dealing with food wastes, they are generally fed to a wet AD digester, or feedstock buffer tank, on the same day that they are delivered to the facility. Prompt feeding to a digester is important as food waste is putrescent, and its decomposition will cause odour and fly infestation issues as well as lower the potential of the feedstock to generate biogas.
No need for pumps and pipework to feed the digesters with substrate, bringing reduced potential for blockage and potentially reduced maintenance requirements.	Filling and emptying of a dry AD digester is labour intensive, compared to a wet AD digester, as is digestate management.

Advantages of batch dry AD compared to wet AD	Disadvantages of batch dry AD compared to wet AD
No need to mix digesters to prevent stratification within the digesters, nor for measures to prevent or remove settled deposits or floating layer material.	From a biological process perspective, dry AD does not allow the same degree of process control as can be achieved by wet AD. The AD process prefers broadly consistent feedstock composition, a high surface area of organic material, i.e. small particle size readily accessed by the microbiota, consistent and controlled temperature, consistent moisture/DM content and regular fresh organic matter to ensure a healthy microbiota. All these aspects are more readily controlled in wet AD processes. In dry AD, the biological process must ramp-up after the batch feed input, helped by ensuring a proportion of the previous batch remains in the digester to act as biological seed material. However, as digestion of the batch progresses and organic matter is consumed, a point will be reached where the microbiota begins to starve and the population reduces. In wet AD, small and regular feedstock input throughout the day prevents the inevitable ramp-up and decline in biological activity inherent in batch dry AD processes.
Potentially smaller footprint area required for the facility as the absence of water addition requires smaller digester/s.	

A3.3.3.1.2 Plug flow process

Not all dry AD processes are batch processes, some are plug flow. In plug flow dry AD systems, the feedstock is input at one end and then moves through the digester, in an unmixed manner, in a ‘plug flow’ as new feedstock is input. The feedstock is often shred to around 40mm to 60mm prior to entering the digester/s, whereas in wet AD <12mm or pulped substrate is common. When in a vertical digester configuration, high head, large capacity, pumps, e.g. piston pumps akin to those used to pump wet concrete up buildings, are used to input feedstock at the top of the digester, and the digester empties at its base under gravity. When in a horizontal configuration, shaft mounted paddles are often employed to progress the material through the digester, giving rise to localised churning/mixing of feedstock, albeit the material still transits in a plug flow manner. Recirculation of liquid within the digester, via percolation, aids the distribution of microbiota throughout the digester and a proportion of the output is reintroduced alongside fresh input feedstock to aid the biological process. Such a design allows larger digesters to be used, with less space required, allows less operator input and provides more consistent gas production but involves more energy to convey feedstock.

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