SUPPLEMENTARY MATERIAL

A tool supporting the selection of food waste management approaches for the hospitality and food service sector in the UK

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A: SYSTEMATIC LITERATURE REVIEW/EVIDENCE MAPPING

Table A-1 shows the key terms selected to address the research question of this rapid evidence mapping grouped following the PICO statement. In total, 41 search terms were selected and grouped into three lists. The key terms within the lists were combined using the OR Boolean operator creating one search string for each list. In contrast, the search strings of the lists were combined with AND Boolean operator, providing the total number of hits that were screened following the eligibility criteria.

Table S1. Key search terms selected according to the PICO statement of this systematic evidence map, including the number of hits identified during the searching stage at Scopus database.

No. search term	Population: Food Waste	Total hits	No. search term	Intervention and Control: FWM technologies	Total hits	No. search term	Outcome: Sustainability assessment	Total hits
#1	"food waste"	12,396	*#22*	"anaerobic digestion"	33,254	*#37*	sustainab* W/5 assessment	13,637
#2	"organic waste"	13,652	*#23*	composting¹	24,840	*#38*	environment* W/5 assessment	100,221
#3	"catering waste"	45	*#24*	"organic recycling"	196	*#39*	environment* W/5 impact	305,126
#4	"food scrap"	264	*#25*	food W/3 ("valorisation" OR "valorization")	562	*#40*	techn* W/5 assessment	94,344
#5	"food residue"	862	*#26*	food W/3 process*	83,764	*#41*	economic* W/5 assessment	22,827
#6	"plate waste"	400	*#27*	"food waste" W/3 management	579	*#42*	financ* W/5 assessment	4,249
#7	"household waste"	2,881	*#28*	aerobic W/3 process*	5,339	*#43*	social* W/5 assessment	18,041
#8	food W/3 waste*	16,635	*#29*	"food waste" W/3 prevention	208			
#9	"food waste" W/3 hospital	25	*#30*	aerobic W/5 food	378			
#10	organic W/3 waste	20,068	*#31*	macerator*	82			
#11	household W/3 waste	5,207	*#32*	"food waste disposal unit"	7			
#12	catering W/3 "food waste"	39	*#33*	co-digestion	3,778			
#13	hospitality W/3 food waste*	38	*#34*	"food waste" W/3 pre-treatment	34			

#14	"food waste" W/3 healthcare	4	*#35*	"food waste" W/5 on-site	26			
#15	Food W/3 spoilage	4,938						
#16	spoiled W/3 food	263						
#17	"surplus food"	289						
#18	"food surplus"	246						
#19	"organic fraction" W/3 "municipal solid waste"	1,395						
#20	"food loss"	1,229						
#21	**#1 OR #2 OR … #20**	**46,675**	***#36***	**#22 OR #22 OR … #35**	**145,732**	***#44***	**#37 OR #38 OR … #43**	**476,919**
Total number of hits			**#21 AND #36 AND #44**			**1,284**		

***:** Replace multiple characters anywhere in a word; W/n: proximity operator means *within n words*; [1]more generic terms than IVC to capture studies that compare different FWM options; ": only those documents containing the related keyword

Regarding the first eligibility criterion (i.e., include only recent studies published since 2011), it is interesting to mention that the majority of peer-reviewed literature (ca. 60%) has been published in the last five years, indicating the increasing research interest in assessing the performance of FWM options moving toward a more circular economy model. Figure A-1 illustrates the research attention to the evaluation of FWM systems up until January 2022.

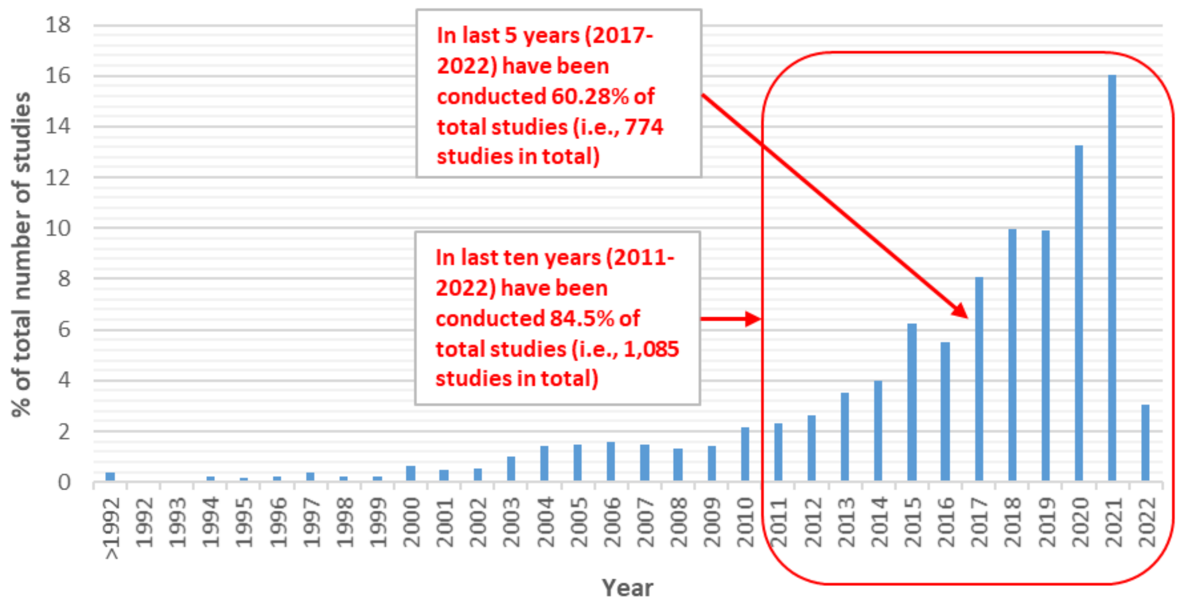


Figure S1. Research attention to the sustainability assessment of FWM system according to Scopus database following a systematic literature searching strategy.

B: PROCESS DESCRIPTION AND QUALITY MANAGEMENT OF FW BIOLOGICAL TREATMENT METHODS

Table S2. Operational factors of commercially available on-site FW processing techniques. Adapted by [1].

	Grinders	**Biodigesters**	**Pulpers**	**Dehydrators**	**IVC**	**AD**
Input	Soft FW[a]	Soft FW; FOG[b] free	FW	Soft FW; FOG free	FW; FOG free	Soft FW
Compostable service-ware	No	No	Yes	No	No	Yes
Output	Slurry of ground-up FW	Liquefied FW – partially treated	1. FW pulp 2. Liquid effluent	1. Semi-dry residue 2. Liquid effluent	Compost	1. Digestate 2. Biogas
Disposal means	1. Sewer* 2. Off-site treatment	Sewer*	1. Off-site treatment 2. Sewer*	1. Off-site treatment 2. Sewer*	1. Off-site treatment 2. Local use	Off-site treatment On-site treatment (CHP engine)
Storage needs	1. No 2. Tank	No	Yes	Yes	Yes	Yes
Could be combined with:	Pulpers	Grinder	Grinders Dehydrators	Grinders IVC	Grinders Dehydrators	Grinders

[a] *Soft FW: excludes bones, shells and pits;* [b] *Fat, oil and grease*
**disposal to sewer denotes treatment of FW slurry or liquid effluent at WWTP, where sewage sludge may or may not be recycled and land applied as a soil amendment – or they may be landfilled [1]*

C: TRADE EFFLUENT CONSENT

The trade effluent discharge is set upon the trade effluent consent; a legal document that allows undertakers to set the conditions and limits of FW slurry disposal making sure these are within the regulatory framework outlined in The Water Industry Act 1991 (England and Wales). It can be calculated using the Morgan Formula [2,3], a mathematical formula that incorporates several variables with key physical and chemical characteristics of the effluent including the volume, chemical oxygen demand (COD) and suspended solids. The formula is as follows [2,3]:

$$\textbf{Trade Effluent Charge} = R + [(V + B_v) \text{ or } M] + B(O_t/O_s) + S(S_t/S_s)^{7} \quad \textbf{Equation 1}$$

Where,

R is the charge for reception and conveyance, given per m^3;

V is the charge for primary treatment, given per m^3;

Bv is the additional volume charge if there is a a biological treatment, given per m^3;

M is the treatment and disposal charge where effluent goes out to sea outfall, given per m^3;

B is the charge for biological oxidation of settled sewage charge, given per kg;

Ot is the chemical oxygen demand (COD) of effluent after one hour quiescent settlement at pH 7;

Os is the COD of crude sewage after one-hour quiescent settlement;

S is the charge for treatment and disposal of primary sewage sludge, given per kg;

St is the total suspended solids of effluent at pH 7 [mg/litre]; and

SS is the total suspended solids of crude sewage [mg/litre].

The undertakers are responsible to obtain effluent samples from the agreed discharge point for monitoring compliance with the conditions in the consent and charging for the subsequent carriage and treatment of the effluent. In case of compliance failure, enforcement action is taken that in severe cases may lead to prosecution in the Criminal Court.

Sewage Undertakers usually discourage the use of macerators despite the claim of their manufacturers that the effluent is safe to be discharged due to the high risk of blockages caused by FOG and other organic substances. FOG can result in fouling and production of toxic and corrosive gases, such as hydrogen sulphide that may create a hazardous environment for sewer workers, and result in infrastructure damages. Therefore, when permission is granted for effluent discharge, HaFS businesses have the responsibility to follow the best practices in disposing of FW and provide training to the catering staff to prevent FOG from being disposed into the sewer.

D: PROCESS DESCRIPTION AND QUALITY MANAGEMENT OF FW BIOLOGICAL TREATMENT METHODS

I. IVC

Composting and AD are biological processes that are carried out by the activity of microorganisms with the presence of oxygen (aerobic), or not (anaerobic). Composting is an aerobic process, where aerobic microorganisms (bacteria) break down and digest the organic matter under optimal conditions to produce CO2, NH3 or other nitrates, sulphates, water, heat and an organic end-product, called compost (European Commission 2017). Compost is a relatively stable product, free of pathogens that is suitable for application to land as a soil amendment or as an organic fertilizer (Fischer and Glaser 2012). The heat generated during the composting process accelerates the breakdown of proteins, fats and complex carbohydrates (e.g. cellulose and hemicellulose), and helps to sanitise the compost by destroying human or plant pathogens, weed seeds and spores (Misra, Roy et al. 2003, European Commission 2017).

During IVC, the most important operational factors that affect the quality of end-products are [4]:

- temperature (60-70^{o}C [5])
- moisture (≥ 65% [6]);
- oxygen

In most IVC systems, operational parameters can be automatically regulated with the use of sensors as well as with intermittent rotation to maximize microbe activity [4]. The quality of the compost needs to be assessed by analytical methods, and via the monitoring of enzymatic activities and phytotoxicity tests [7]. The compost quality can be determined by analysing a wide variety of properties that can be grouped into [8]:

- agronomic value properties, the determination of which should be mandatory including nutrient content (NPK) (N: ≥ 1.5%[9]), electric conductivity, germination index (GI), pH (6.7-9 [6]), particle size, and impurities;

- end compost properties, of which at least one should be determined including C/N (25-30 [6]), cation exchange capacity (CEC) and organic matter (≥ 50% [9]);
- type of input feedstock properties, the determination of which should be mandatory including pathogen (E. coli < 10 cfu/g; Pseudomonas aeruginosa < 10 cfu/g;
- Salmonella: Absent; Staphylococcus aureus < 10 cfu/g [9]) and heavy metal content (Cr ≤ 200 mg/kg; Pb ≤ 300 mg/kg; Ni ≤ 150 mg/kg; Cd ≤ 5 mg/kg; Hg ≤ 2 mg/kg; As ≤ 50 mg/kg [9]);
- composting conditions properties, of which at least one should be determined including stability test, self-heating test, CO_2 evolution and O_2 uptake rate; and
- additional properties such as colour, odour and moisture content (≤% 30% [9]), the determination of which is not mandatory.

II. AD

Anaerobic digestion is the biological conversion of organic matter into biogas, comprising mainly CH4 and CO2 as well as trace amounts of other gases (e.g. nitrogen, oxygen, and hydrogen sulphide), and digested under the absence of oxygen [10,11]. The main steps involved in AD are: 1) hydrolysis, 2) acidogenesis, 3) acetogenesis and 4) methanogenesis each describing different stages of biodegradation from complex carbohydrates to lipids, acids and alcohols [12]. The methanogenesis is the final stage of AD, where the end-products are produced. These are the biogas, which typically contains 65% CH4, 25% CO2, 5% other gases, and the digestate. The generated biogas is commonly used for the generation of heat and electricity in CHP plants, while digestate is used as a soil conditioner or fertilizer. Typically, via AD 40% w/w of FW is recovered as biogas, while the remaining is converted into digestate [10].

The main operational factors that affect the efficiency of the AD process are the reactor type, loading rate, hydraulic retention time, pH, and temperature [10,12]. FW heterogeneous composition is a limiting factor since the quality of the final digestate becomes highly variable creating issues to its applicability as fertilizer, while a high presence of nitrogen-rich protein components can lead to the formation of free NH3 and salts, which, in turn, can have adversely affect the microbial activity in the reactor and bring the digestion process to a halt [10]. This problem is usually addressed via the co-digestion of FW with a low nitrogen and lipid content waste, such as sewage sludge and manure leading to higher CH_4 yields [11,13].

Pre-treatment processes are usually employed to enhance biogas production and accelerate the process, and can be grouped into [14,15]:

- Mechanical (e.g. compactors/ pulpers/ de-waterers, screw press, disc screen and shredder [16]) - increases the surface area available to microbes leading to better contact between the substrate and bacteria and thus promoting better digestion [4,15,17]
- Chemical (e.g., dilute-acid, oxidative and alkaline pre-treatment) - hydrolyses the cellulosic content of FW enhancing the surface area for further enzymatic attack [17]
- Thermal (e.g., steam explosion, microwave heating, hydrothermal treatment) - promotes degradability and reduces the processing time [14], while it pasteurises FW and reduces the viscosity of the digestate [17].
- Biological (enzymatic hydrolysis, use of fungal species, and drying) - increases the production of hydrolytic enzymes and improves the hydrolysis efficiency of complex substrates preventing the inhibition of the AD process arising from VFA accumulation [17].

The most important operational factors that are monitored and closely controlled to ensure good quality of end-products (biogas and digestate) are:

- Temperature - should be kept in a range of 25-40 ^{o}C;
- pH - optimal range between 5-6 or 6.5-8 depending on the alkalinity of the system, VFA and content of bicarbonate;
- Retention time - typically 10-40 days depending on the organic loading rate (OLR), substrate configuration and operating temperature;
- C/N ratio - must be kept at 20:1- 30:1 to ensure microbial activity [16], otherwise, it may lead to CO_2 accumulation in biogas [4]
- VFA accumulation – must be monitored as it can lower the pH which in turn may inhibit the activity of acid-sensitive enzymes; and

- OLR – around 4.4-22 g_{VS}/L/day to ensure stability and economic performance and energy recovery efficiency of the process [15].

Additional input requirements to the wet mesophilic AD process is water to create a slurry with total solids not exceeding 10-15%, orthophosphates for proper microbial activity, and chemical to achieve a neutral pH in the digester since most of the methanogens grow at a pH range of 6.7-7.5 [4,16].

E: FLOWCHARTS OF THE TWO-TIER DECISION-MAKING FRAMEWORK FOR DIFFERENT FW PROCESSING CAPACITIES

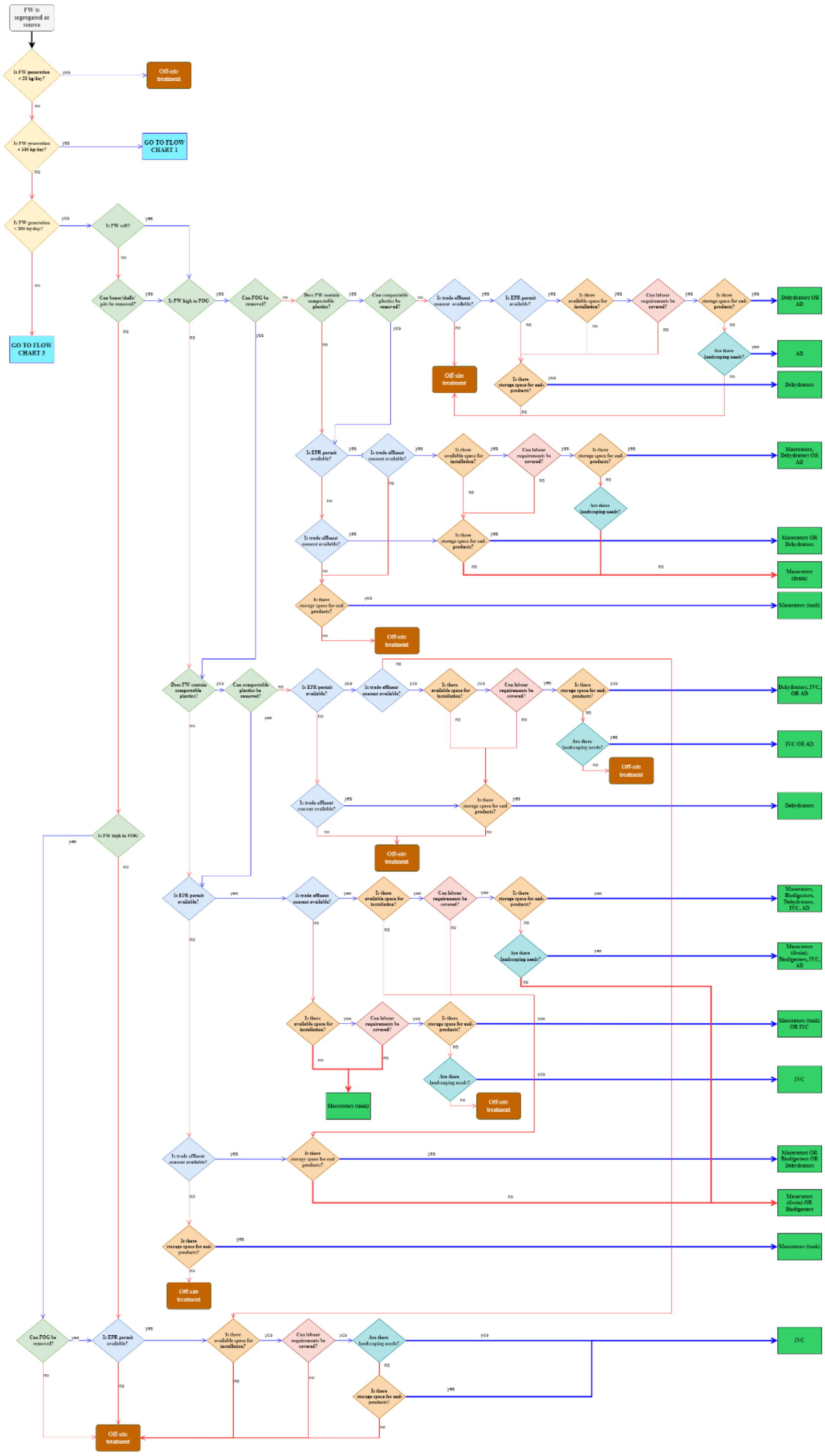


Figure S2. Binary conditional flow chart as a guiding tool for the decision-making of HaFS sector for on-site FWM systems with an FW processing capacity ≥ 100 AND < 200 kg /day, according to seven criteria. For better resolution and editing go to https://app.diagrams.net/.

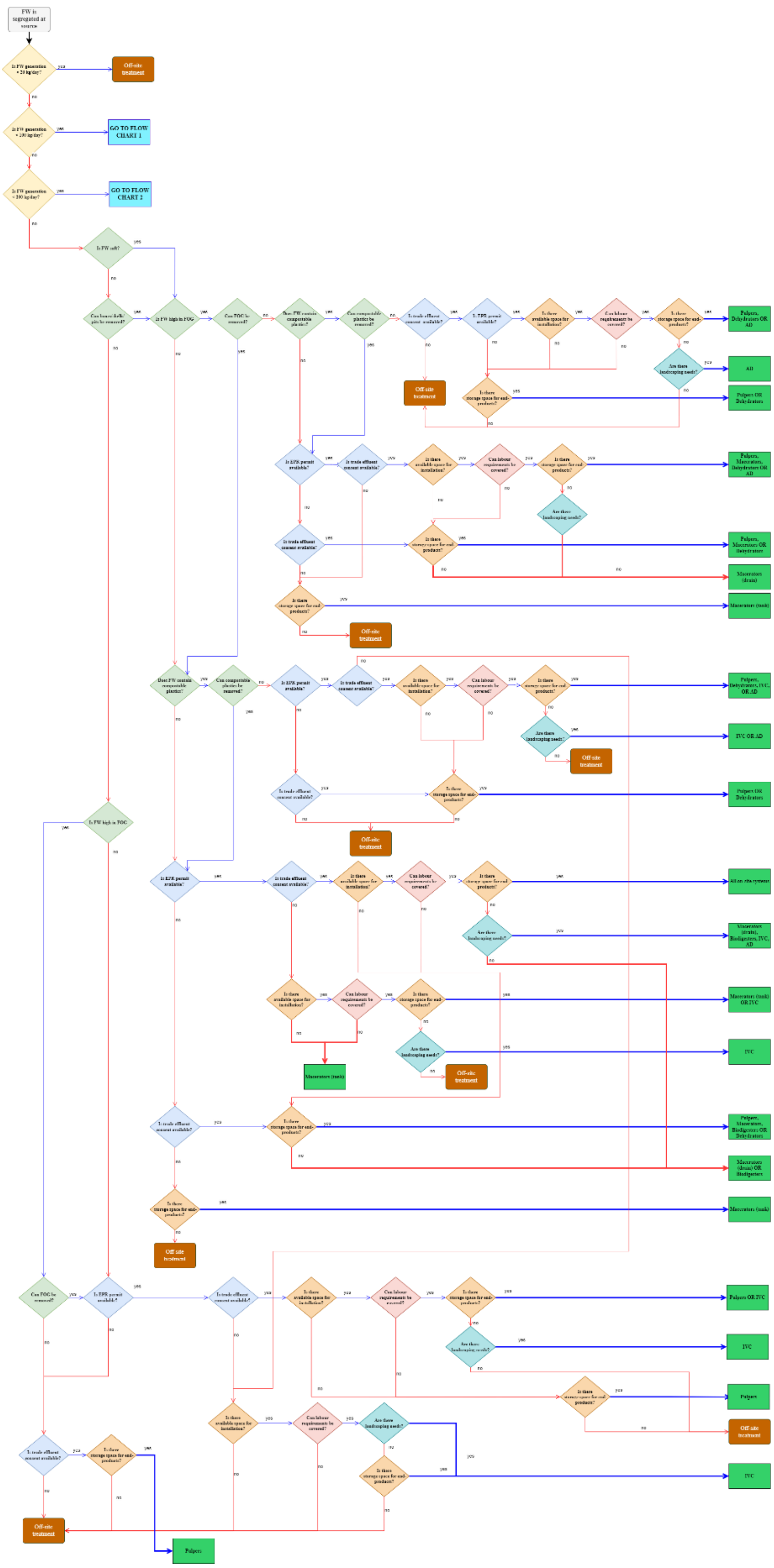
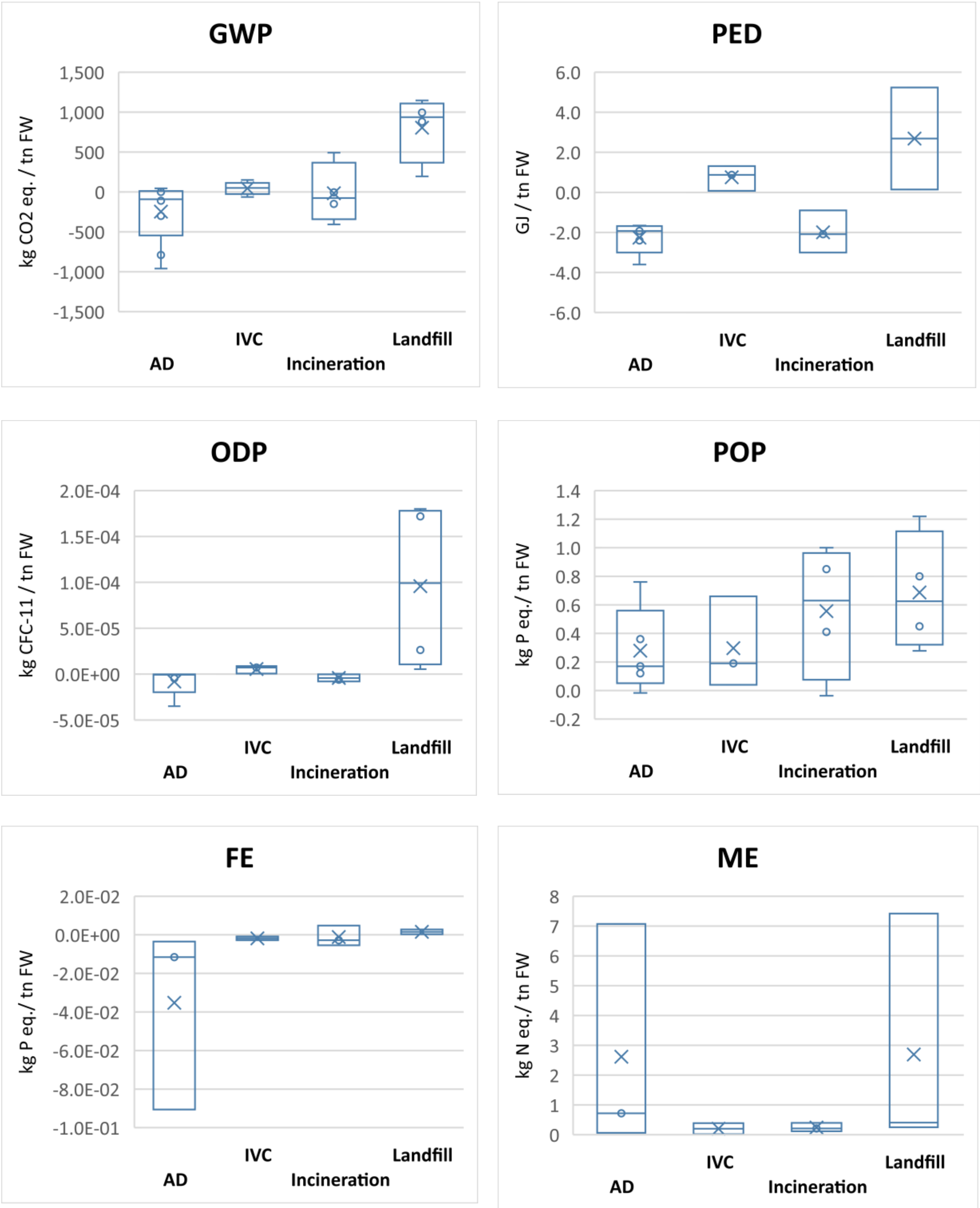


Figure S3. Binary conditional flow chart as a guiding tool for the decision-making of the HaFS sector for on-site FWM systems with an FW processing capacity ≥ 200 kg /day, according to seven criteria. For better resolution and editing go to https://app.diagrams.net/.

F: ADDITIONAL INFORMATION ON SUSTAINABILITY PERFORMANCE OF OFF-SITE FWM METHODS

I. QUANTITATIVE ENVIRONMENTAL IMPACT OF OFF-SITE FWM METHODS

For specific LCA impact categories, we found sufficient quantitative data enabling us to provide variability plots that visualise the range of FWM options' contribution to environmental impacts. **Figure F-1** shows that AD and incineration may provide savings in GWP, PED and AP depending on the efficiency of technology and end-products applications due to avoided impacts as well as AD may provide savings in ODP and FE. In case of AD, the results of this report are in agreement with a recent review study that reviewed existing LCAs of FW processing through AD indicating that GWP was ranged between -860 to 290 kg CO2 eq. per ton of FW treated in AD depending on operational parameters (e.g., biogas and energy yields, fugitive emissions during AD, energy conversion efficiency and end-products application), while methodological options (e.g., LCA method and boundary conditions) were also reported as influential factors [18]. A relatively old study reviewed 82 LCA studies to compare the environmental performance of several management methods of organic waste including FW and green waste indicating that AD (-250 kg CO2 eq. / tn) and composting (-70 kg CO2 eq. / tn) performed better in terms of GWP compared to incineration (20 kg CO2 eq. / tn) and landfill (160 kg CO2 eq. / tn) [19]. These values fall within the boxplots of **Figure F-1**. It must be noted that **Figure F-1** does not include quantitative values from studies that assumed biogas was upgraded into bio-methane, since this scenario does not represent the current situation of energy recovery from AD in the UK.


GWP
kg CO2 eq. / tn FW
1,500
1,000
500
0
-500
-1,000
-1,500
AD
IVC
Incineration
Landfill
PED
GJ / tn FW
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
AD
IVC
Incineration
Landfill
ODP
kg CFC-11 / tn FW
2.0E-04
1.5E-04
1.0E-04
5.0E-05
0.0E+00
-5.0E-05
AD
IVC
Incineration
Landfill
POP
kg P eq./ tn FW
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
AD
IVC
Incineration
Landfill
FE
kg P eq./ tn FW
2.0E-02
0.0E+00
-2.0E-02
-4.0E-02
-6.0E-02
-8.0E-02
-1.0E-01
AD
IVC
Incineration
Landfill
ME
kg N eq./ tn FW
8
7
6
5
4
3
2
1
0
AD
IVC
Incineration
Landfill

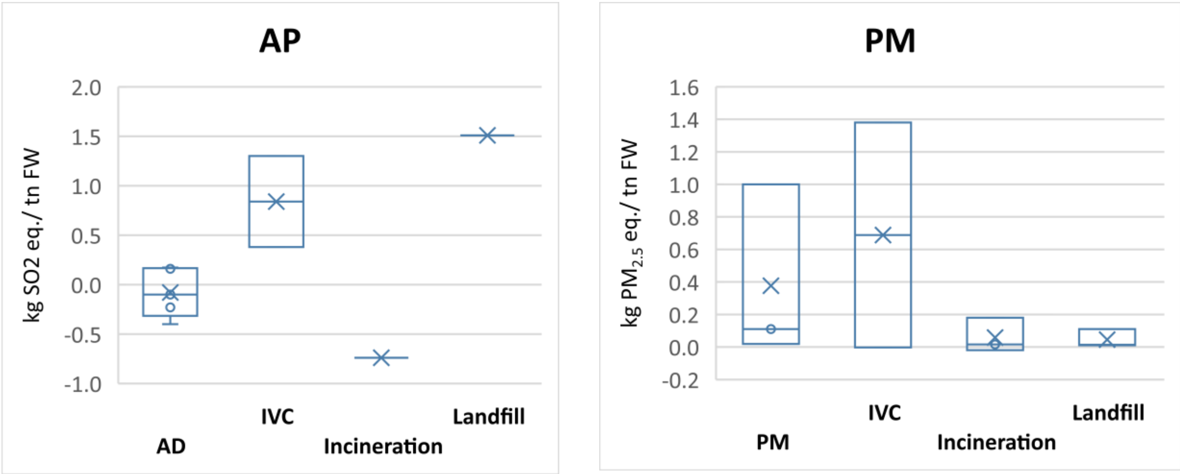


Figure S4 Variability boxplots of the contribution of FWM options to several LCA impact categories according to the systematic evidence map that collected quantitative data only from UK and European studies. (GWP: Global warming potential; PED: Primary energy demand; ODP: Ozone depletion potential; POP: Photochemical oxidation; FE: Freshwater eutrophication; ME: Marine eutrophication; AP: Acidification potential; PM: Particulate matter)

II. APPLICATION OF END-PRODUCTS FOR NUTRIENT RECOVERY

Presently, there is limited LCA studies that assess the carbon storage potential in soils from compost or digestate utilisation and compensation for the production of synthetic fertiliser, with benefits arising from their application receiving less attention [20,21]. The actual market value of compost and digestate as organic fertilisers is low due to the variability of return on investment from their application, whilst their strongest effects are usually long-term making farmers reluctant to buy and use them [22]. Therefore, compost and digestate are used more often as soil improvers due to their high organic carbon content rather than as fertilisers [22].

III. SUSTAINABILITY PERFORMANCE OF DIFFERENT TYPES OF IVC REACTORS

Table F-1 presents the performance of the main types of IVC reactors according to several sustainability impact categories through a ranking system assessment. However, it should be noted that this ranking is conditional while system sustainability cannot be accurately assessed without considering the exact technical specifications of the system [23].

Table S3 Ranking of different types of IVC (large scale) according to several sustainability impact categories (value 1 indicates the best and value 3 indicates the worst in terms of the respective impact category). Green: Best option; Red: Worst option; Amber: intermediate option. Adapted by [23].

Sustainability impact categories		Horizontal	Vertical	Rotating
Environmental	Air emissions	2	1	1
	Leachates	3	2	1
	Energy needs	2	1	1
Economic	Investment cost	1	2	3
	Operating cost	1	2	3
	Maintenance cost	1	2	2
	Land requirement	3	1	2
Social	Odour impact	2	1	1
	Noise impact	3	1	2
	Visual impact	1	3	2
	Social acceptance	1	2	2
Technical	Treatment efficiency	2	3	1
	Ease of implementation	1	2	2
	Flexibility	2	3	1
	Health & safety risks	1	2	2
Best	**Second best** **Worst**			

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