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A Tool for the Selection of Food Waste Management Approaches for the Hospitality and Food Service Sector in the UK

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Abstract: The UK government has been calling for action in tackling food waste (FW) generation, to which the Hospitality and Food Services (HaFS) sector contributes substantially. Decision-making tools that inform the selection of appropriate FW management (FWM) processes in the HaFS sector are lacking. This study fills this gap by offering a conceptual decision-making tool that supports selecting appropriate and commercially available FW processing techniques for the HaFS sector. The study initially conducted an exploratory analysis of on-site and off-site FWM options commercially available in the UK to inform the development of a two-tier decision-making framework. A set of steering criteria was developed and refined via stakeholder consultations to create flowcharts that guide the selection of FWM options, i.e., Tier 1 of the framework. Tier 2 refines the FWM process selection using a comparative sustainability scorecard of FWM options performance developed through a rapid systematic evidence mapping. The main outcome of this study is a flexible decision-making tool that allows stakeholders to participate in the decision-making process and facilitate the selection of tailored-based FWM processes that better suit their circumstances and needs. This approach to decision-making is more likely to enable solutions that facilitate the sustainable management of wasted resources and promote circularity.

Keywords: food waste management; hospitality and food service sector; decision-making tool; sustainability performance; criteria-based approach

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1. Introduction

In the UK, the post-farm gate food waste (FW) generated in 2018 was around 9.5 Mt, of which 69% came from households. The rest 31% of FW generated came from the food manufacture (16%), retail (3%) and hospitality and food service (HaFS) (12%) sectors [1,2]; with the latter (HaFS) contributing considerably to the generation of FW [3]. Therefore, the role of the HaFS sector in improving the sustainability of FW management (FWM) is essential, as the increasingly changing lifestyle that relies on out-of-home dining and on-the-go consumption, as well as tourism, will likely increase food waste generation [4].

Within a circular economy, the UK government waste policy has developed actions to increase recycling rates, including FW. For example, the Courtauld Commitment 2025 and the UN's Sustainable Development Goal (SDG) 12.3 have set ambitious FW prevention targets, with the former aiming to reduce greenhouse gas (GHG) emissions and FW generation across the supply chain of the food and drinking sector in the UK by 20% between 2015 and 2025 and the latter to reduce FW generation by 50% between 2007 and 2030 [5]. In addition, the Environment Act 2021 is the new framework of environmental protection in the UK, yet to come into force; this framework suggests that FW from the

HaFS sector must be collected as a separate recyclable waste stream at least once a week for recycling by 2023 [6]. Therefore, the HaFS sector should introduce source segregation of FW (e.g., bins, tanks and on-site pre-processing technologies) [7].

According to the waste hierarchy (WH)—proposed in Article 3 of the Waste Framework Directive (2008) (WFD08)—FWM management methods can be classified into the disposal, recycling, recovery and reuse practices. Disposal denotes all methods that may (or may not) treat FW with limited value capture. In contrast, recycling and recovery (often merged) indicate processes that turn FW into value-added products (e.g., compost, steam, biogas) [8]. Therefore, 'disposal' is regarded as a non-preferable option for dealing with FW as it negates the value embedded in FW (value loss). At the same time, it also causes adverse environmental, economic and social impacts. FWM processes under disposal include landfill, incineration without energy recovery, and waste-to-sewer. 'Recycling' is considered the optimal option for managing FW because it recovers value from it providing typically lower environmental, economic and social impacts than FW disposal. FWM processes under recycling include composting and FW valorisation, incl. anaerobic digestion (AD) [9]); it is worth noting that AD is also considered to be a 'recovery' process due to energy recovery via biogas production. The 'recovery' is a debatable option for FWM as it includes methods with high-value recovery potential (e.g., AD, enzymatic catalysis) and processes with low-value recovery potential, which return less positive impact; these low-value recovery processes include incineration of FW with energy recovery and mechanical biological treatment (MBT).

In FW reuse, the redistribution of surplus food to people in need and its use as animal feed is considered the optimal route for FWM. Regulatory restrictions, safety concerns and logistics related to the collection, transport and processing of surplus food burden its redistribution. At the same time, the lack of structure, organisation and knowledge on food hygiene and safety prevents businesses from donating their surplus food to people. The reason volunteering businesses hesitate to donate surplus food is due to the risk of brand defamation in case of an incident, as well as due to financial and administrative burdens [2].

In the UK, animal feeding is subject to strict legal obligations due to the risks associated with the transmission of viruses and diseases due to decomposition, contamination and animal by-products issues that can lead to long-term environmental and socio-economic consequences [10]. As a result, the UK government introduced the Animal By-Products (Enforcement) (England) Regulations 2013 (as amended by the Animal By-Products (Enforcement) (England) Regulations 2015) and the Commission Regulation (EU) No 142/2011 to ban intra-species recycling. Intra-species recycling refers to animal feeding from material derived from a species to a creature of the same species; this ban also includes feeding of catering waste to farmed animals [10]. Control regulations administered by the Department for Environment, Food and Rural Affairs (DEFRA) and Animal and Plant Health Agency (APHA) have been developed to ensure that catering waste is kept out of the system of animal feeding [10]. Feeding pigs with catering waste is illegal, and the UK government and the National Pig Association (NPA) have joined forces to control that [11]. Due to the complexities and restrictions associated with surplus food redistribution and FW use in animal-feed production, respectively, reuse as an FWM option is excluded from the scope of this work.

The FW produced in the HaFS sector is highly heterogeneous, and its putrescible nature and moisture content make handling and processing challenging. The segregation of FW at the source is necessary to involve the removal of inorganic waste items and other organic waste materials that might be inappropriate for treatment. A pre-treatment, either on-site or off-site (e.g., FW pre-processing and addition of ancillary materials), especially for large volumes of FW, is required to achieve efficient FW processing [12]. Segregation at source usually indicates treatment that belongs to recycling/recovery (high-value spectrum) processes, whereas no-segregated FW is likely treated via recovery (low-value spectrum)/disposal processes.

As businesses in the HaFS sector may vary in size and services provided, the FW generated may also vary in volume and composition. At the same time, selecting the best available techniques for FWM to reduce negative impacts and promote circularity requires a tailored-based approach, a prerequisite often overlooked. Depending on their needs, local conditions, and cost, the HaFS sector can employ various methods for FWM, which can be on-site or off-site. However, the decision-making tools that support such decisions are lacking; therefore, this study aims to fill this gap by offering a conceptual decision-making tool that helps select appropriate and commercially available FW processing techniques for the HaFS sector, choosing the UK as a case study. The study is designed in two parts. Part one identifies a suite of on-site and off-site FWM processes that the HaFS sector could employ and examines their performance. This is completed via an explorative analysis of commercially available FWM processes complemented by a scoping analysis of their technical feasibility and regulatory viability in the UK. In Part two, a two-tier framework is developed to support the HaFS sector's decision-making process of selecting the optimal FWM option. The framework is informed by context-specific characteristics (i.e., the UK) (reported as Tier 1) translated into metrics that are used in the development of decision-making flowcharts, and a comparative sustainability performance matrix (reported as Tier 2) on the identified FWM options (incl. on-site, off-site and combinations of them). The latter is compiled via a systematic evidence mapping of FWM processes' life-cycle impacts, including environmental, economic, social and technological aspects.

Following Introduction is the Methodology section that describes the systematic evidence map protocol followed to identify the sustainability performance of FWM processes that the HaFS sector could employ in the UK (Section 2). In the Results, a sub-section is dedicated to specifying the available FWM processes in the UK (Section 3.1), including key technical and regulatory considerations for the use of on-site (Section 3.1.1) and off-site (Section 3.1.2) FWM processes, and a sub-section is related to the conceptual decision-making tool (Section 3.2) formed by Tier 1 (Section 3.2.1) and Tier 2 (Section 3.2.1). Finally, the Discussion delves into the implications to policy and practice (Section 4), followed by the main takeaway messages in the Conclusions section (Section 5).

2. Methodology

The initial stage of the analysis is an exploration of on-site and off-site FWM processes that are commercially available in the UK to identify the processes, which can practically be employed for FWM by the HaFS sector in the UK, focusing on context-specific characteristics. Following the explorative analysis, a set of criteria was created and validated following consultations with stakeholders in the HaFS sector, waste management and water industry in the UK, and validation by policy-makers and regulators. The criteria developed were used to create the two-tier decision-making framework, specifically in creating decision-making flowcharts. The flowcharts (Tier 1) were designed to return one or more FWM processes. Therefore, sustainability scorecards were developed following the systematic evidence mapping to further inform the FWM process selection (Tier 2).

This study selected a systematic evidence-based approach for developing sustainability scorecards. Systematic evidence-based approaches are primarily used in clinical decision-making. The methodology has helped medical practitioners reach reliable conclusions on the efficacy of clinical interventions [13]; this method seems appropriate given the complexity, contradiction and heterogeneity of FWM processes.

The research question formulation is a preliminary step to systematically mapping evidence. The PICO (population, intervention, control, outcome) statement was used, where [14]: (P) refers to the specific population that is investigated—herein is FW; (I) refers to the intervention to be considered, i.e., the selected FWM compatible with the WH-concept and circularity notion; (C) refers to a control or comparison intervention—herein is landfill which is a disposal method according to WH used as a baseline for off-site methods (no control intervention was used for on-site methods); and (O) refers to the effect of the intervention/outcome of interest—herein is the sustainability assessment of the FWM options considering the four sustainability pillars (i.e., environmental, economic, social and technical). The literature searching and evidence collection strategy was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach, which consists of 4 stages including planning, searching, screening, and eligibility [15]:

Planning: 41 search terms grouped into three lists following the PICO statement, i.e., population terms, intervention and control terms, and outcome terms, were used to gather all relevant studies. Search terms included synonyms, singular/plural forms, verbal forms, adjectives and different spellings.

Searching: Scopus was used to access peer-reviewed literature relevant to the scope of the study. The peer-reviewed literature search was supplemented with relevant grey literature from the WRAP and Environmental Protection Agency (EPA). The search terms from the planning stage were combined with several Boolean operators (e.g., OR, AND, proximity operators, etc.) to perform an advanced peer-review literature search. The lists with the key terms, the number of hits for each term, and how Boolean operators were used to combine the search terms are provided in Supplementary Material A (Table S1).

Screening and Eligibility: the identified literature was checked and screened against the eligibility criteria. The eligibility criteria were: (1) studies published between 2011 and 2021 to include only up-to-date information on the performance of FWM options a decision informed by a preliminary search (see Supplementary Material A); (2) quantitative and qualitative data derived only from case studies with similar geographic and socio-economic conditions to the UK (e.g., European countries—US was not included due to differences in FWM strategies and regulatory perspectives); and (3) studies that provided information on the sustainability performance of FWM methods excluding those not widely implemented in the UK (e.g., animal feeding, pyrolysis, torrefaction, vermicomposting, etc.). At the first screening stage, studies were screened for eligibility by reading the title and the abstract. Studies that fulfilled the eligibility criteria and studies that were not clear whether they were eligible or not at the first stage of screening, were screened further at the second screening stage by reading the full text. In total, we identified 91 eligible studies. All references were recorded and cited using the reference manager EndNote. In Figure 1, we present the PRISMA graph detailing the results of the literature searching strategy.

The quantitative and qualitative data were collected from life cycle analysis (LCA) and life cycle cost (LCC) studies and critically curated to develop sustainability scorecards using a traffic light colour coding system for illustrating the ranking amongst different FWM processes and impact categories; this provided an illustrative comparative assessment of the performance of FWM technologies (both on-site and off-site) in terms of various environmental, economic, social and technical impact categories. In addition, variability plots offered additional insights into the ability of selected FWM processes (off-site) to provide positive and negative impacts for several environmental impact categories, for which available information was sufficient (data from at least three studies).

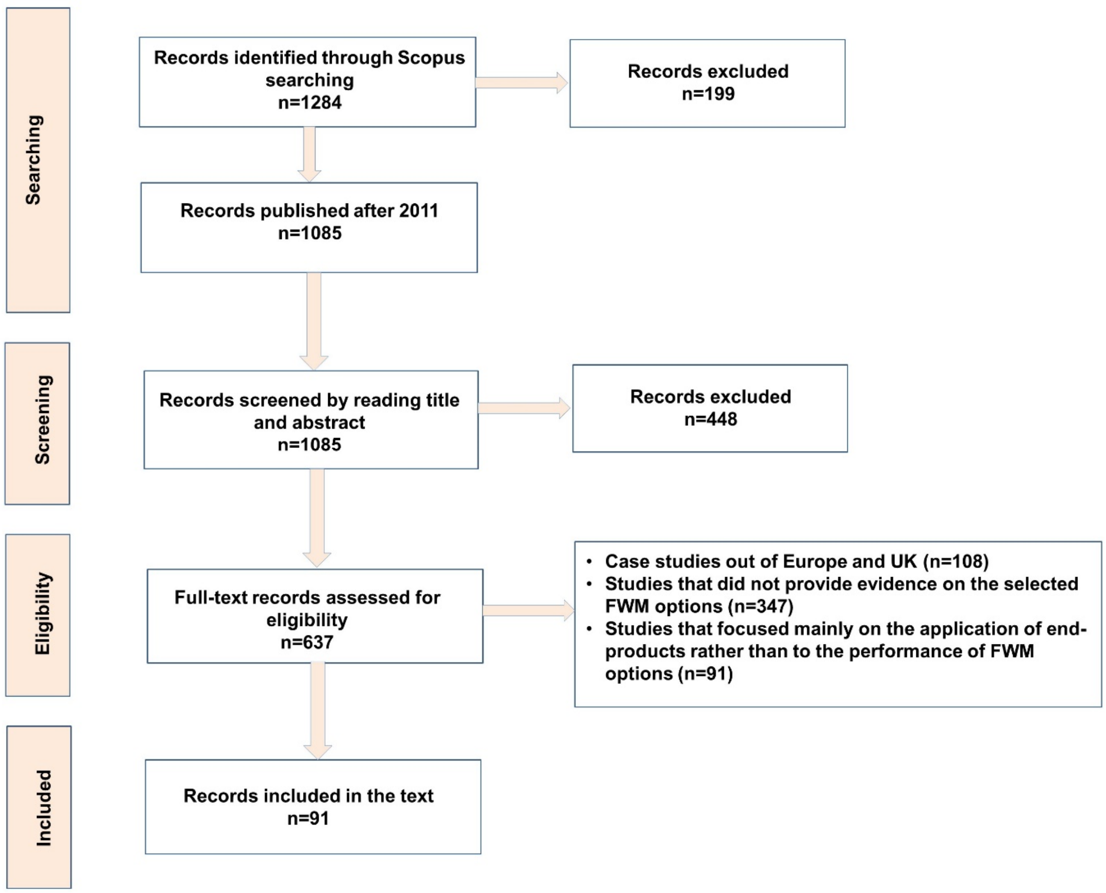

Figure 1. PRISMA graph of literature searching strategy for the sustainability assessment of FWM options most commonly used in the UK.

3. Results

3.1. Explorative Analysis of FWM Processes Available in the UK

The study distinguished FWM processes into on-site and off-site treatment processes. The HaFS sector can employ on-site FWM processes at the premises where FW is generated. Off-site management processes occur elsewhere, usually at permitted centralised waste management facilities. The latter option (off-site) requires a formal arrangement with a waste management contractor responsible for the collection and management of FW, whether mixed with other wastes or separated. On-site FWM processes can be grouped into six technologies [16]. These are the following:

- **Grinders** (also known as macerators): mechanically reduce the volume of FW by macerating it into a slurry that is disposed of in the sewer system for treatment at the wastewater treatment plants (WWTPs);
- **Biodigesters** (also known as aerobic digesters): continuous feed systems that biologically break down and decompose FW at an accelerated rate (typically within 24 h) under aerobic conditions using a mechanised aeration technology (e.g., turner, agitator, or paddle arms). Most commercially available biodigester systems are equipped with scales and an integrated tool that measures the amount and type of FW fed into the unit [16];
- **Pulpers** (also known as dewatering systems or compactors): mechanically press out the liquid content of FW through a vacuum or pressure pump;
- **Dehydrators:** use heat (operate in a temperature range of 40–150 °C) to remove moisture from FW creating dry biomass; they typically have sensors that detect moisture

content up to a level of 4–6%, enabling the completion of drying cycles, while steam generated from dehydration is condensed, filtered and discharged into the sewer [17];

- **In-vessel composters (IVC)**: biologically break down and decompose FW under aerobic conditions inside an enclosed container or vessel, producing compost in the shortest time (typically within 1–2 weeks), although post-curing is usually required. The main types of IVC are horizontal reactors that can be further divided into channels, cells, containers and tunnels; vertical reactors involve some type of cylindrical container or tank and rotary drums that incorporate internal vanes [18];
- **Small-scale anaerobic digesters (AD)**: batch systems that can be divided into two types—a liquid with a variety of control and mixing methods and dry, where liquid percolate is sprayed into the digester over the digesting feedstock to ensure enough moisture to foster microorganisms [19]. The latter fits better with FW processing. However, small-scale AD has longer reaction times and lower methane gas production than large-scale off-site AD [20].

The FWM processes can be used in joint configurations, delivering end-products with variable quality. Each category has different requirements in terms of inputs, including acceptable FW and ancillary resources (i.e., energy, water, and additives), resulting in other end-products and post-treatment options [16,21] (see Supplementary Material B); it is worth noting that FW is not commonly fully treated with the on-site FWM processes; instead, it is pre-processed into an end-product that requires further processing that usually takes place off-site [16,20]. There are exceptions, as a few technologies such as IVC and AD can produce an end-product (e.g., organic fertiliser as soil amendment) that can be used in limited applications (e.g., landscaping).

Off-site FWM processes are usually centralised, large-scale facilities providing waste management services to many local authorities and businesses. A range of off-site FWM techniques is available for managing FW in the UK; these can be broadly distinguished into

1. biological processes, i.e., composting and AD;
2. thermal processes, i.e., incineration with energy recovery; and
3. disposal in landfills.

Regardless of the type of FWM process selected, FW storage (e.g., bins, tanks, freezers) is needed and may depend on the size of HaFS businesses and the waste collection contract with the private waste management contractors [20].

Figure 2 illustrates the selected technologies that can be employed on-site and off-site that are available to HaFS businesses and primarily used in the UK.

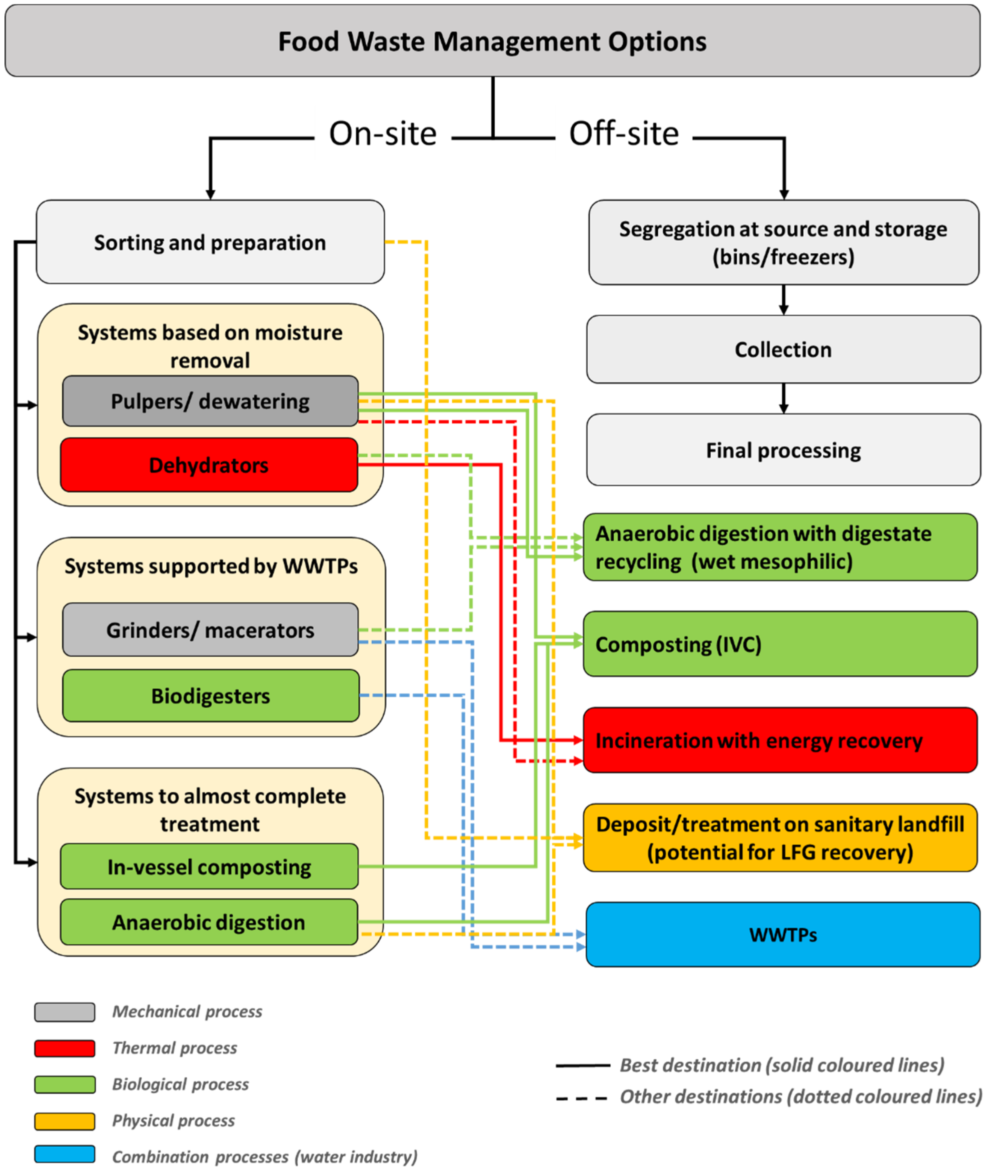

Figure 2. Food waste management methods are classified into on-site and off-site technologies (as conceived by the authors of this research).

3.1.1. Key Considerations Regarding the Use of On-Site Technologies

Rapid market research analysis has shown that the processing capacity of the on-site FWM technologies varies widely depending on the technology type. For instance, IVC, dehydrators handle up to 100 kg FW/day; macerators and AD can handle up to 200 kg FW/day [22]. There is currently no commercially available system for a processing capacity of less than 20 kg FW/day. Figure 3 presents the typical operational factors of on-site FW processing techniques, including inputs, outputs, and final end-product destinations.

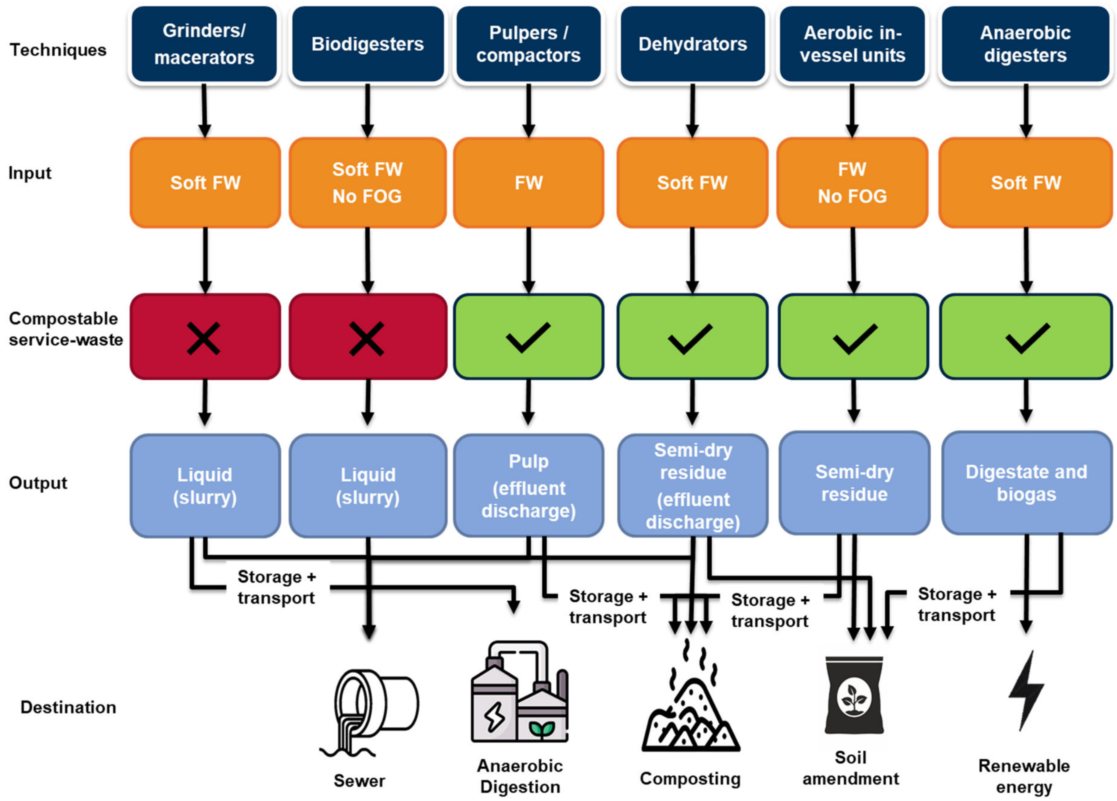

Figure 3. Operational factors of commercially available on-site FW processing techniques. Adapted by [16]. NOTE: Soft FW: excludes bones, shells and pits; FOG: Fat, oil and grease; Compostable service waste: Compostable plastics.

Grinders (macerators) and biodigesters are wastewater-based systems that produce a liquid end-product (Figure 3) that is typically sent for treatment to WWTPs through the sewer system. Even though these processes are a hygienic, practical, convenient and relatively affordable way to manage FW at the source, the disposal of liquefied FW down the drain shifts the burden of FWM from the waste producer to the water industry. The water industry besides treating the organically-rich influent at the WWTPs also needs to maintain the performance of the sewer system [16]. FW includes fats, oils and grease (FOG), which may contribute to sewer blockages, flooding, malodour and the risk of rat infestation. Therefore, FW disposal to the sewer could result in a considerable extra cost of cleaning up the sewers of millions of pounds annually [23]. Therefore, the disposal of liquefied FW effluent from macerators to the sewer that is of non-domestic nature is heavily regulated by the Sewage Undertakers [23]. Sewerage Undertakers or 'undertakers' are companies in England and Wales that provide water and sewerage services, and whom businesses in the HaFS sector must contact to explore whether or not they are allowed to discharge their FW effluent in the sewer [23]. The undertakers may provide permission, called the *trade effluent discharge*, depending on their area-specific characteristics and sewer conditions. More information on the trade effluent consent can be found in Supplementary Material C.

It must be specified that biodigesters produce an FW slurry with a lower organic load (i.e., BOD) than macerators. Therefore, biodigesters may reduce the extra strain in WWTPs but the biogas yield in the AD of sewage sludge is lower. Factors such as the organic load and biogas potential are highly dependent on FW composition and biological supplements [16]. Adequately sized grease traps or interceptors that are operated and maintained correctly, and the separate collection and storage of waste oil to keep it away from the drains, are considered good practices when using biodigesters and macerators [23].

Pulpers and dehydrators also generate a liquid effluent that could be discharged into a trade water outlet or sewer raising concerns about the effluent charge consent. Nonetheless, the net environmental burden of this discharge has not been thoroughly explored in the literature. The main limitation of using pulpers is that the pulped FW is not stable for long-term storage and must be refrigerated or frequently collected to prevent odours and pests/vermin attraction [24]. Pulped FW must be processed off-site or used as feedstock in dehydrators, IVC or anaerobic digesters (i.e., in a combined configuration) on-site [24]. Generally, pulpers constitute an appropriate pre-treatment method when FW is destined for off-site AD [25].

Dehydrators can offer several benefits to FWM (more information is provided in Section 3.2.2). However, the direct application of dehydrated FW to land is not recommended. Specifically, dehydrated FW has poor nutrient levels leading to soil malnourishment and relatively low pH that is considered too acidic for plant growth [26]. Dehydrated FW that has not been biologically decomposed and experiences rapid fungal growth indicates its unsuitability for soil amendment [24]. At the same time, the use of dehydrators as pre-treatment for off-site composting and AD is not recommended due to creating an incorrect balance between carbon, nitrogen and moisture unless FW is mixed with other organic waste [26,27].

The selection of IVC and AD for FW in the UK are subject to environmental legislation and environmental permitting controls [28]. Animal By-Product Regulations (ABPR), outline measures for ensuring public and animal health. Animal by-products are defined as 'entire bodies or parts of animals, products of animal origin or other products obtained from animals that are not intended for human consumption" according to Article 3 of Regulation (EC) 1069/2009 [28]. For instance, the use of aerobic IVC is conducted under a fully enclosed, controlled environment to avoid odour problems and vermin traction [29] offering versatility for customised designed needs [30]. FW can be sprayed with commercially available enzyme supplements to enhance microbial activity. At the same time, the temperature is maintained between 60–70 °C to ensure hygienic conditions providing a pasteurised compost-like product [29], that can be applied to landscaped areas. Modern automated IVC systems are commercially available for monitoring temperature and moisture to determine the frequency of automated mixing and aeration [29].

The compost-like product and digestate produced in IVC and AD, respectively, must be checked against the specifications outlined in the BSI PAS100 (Compost)/PAS110 (Digestate) and the Quality Protocol (QP) (BSI 2011) to ensure that it complies with the end-of-waste criteria, for land application. The QP sets out the criteria that must be met for producing quality compost/digestate from the composting/AD processes of source-segregated biodegradable waste (biowaste) [31]. According to this protocol, the compost/digestate can be used in agriculture, forestry and soil/field-grown horticulture as fertiliser or soil conditioner, or land restoration (e.g., soil manufacture, blending operations, and land reclamation) [31]. The compost-like product of on-site IVC is unstable and only suitable for soil amendment within 1–4 weeks of its production during warmer months [29,32]. Even its use as a soil amendment requires close monitoring of the composting process [33,34]. Landscaping needs near the business operating on-site IVC, and quality testing of the end-product are key prerequisites of IVC application. Alternatively, the end product from on-site IVC could go through additional curing off-site, which would result in extra costs, potentially making it uneconomical [35]. Even with landscaping needs, the excess amount of compost-like output generated will need to be disposed of leading to increased costs and environmental impacts associated with transportation and avoided nutrient recovery [35]. The use of digestate in covering landscaping needs is difficult due to limited quality control measures and scientific evidence to provide confidence in its safety.

Furthermore, small-scale FWM systems such as AD and IVC might require environmental permits published by the Environment Agency (EA) [36]. Obtaining a permit mainly involves permit application, subsistence fees, management systems, and technical competence. However, waste exemptions are set out in the Environmental Permitting Regulations (EPR) for both processes, composting [37] and AD [38], known as Low-Risk Waste Position (LRWP). In situations where activity is considered low risk and it would be disproportionate to require a permit, EA may publish a regulatory position statement (RPS) [39]. RPS is issued when small-scale systems do not fit well within the waste exemptions (i.e., LRWP); it must be noted that different permitting scenarios depend on the type of FWM system and the scale of operation.

Lastly, the selection and use of small-scale AD depends on space requirements that should be sufficiently provided to cater for maintenance and housekeeping needs. Otherwise, the unit's operation becomes tricky [12], and the equipment longevity is reduced due to NH_3 release during processing [12]. Storage requirements for FW (e.g., use of a pre-digester tank) are needed as the process can treat a specific load for a particular time (typically 20–40 days, depending on operational factors such as temperature, organic loading rate and technical specifications). To that end, malodours may arise, especially in periods of heavy feeding. The biogas produced will need to be treated into suitable equipment such as a combined heat and power (CHP) engine, for which an operating licence is required as there are no type-approved off-the-self heating appliances in the UK.

3.1.2. Key Considerations Regarding the Use of Off-Site Technologies

Outsourcing the FWM to waste facility managers lifts the responsibility of HaFS businesses to monitor and control the processes on-site of which the risk of failure is higher. Depending on the off-site FWM process selected, businesses may need to take on the responsibility of FW segregation [40]. Segregation at the source can not only improve the quality of FW and the recovery of value from it, but it can also support the improved management of dry waste (i.e., glass jars and bottles, plastic packaging, paper and board, metal tins and cans) and residual waste generated on-site (mixed waste); this could also facilitate recyclable waste materials sorting processes allowing for improved sustainability within the business [41]. The separate collection of FW is an essential precondition for selecting high-value recovery options, where biological processes can be employed for its valorisation [41,42].

Biological processes:includes centralised IVC [43] and wet mesophilic AD, which use macerators as a pre-treatment method to produce a homogenous feedstock [12]. Details on the process description of IVC and AD including crucial operational factors are provided in Supplementary Material D).

Thermal processes: refers to incineration with energy recovery commonly practised in the UK. FW incineration produces heat that can be converted into electricity, which can be exported to the grid. However, incineration's potential for electricity and heat production must be balanced against the environmental impacts and costs of construction, including land-use change, air pollution control equipment and incineration residues (i.e., incombustible waste and air pollution control residuals) management and disposal. Residues (i.e., incombustible waste and air pollution control residuals) are often landfilled. Air pollution control equipment is typically employed to remove harmful substances from industrial exhaust gases before their release into the environment.

Disposal: refers to landfilling. The design and operation of the landfill sites in the UK are controlled to minimise contamination and pollution of the surrounding environment, landfilling negates the value of wasted resources and contributes to carbon emissions, and hence, climate change. Therefore, landfill is the option that goes against the net-zero carbon emissions ambition, further aggravated by transportation and pre-treatment.

3.2. Development of the Two-Tier Decision-Making Framework

3.2.1. Tier 1: Flow Charts Aiding the Selection of an On-Site FWM System

This step involves the development of binary (yes or no) conditional flow charts that are linked together and aid the selection of suitable FWM process(es). The development of the flow charts was based on a set of criteria formed via the explorative analysis of the FWM processes characteristics and discussions/consultations with relevant stakeholders from the HaFS sector, waste management and the water industry.

The criteria aim to capture high-level aspects of the FWM practices in the UK and their potential implementation; they are, thus, steering, simple and generic rather than decisive, firm and all-inclusive. The criteria were debated and validated via personal communication and discussions with professionals and practitioners from the HaFS sector, EA, DEFRA, waste management sector and water industry. The following criteria were selected:

1. **Processing capacity:** it was divided into four ranges according to the processing capacities of on-site systems: (i) <20 kg/day, (ii) 20–100 kg/day, (iii) 100–200 kg/day, and (iv) ≥200 kg/day. Since there are no on-site systems with a processing capacity of less than 20 kg/day, on-site management of FW is not logistically possible, and diversion to off-site FWM options is the only suggested route. The flow charts are therefore split into three routes, according to each processing capacity range (ii–iv).
2. **FW characteristics:** this is distinguished into (1) the absence of bones/shells/pits, characterised as soft FW; (2) the absence of FOG; and (3) the absence of compostable plastics; it must be clarified that this is not the same as the FW composition. FW composition can vary widely between businesses in terms of solid vs liquid and proportional distribution of carbohydrates, lipids, and proteins (e.g., restaurants, cafeterias, patisseries, etc.); hence this was excluded from the decision-making process. Each user must make his own decision based on FW composition and how seasonality affects it.
3. **Legislative compliance:** this is separated into categories of compliance as (i) EPR permit that typically refers to the installation of a waste recycling operation [36], usually on-site IVC and AD, and (ii) trade effluent consent (see Section 3.1.1) that typically refers to all on-site systems disposing of a discharge down the drain, excluding IVC (no effluent is generated) and macerators that are connected to a storage tank. To mark this difference in the macerators configuration settings, flow charts refer to macerators (tank), macerators (drain), and macerators for both configurations.
4. **Space requirements:** these are classified into small and large-size requirements, referring to the size of the systems and the space needed for their installation; it must be noted that variations exist from one supplier to another that the users should consider; this should not be confused with the location characteristics and conditions that must be met for health and safety regulations, permitting regulations, connection to the drain, distance from the kitchen, weather, etc.; users must incorporate location in their decision-making based on their site characteristics and spatial conditions, as these can vary widely.
5. **Labour requirements:** are classified into low labour needs with limited technical knowledge and increased labour requirements with advanced expertise, skills and knowledge. According to market research, high labour and space requirements have been considered only for IVC and AD [16,22].
6. **Landscaping needs:** this is when the end-product of the FWM process can be utilised on-site, assuming that the assured quality of their end-products is a prerequisite. Therefore, the quality characterisation of end-products is highly recommended before application despite system manufacturers' specifications; this criterion must be used with caution as there can be an overproduction and excess of end-product (e.g., compost-like products, digestate).

7. **Storage requirements:** FW and end-product storage requirements are intermediary steps before final treatment off-site. The logistics can vary based on the storage bin size, storage bin type (swapping or tipping), bin location, and road miles (distance from the site to the centralised facility for management).

Three binary conditional flowcharts were created incorporating the seven criteria to guide HaFS practitioners in selecting on-site FWM systems. Figure 4 presents the flow chart for FW processing capacity <100 kg/day. For FW processing capacities of 100–200 and >200 kg/day, flows charts are provided in Supplementary Material E (Figures S2 and S3, respectively).

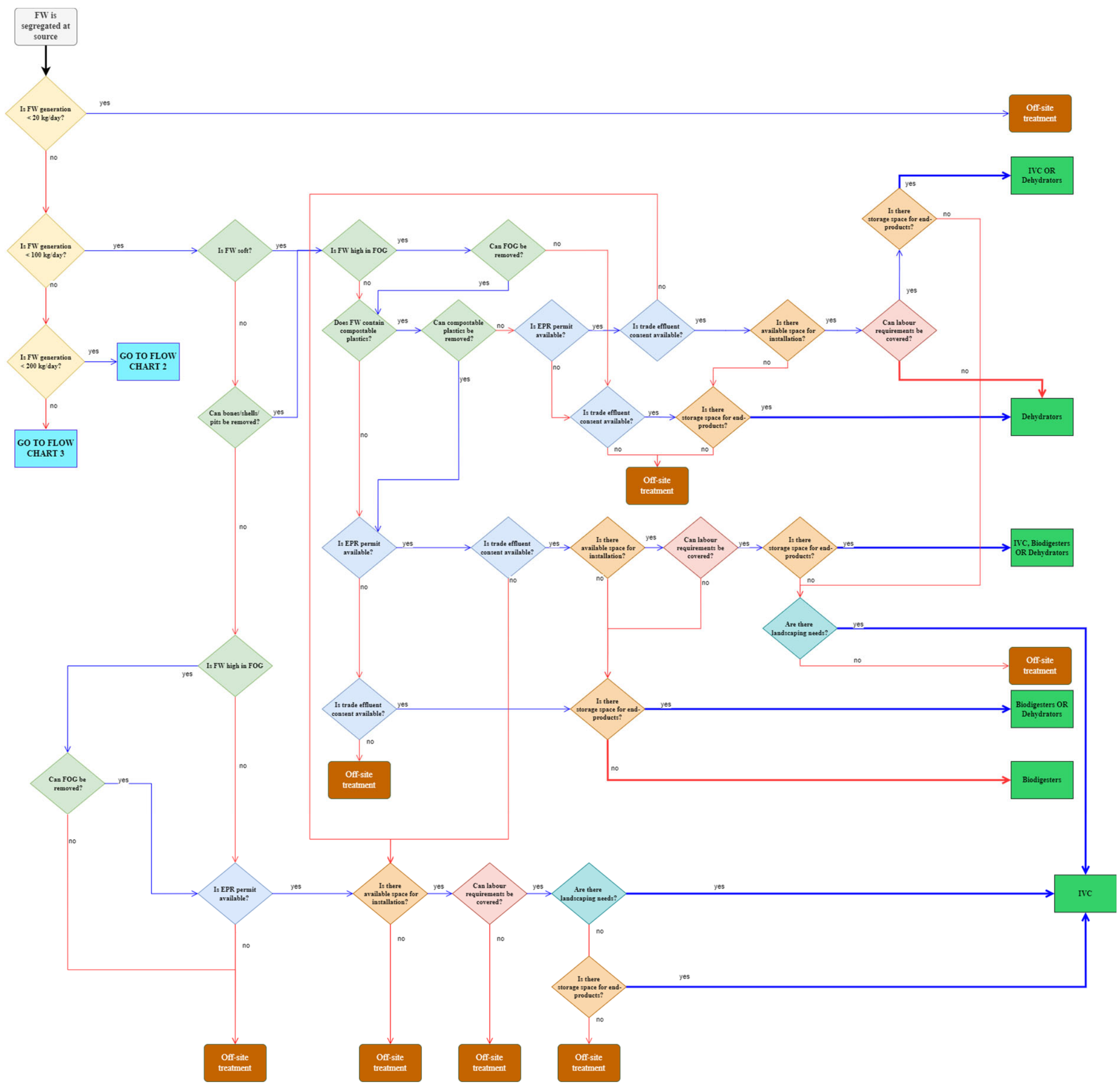

Figure 4. A binary conditional flow chart to select on-site FWM systems with a processing capacity <100 kg/day. For better resolution and editing go to https://app.diagrams.net/ (acceded on 16 September 2022). Navigation notes: oval rectangles indicate the start (i.e., segregation at source) and endpoints (i.e., off-site FWM with brown colour), whereas the diamond-shaped boxes denote decisions with different colours illustrating a criterion as follows: light yellow, "processing capacity"; light green, "FW characteristics"; light blue, "legislative compliance"; orange, "space requirements"; pink, "labour requirements"; bright blue, "landscaping needs". The dark green rectangle indicates on-site FWM processes. The arrows represent the answer given for each condition: red-coloured arrows indicate the answer is 'No'; blue-coloured arrows indicate the answer is 'Yes'.

3.2.2. Tier 2—Sustainability Assessment of FWM Options

The flow charts provide a preliminary selection of one or more FWM processes. Therefore, a comparative sustainability performance of FWM processes could further facilitate the selection of processes prevalent in the UK, including on-site and off-site technologies. The sustainability performance of all off-site and on-site FWM options was assessed to determine their potential to maximise positive and minimise negative value. Value refers to environmental, economic, social and technical aspects that the HaFS businesses need to consider alongside technical, regulatory and logistic aspects as captured by the flow charts [2,44].

Sustainability Performance of Off-Site FWM Processes

According to the global literature, the most commonly used methods for FWM across the globe are AD, composting (mainly in-vessel), incineration and landfilling [29,45–48], which is in line with the off-site FWM methods most prevalent in the UK (see Section 3.1.2.). Published quantitative data on LCA impact categories for the UK- and Europe-based studies were collected and curated to carry out a comparative environmental performance of FWM options across the LCA impact categories. A ranking score system was used to visualise the results of the comparison (i.e., value one means the best and value four means the worst). The scoring is presented in Table 1.

In cases where no clear comparative evidence is available, FWM methods were scored only according to the traffic light colour coding system illustrating green as the best option, orange as the intermediate option and red as the worst option. There were limitations in extrapolating information and quantitative data from the selected literature; this limitation was due to the absence of calculated results (e.g., graphs provided, making it impossible to extract data) and the use of incompatible functional units (e.g., expressed as the total amount of FW generated per year in a specific area); this was also discussed elsewhere [49].

Table 1. Comparative assessment and ranking of FWM options in terms of LCA impact categories according to the systematic evidence map that collected quantitative data only from the UK and European studies. Green: Best option; Red: Worst option; Amber: intermediate option.

LCA Impact Category	Unit	AD	IVC	Incineration	Landfill	Evidence of Scoring Card	Contradictory Evidence of This Scorecard	Reference of Contradictory Evidence
GWP	kg of CO_2 eq.	1	3	2	4	Systematic evidence mapping	Incineration is better than AD	[50,51]
ADP	kg Sb eq.	1	3	2	4	[52,53]		
PED	GJ	1	3	2	4	Systematic evidence mapping	Landfill better than IVC	[46]
							Incineration is better than AD	[50,52]
FD	kg oil eq.	1	4	2	3	[46,52,53]		
ODP	kg of CFC-11 eq.	1	3	2	4	Systematic evidence mapping	Landfill better than IVC	[46]
							Incineration is better than AD	[50]
HT	kg 1,4-DB eq.					Systematic evidence mapping	AD is better than incineration	[46]
							Incineration is better than AD	[52]
IR, hh	kg U235 eq.						Different ranking by 3 studies	[46,50,54]
POP	kg NMVOC eq.					Systematic evidence mapping	IVC is better than AD	[50,53]

							Landfill better than ICV	[46]
EP	kg PO_4^- eq.	2	3	1	4	[52]		
FE	kg P eq.	1	2	4	3	[46]		
ME	kg N eq.					Systematic evidence mapping	Incineration is better than IVC AND AD is better than landfill	[46]
							AD is better than incineration	[50]
FET	kg 1,4-DB eq.						Different ranking by 3 studies	[46,52,54]
MET	kg 1,4-DB eq.					[46,52]		
TET	kg 1,4-DB eq.					[46,52]		
AP	kg SO_2 eq.	2	3	1	4	Systematic evidence mapping	Landfill better than incineration, AD, IVC	[46]
TA	kg SO_4 eq.	3	4	2	1	[46]		
TE	mol N eq.	3	No info	2	1	[54]		
PM	kg PM2.5 eq.					Systematic evidence mapping	Landfill better than incineration	[46]
							Incineration is better than landfill	[54]
							IVC is better than AD and incineration	[50]
MD	kg Fe eq.	1	3	4	2	[46]		
LO	m2yr	2	3	1	4	[50,54]		

Grey boxes indicate that evidence is inconclusive; GWP: Global warming potential; ADP: Abiotic depletion potential; PED: Primary energy demand; FD: Fossil fuel depletion; ODP: Ozone depletion potential; HT: Human toxicity; IR, hh: Ionising radiations, human health effects; POP: Photochemical oxidation; EP: Eutrophication potential; FE: Freshwater eutrophication; ME: Marine eutrophication; FET: Freshwater ecotoxicity; MET: Marine ecotoxicity; TET: Terrestrial ecotoxicity; AP: Acidification potential; TA: Terrestrial acidification; TE: Terrestrial eutrophication; PM: Particulate matter; MD: Metal depletion; LO: Land occupation.

Table 1 indicates that AD performed better in most LCA impacts, followed by incineration (with energy recovery), IVC and landfill. However, this ranking is indicative and should not be considered a general rule. Area-specific indicators influence the system boundaries and therefore, the LCA results; this is supported by the contradictory evidence, also reported in Table 1. Quantitative evidence on the variability of the off-site FWM methods' environmental performance in terms of specific LCA impact categories is provided in Supplementary Material F (see Figure S3).

It must be emphasised that the environmental performance of IVC and AD is influenced by the application of end products [54,55]. The application of recycled end-products (i.e., compost and digestate) depends on site-specific characteristics, such as soil profile (e.g., higher leaching of Cu into the sand and silt soil than loam [56]); weather (e.g., increased leaching of metals into soils under extreme precipitation [56]); crop factors (e.g., rice crops require fertilisers with high potassium (K) content, while soybeans crops require high nitrogen (N) content fertilisers [26]) [57]; and seasonal conditions (e.g., low leaching effects in high irrigation conditions [56]). More information on compost and digestate is provided in Supplementary Material F.

Environmental impacts of AD: AD appears to perform negatively in terms of acidification potential [54,58] and particulate matter formation [59] due to fugitive emissions released from digestate handling and application [46], biogas leakage during operation

[60] and biogas combustion in CHP plant [61]. Therefore, to maximise the benefits of AD, gas emission treatment equipment [62], the development of technologies to enhance the quality of digestate [41,45] and an increase in biogas production efficiency [63,64] need to be considered. In most cases, biogas is combusted in a CHP unit for the generation of heat and electricity (with conversion efficiency having a typical range of 24–40% [65,66]) that covers the on-site energy demands, and any excess electricity is typically exported to the grid [46,67]. For example, the replacement of coal electricity with biogas electricity would lead to a higher reduction of GHG emissions (i.e., 130%), while the replacement of grid natural gas with upgraded bio-methane would lead to a lower reduction in GHG emissions (i.e., 20%) compared to the current use of biogas in CHP plants in the UK [63]. Digestate handling may significantly increase the competitiveness and attractiveness of AD [64] also contributing to the reduction of odour emissions—a neglected aspect in LCA studies [62].

Environmental impacts of IVC: evidence mapping showed that IVC negatively impacts the environment mainly in terms of GHG emissions and primary energy demand as it is a net consumer of grid electricity [46,57,59]. Electricity use and non-methane volatile organic compounds from the composting process can result in photochemical oxidants formation and ozone depletion potential [46,58,68]. IVC also contributes to terrestrial acidification and eutrophication due to ammonia (NH_3) released into the atmosphere at the compost maturation stage [46,50,58], which in turn, reduces compost's added value due to N loss [69]. Mitigation strategies for preventing NH_3 release from compost include the co-composting with green waste, adjustment of aeration rates and the use of bulking agents and chemical additives) [69]. However, the latter contributes to additional resource consumption; it should also be noted that IVC's land use requirements are not high compared to other composting systems. Still, the compost maturation typically occurs in large, aerated windrows with higher space requirements [32,46,53,70]. Compost as a soil amendment can sequester carbon in depleted soils leading to a reduction in carbon emissions; it can improve soil moisture retention, reduce irrigation requirements, and it may offset the production and use of artificial fertilisers [46,50,71]. The displacement of artificial fertilisers can partially offset IVC's high energy requirements [68]; it could lead to a net-negative contribution to freshwater eutrophication [46] and a considerable reduction in GWP and depletion of abiotic resources [50]. It is worth mentioning that the type of IVC used can influence its environmental performance as more frequent mixing can lead to more gaseous emissions than no mixing. However, mixing helps with aeration leading to faster degradation and maturation [33]. Rotating drums could bring out the optimal balance among environmental, financial/economic, social, and technical criteria followed by vertical and horizontal composting reactors [72].

Environmental impacts of incineration with energy recovery: incineration can enhance metal depletion due to its intensive demand on equipment, facility operation, and auxiliary materials to control emissions (e.g., NH_3 injection to control NOx emissions, lime to control SO_2 and HCl, and activated carbon to capture heavy metals [50]) and eutrophication potential due to the presence of phosphates in fly ash that is emitted to the environment during wastewater treatment and landfilling [46]. However, the strict control of NOx emissions in modern incineration plants may alleviate its contribution to eutrophication potential [73]. Moreover, using ash products from FW incineration as feedstock for agricultural production or building materials could significantly increase the sustainability performance of FW incineration [71].

Energy generation potential of incineration with energy recovery: the exceptionally high energy requirements for FW moisture content evaporation, and the air pollution control and water needs for ash quenching and cooling constitute key environmental burdens [71]. If the moisture content of FW is beyond 50% of its volume, then the energy output of incineration might not be positive [50].

Environmental impacts of landfilling: a severe negation of the multi-dimensional value embodied in FW and the creation of negative value, environmental, economic and social. Anaerobic conditions usually prevail when FW is disposed of in landfills leading to biogas formation (also known as landfill gas (LFG)) [71]. In cases where LFG is recovered, LFG is collected, stored and used on-site (e.g., for heat or electricity generation) or off-site through injection directly into natural gas pipelines [71]. However, LFG is not commonly recovered, and it may burn (i.e., landfill with LFG treatment) contributing to heat waste. Landfilling of FW leads to the highest CH_4, organic nitrogen and phosphate emissions enhancing toxicity, acidification and eutrophication potential compared to any other FWM system [67,74]. In addition, landfilling has the highest negative influence on marine eutrophication caused by leachate management [59,75] and resource depletion due to energy consumption used for leachate management [71]. Sanitary landfill is the FWM option with the highest land use requirements unless they are reclaimed for natural land transformation at their end of life [46].

Unlike environmental performance, evidence of the economic performance of FWM options is minimal. Table 2 shows the cost for different life cycle costing impacts according to a UK-based study, which was the only available quantitative information; it must be highlighted that the economic performance of FWM options is highly sensitive to waste collection costs, gate fees and electricity prices which can arbitrarily vary by ±25% [70]).

Table 2. Main contributors to the economic performance of FWM options. Green: Best option; Red: Worst option; Amber: intermediate option. Data from [46].

Life Cycle Costs (GBP/t FW)	AD [1]	IVC [2]	Incineration [3]	Landfill [4]
Costs to local authorities for gate fees	29	46	83	107
Cost to local authorities for FW collection	108	63	25	25
Costs to local authorities (FW collection and gate fees)	137	109	108	132
Capital costs to operators *	7	4	28	12
Operating costs to operators *	8	14	26	5
Revenue for operators from tipping fees	29	46	83	22
Revenue for operators from end-product sales	14	0.23	8	3
Overall cost	110	80	71	123

[1] Mesophilic AD, biogas is utilised in a 1 MW CHP reciprocating internal to supply all on-site demand with the excess electricity exported to the grid, digestate is used as fertiliser; [2] Horizontal rotating steel drum, the treated compost is then matured in open windrows over 10–14 weeks, end-product used as mineral fertiliser; [3] Moving-grate furnaces, electricity fed into the grid, ash is landfilled; [4] Sanitary landfills, landfill gas (LFG) is collected and utilised for energy generation, leachate is collected for treatment; * This FWM ranking agrees with [54] reporting AD, incineration, and landfill at the European level.

It should be noted that costs and economic impacts may vary according to local conditions. Some further considerations about the economic impacts of each off-site FWM option are worth discussing.

Economic impacts of AD: AD can be considered a more economically attractive FWM option than IVC [76] due to product revenue arising from the electricity generation (GBP 4/t FW) and the electricity exported to the grid (GBP 13/t FW) [46]. In the UK, the digestate has no market value and operators may force to pay users to take it away (GBP 4/t FW) [46]. Increased biogas yields (≥190 m^3/t FW) can lead to a positive net present worth (i.e., economic desirability considering cost and revenues) [61].

Economic impacts of IVC: IVC's most economically attractive impact is compost application to replace peat [66]. Literature evidence has implied that revenues from selling compost (GBP 0.23/t FW) are negligible in the UK [46]. Poor revenues are considerably lower than AD with and without digestate recycling and incineration, as well as high operational costs, have been reported [77].

Economic impacts of incineration with energy recovery: revenues from electricity production and low collection and sorting costs, make incineration quite favourable [46,77]. However, incineration of FW can become more costly under reduced exergy output arising from the high moisture content of FW, while AD can become more financially attractive [78]. Incineration is considered a more economically attractive FWM option since FW is typically co-treated with MSW leading to net energy recovery [79]. However, the removal of FW from MSW would increase the calorific content of MSW and therefore improve the performance of incineration [65]. Currently, in the UK, the collection cost per tonne of FW is high due to the relatively small share of FW presently segregated in the source [46]. However, if the total amount of FW were treated through AD instead of the current UK situation, the annual life cycle cost savings would be more significant. Therefore, AD would be the most sustainable method from an economic perspective over incineration [46].

Economic impacts of landfilling: landfill is the most expensive FWM option due to landfill tax. Otherwise, it would be the cheapest option [46]; pointing to the success of the monetary instrument in limiting its use. In cases where the LFG is collected and recovered, some venues can be obtained from the sale of electricity, yet, the high landfill tax outperforms any economic benefit [46].

Segregation at source is highly encouraged for IVC and AD systems that are sensitive to impurities [46,52,68,80]. Contamination and impurities can disturb the aerobic and anaerobic activity, and consequently, affect the quality of the outputs as well as cost savings of compost analysis [41,42,81]; in extreme cases it could bring the aerobic/anaerobic processes to a complete halt, leading to rejects that end up in landfills [18,41,81,82]. Segregation at source can be time-consuming [83], however, the cost for collecting FW segregated at source is lower (GBP 7/ household) than this of residual waste (GBP 14/ household) since FW have a lower volume, the considerably lower amounts of FW generated compared to residual MSW increase the collection costs of FW [46]. The current collection costs for FW segregated at source in the UK are accounted for GBP 108 per tonne FW, while the cost of FW embedded in MSW is accounted for GBP 25 per tonne FW [46].

Sustainability Performance of On-Site FWM Processes

There are two ways on-site systems can be viewed and affect their sustainability performance: (1) On-site systems as stand-alone systems, i.e., IVC and AD; and (2) On-site systems as pre-treatment processes for off-site management, i.e., Pulpers, dehydrators, macerators and biodigesters. Table 3 presents the sustainability performance of on-site systems through a ranking score system that compares them from the environmental, technical, social and economic perspectives. The scorecard shown in Table 3 is based on collected evidence, while quantitative data were obtained from the rapid research market [16,21,22,84]; it is important to note that in the case of electricity consumption, quantitative evidence is not provided due to different units of electricity consumption. Additionally, on-site IVC and AD performance might be different for specific (not all) impact categories depending on whether landscaping needs are available. In Table 3, these differences are also provided. For example, symbol ** shows that the presence of landscaping needs makes IVC, and AD performs similarly to pulpers and dehydrators. The further description in parenthesis indicates their performance if landscaping needs are available. Finally, it must be clarified that the scorecard in Table 3 is based on two assumptions: (i) macerators are connected to the drain; (ii) AD is available in WWTP. Otherwise, the use of wastewater-based systems is highly discouraged. About the former, the liquefied FW from macerators can be alternatively stored in a tank and sent for final treatment to AD.

Table 3. Comparative ranking of the sustainability performance of all on-site FWM systems across all domains of value (i.e., environmental, technical, social and economic) based on the findings of a

systematic evidence map. Green: Best option; Red: Worst option; Amber: intermediate option; Grey: unspecified.

Domain	Metric	Pulpers	Macerators (Connected to Drain)	Biodigesters	On-Site IVC	Dehydrators	On-Site AD
Environmental	FW volume reduction (%*w*/*w*)	85–88	Reported as significant, but no evidence is given		15–80	80–93	40–80
	Water consumption (m^3/h)	0.2–0.7	0.2–1.8	≥ 0.05	No	No	*
	Electricity consumption						
	Potential for energy recovery	3	4	5	6	2	1
	Diversion from landfill				(landscaping needs: green)		(landscaping needs: green)
	Other input requirements						
	End-product to off-site incineration		NA	NA	NA		NA
	End-product to off-site AD				NA		NA
	End-product to off-site IVC		NA	NA	(available landscaping needs: NA)		(available landscaping needs: NA)
	Carbon savings from avoided waste collection				**		**
	BOD load of effluent discharged		Macerators are worse than biodigesters		NA		
Technical	Continuous FW processing						
	Operability (time and effort)						
	Long-term storage potential of end-products		NA	NA	(available landscaping needs: NA)		(available landscaping needs: NA)
	Maintenance						
	Analytics technology (scaling and/or conditions monitoring) [1]						
Social	Odour						
	Hygiene (vermin/pests)						
Economic	Capital cost	3	1	2	5	4	6
	Savings from FW collection costs and tipping fees				**		**

* Water addition for wet AD depending on FW moisture content; ** If landscaping needs are available, otherwise IVC and AD have similar performance with pulpers and dehydrators; [1] Highly dependent on the model and company; NA: not applicable.

Table 3 shows that the wastewater-based systems (i.e., macerators and biodigesters) outperform other on-site systems for most sustainability impact categories; this is because these systems shift the burden from the FWM sector to the wastewater treatment sector. For example, they may perform best in diversion from landfills, avoided carbon emissions associated with waste collection, transportation and management [85–87]; and hygiene, but shift FWM to the water industry. Perceived benefits only result from the lack of insight into the negative implications to the sewerage system (e.g., blockages, malodour issues, flooding under frequent rainfall events) and the WWTPs, which are not yet well understood [16]. If the well-performing wastewater-based systems are excluded from the analysis the comparison between the rest of the on-site FWM processes becomes more informative. Table 4 compares on-site systems assuming that effluent from macerators is collected in a tank.

Following this scorecard, it is difficult to draw any conclusive remark regarding the best on-site system. The selection of the best on-site system depends on the destination of end-products (off-site FWM option or on-site application).

A reduction in FW volume by 88%*w*/*w* through dewatering can lower the operational expenditures of FW management [83]. Interestingly, the pre-treatment efficiency of pulpers concerning energy needs and loss of organic material and nutrients is not critical in terms of the GWP of an AD system [88]. Nonetheless, system optimisation is needed since pulpers may consume higher amounts of water during the dewatering process [25]. The recirculation of rejected washing water can be a strategy for water use minimisation [25].

Table 4. Comparative ranking of the sustainability performance of on-site FWM systems across all domains of value (i.e., environmental, technical, social and economic) based on the systematic evidence map (wastewater-based systems were excluded). Green: Best option; Red: Worst option; Amber: intermediate option; Grey: unspecified.

Domain	Metric	Pulpers	Macerators (Connected to a Tank)	On-Site IVC	Dehydrators	On-Site AD
Environmental	FW volume reduction (%*w*/*w*)	85–88	No evidence	15–80	80–93	40–80
	Water consumption (m^3/h)	0.23–0.68	0.23–1.82	No	No	*
	Electricity consumption					
	Potential for energy recovery					
	Diversion from landfill			(landscaping needs: green)		(landscaping needs: green)
	Other input requirements					
	End-product destination to off-site incineration			NA		NA
	End-product destination to off-site AD			NA		NA
	End-product destination to off-site IVC			(landscaping needs: NA)		(landscaping needs: NA)
	Carbon savings from avoided waste collection			**		**
	BOD load of effluent discharged					
Technical	Continuous FW processing					
	Operability (time and effort)					
	Long-term storage potential of end-products			(landscaping needs: NA)		(landscaping needs: NA)
	Maintenance					
	Analytics technology (scaling and/or conditions monitoring) [1]					
Social	Odour issues					
	Hygiene (vermin/pests)					
Economi	Capital cost	2	1	4	3	5

Domain	Metric	Pulpers	Macerators (Connected to a Tank)	On-Site IVC	Dehydrators	On-Site AD
	Savings from FW collection costs and tipping fees			**		**

* Water addition for wet AD depending on FW moisture content; ** If landscaping needs are available, otherwise IVC and AD have similar performance with pulpers and dehydrators; [1] Highly dependent on the model and company; NA: not applicable.

Dehydrators followed by incineration are considered to be a beneficial combination since the heating value of dehydrated FW is increased, which in turn increases the energy efficiency of the incineration process [26]; this can lead to savings in primary energy demand, fossil fuel depletion, and carbon emissions can be achieved due to energy recovered—however, savings depend on the process efficiency [46,78]. Therefore, for the combined process to be economically viable the energy consumed during the drying process must be compensated by the increased heating value of dried FW during incineration [89]. To reduce energy consumption, dehydrators can be combined with pulpers [30]; this is because the energy consumption and the operational time of dehydrators depend on moisture content and physical properties of FW (e.g., the higher the material porosity, the higher the water amount that is retained) [90]. Dehydrators can be an economically feasible option if the achieved FW weight reduction is ≥53% [91].

On-site IVC offers environmental and financial benefits when technological and logistical requirements (e.g., space, knowledge and skills, and quality assurance of compost) are in place [33,92,93]. During IVC, there are bioaerosol and odour emissions that are typically treated with biofilters by the aeration rate which is a critical parameter associated with odour formation [94]. For example, high aeration rates are associated with NH3 and fungi emissions, while low aeration rates are associated with highly odorous sulphur-reduced compounds and anaerobic bacteria [94]. IVC processes in the UK may operate in an oxygen-limited mode to achieve rapid FW sanitation according to ABPR leading to partially anaerobic conditions and consequently CH_4 emissions in exhaust gases as well as in high levels of odour emission during outdoor compost maturation [94]. Therefore effective odour reduction requires optimal operation of the system consistently for ensuring good aeration levels, monitoring of exhaust gas characteristics (odour concentration and odour compound profile) and temperature, monitoring of biofilter moisture content, back pressure and characteristics of output emissions [94].

4. Discussion

As indicated by the analysis, the sustainability performance of FWM methods shows significant variability [48], while impacts arising from energy and water requirements of FWM methods remain largely underexplored [71]. The evidence collected is based on studies that made assumptions [47] regarding the FW characteristics, stage of collection and transportation, pre-treatment, the way of accounting for the energy recovery and displacement [46], composting emissions, land use application, avoided impacts [52,80], and eco-profiles of end-products [48]. Additionally, the evidence collected also depends on the functional unit; system boundaries [80,95]; and indicators used to measure sustainability [45,48,54,96].

Yet, as validated by the two-tier decision-making framework, off-site FWM systems may outperform on-site FWM processes. Particularly, FWM scenarios with relatively high participation of off-site AD might be beneficial from an environmental and economic perspective [70]. AD can be a less carbon-intensive process for managing FW [49,50,62,77,97–99]; it provides the best carbon return on investment. Carbon return on investment is a metric that shows the carbon savings as a function of the cost of investment among FWM methods [100]. As carbon emissions are highly sensitive to the use of biogas and avoided impacts (carbon savings) from its use [46,55,57,58,64,101], its combustion in CHP units for the generation of heat and electricity that is typically exported to the grid [46,67], may result in significant carbon emissions reduction and financial benefits; this aligns with the UK policy of using 'good quality CHP with high power to heat ratio [55]. Biogas that can be upgraded to biomethane and used as cooking gas or vehicle fuel may provide fewer benefits than its current use due to considerable energy consumption during the upgrading process; however, further research is required to firmly confirm this [67]. Additionally, the future decarbonisation of the UK grid could lower the energy recovery potential of FWM options [70].

Nonetheless, compost's carbon sequestration potential and the limited demand for by-products can make off-site IVC a preferable FWM option compared to AD (e.g., wastewater treatment effluent and digestate dehydration) and incineration (e.g., air pollution control) [50,80]. The partial replacement of synthetic fertilisers with compost could impart a preference for IVC. Using compost can improve crop yield and soil fertility, reduce soil acidification, increase bacterial diversity, reduce N_2O emission due to reduced inorganic nitrogen surplus [102] and improve soil texture and water capacity, and suppress plant disease [103]. Yet, considering that only 19 kg of synthetic fertilisers are avoided by the compost produced via the IVC of 1 tonne of FW, the credits of IVC for displacing the production of artificial fertilisers are low [46].

Evidence on the sustainability performance of on-site systems is very limited [16,104]. There are several concerns about their performance that require more evidence and necessitate careful planning before their installation [24]. The sustainability performance between on-site and off-site IVC remains underexplored. Only one study reported that on-site IVC could return less environmental benefits compared to off-site IVC due to its considerable electricity consumption [105]. The electricity consumption per composted material in a large-scale process (off-site composting) is much lower [105]. From an economic perspective, the cost of compost management does not significantly differ between on-site and off-site IVC. Still, the on-site IVC's compost quality is lesser than that produced off-site and is freely provided compared to off-site compost that is typically sold [105].

Regarding, on-site versus off-site AD both systems perform similarly in terms of outputs (e.g., 220 m^3 biogas/t feedstock with 60.6% CH_4) and energy requirements [106]. From an economic aspect, on-site AD systems are less favourable than off-site ones. Large-scale centralised AD facilities not only have a proven knowledge capacity and technical capability to handle FW and operational challenges, but revenues can compensate for the high capital and operational costs [106,107]. However, AD systems need a relatively homogenous feedstock composition to operate efficiently, a criterion that is more difficult to be fulfilled in on-site systems [12]. Centralised AD facilities have the flexibility to modify feedstock composition to ensure process efficiency and economic feasibility [12]. Furthermore, fugitive emissions arising from AD are more likely to be a problem in small-scale plants [29], e.g., biogas leakage from pipes valves, over-pressure of the system and FW and biogas storage [55]. For example, fugitive emissions ranging from 2 to 5% may increase carbon emissions by 55%, indicating the importance of emission monitoring and control during AD [55].

Yet, on-site processes are more likely to provide environmental benefits if process-related carbon emissions are appropriately managed (i.e., via the proper handling of FW, system operation and end-products storage and use). Of particular interest are the wastewater-based FWM processes (i.e., macerators connected to the drain and biodigesters), of which sustainability depends on whether they shift the burden to the WWTPs, or offer synergistic benefits for both the waste and water industry. Some of the challenges reported include [86,108]:

- potential damage to the sewerage system as an extension of its ability to receive liquefied FW, e.g., the slope of pipework (i.e., smooth slopes inhibit self-scouring velocities leading to organic trapping and degradation, leading to malodour formation and corrosion, and clogging [109]), pipe capacity, the flow rate of water, size/age (i.e., new pipes have greater carrying capacity and smaller friction from water flowing in the pipe, while aged pipes are rougher catching the debris leading to odours and clogs [110]), and pump maintenance and accessibility (i.e., pumps need to be designed with easy access for cleaning and maintenance activities [110]);

- processing efficiency of WWTPs (e.g., flow rates, organic and nutrient removal performance, the capacity of sewage sludge production, available technology for energy recovery) to properly treat liquefied FW [86];
- loss of value (e.g., nutrients, lower biogas generation yield, and fugitive emissions);
- other area-specific features [109], such as weather events and business practices;
- policy drivers for their implementation according to legislative requirements and regulations of local municipalities; and
- costs shifted to municipal ratepayers that bear the added expenses of sewer maintenance and additional treatment [16].

For the rest of the processes, segregation of FW at source maximises the likelihood of valorisation and, thus value recovery. At the same time, it raises awareness of the volume and characteristics of FW generated (incl. composition) that could better inform the selection of the FWM process.

FW prevention may be out of the scope of this work, yet, we must reiterate that this is the most preferable and optimal FWM option; it has been estimated that halving FW between 2016 and 2030 can save 15 times more GHG emissions than the best FW treatment scenario indicating that the improvement of FWM strategies should be accompanied by an effective prevention strategy [70].

5. Conclusions

No single FWM option outperforms all other options across all sustainability impact categories; this could be attributed to limited quantitative and qualitative evidence on the sustainability performance of on-site FWM systems and the fact that FWM options can perform differently in different settings, making it difficult to draw robust conclusions. A bespoke, tailored-based approach is needed to aid the selection of the most sustainable FWM option that is likely to deliver maximum value. Further case study-specific research could shed more light on the potential of different FWM options to return sustainability benefits.

The two-tier decision-making tool developed herein could facilitate the adoption of a tailored approach as it helps those involved and interested in promoting sustainable FWM in their businesses to navigate through the breadth of FWM options and evaluate their feasibility and viability according to area-specific characteristics and circumstances. The criteria used are simple and may be specific to the UK context; still, they are steering and, thus, relevant to other areas making the tool versatile and applicable to other spatial contexts. Local specificities (e.g., waste composition, assurance of processing capacity, logistical characteristics of the region, marketability of end-products), and consideration of existing and planned regulatory requirements (e.g., EPR permit, trade effluent consent, and biogas, digestate and compost quality assurance), space requirements, technical knowledge, support and monitoring are needed to inform the process. Moreover, additional criteria can easily be incorporated into the decision-making framework by those in charge of the selection process to account for context-specificities. Tier 2 can and should, be tailored to specific areas to account for environmental, economic, and social aspects. Therefore, this two-tier framework makes it easy to support the different practitioners' needs and highlights the importance of user-generated evidence. In turn, this emphasises that all stakeholders (i.e., HaFS practitioners, water and waste industry, regulators and policy-makers) participation in decision-making processes is critical. With its proper use, the framework can enable policy development in the food waste management field. Additionally, it can be used as a means to monitor the progress of adopted FWM processes.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/article/10.3390/resources11100080/s1, Figure S1: Research attention to the sustainability assessment of FWM system according to Scopus database following systematic literature searching strategy; 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; Table S2 Operational factors of commercially available on-site FW processing techniques. Adapted by [1]; 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/; 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 the 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); 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].

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