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Spatial and Environmental Requirements for Integrating Decentralised Wet Anaerobic Digestion Systems in Heritage Urban Contexts: George Town, Penang

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ABSTRACT

Integrating decentralised food waste-to-energy (FWtE) systems within heritage urban environments demands alignment between technical infrastructure, spatial feasibility, and conservation responsibility. While decentralised wet anaerobic digestion (AD) systems have been extensively studied from engineering and environmental perspectives, limited research has translated their operational parameters into architectural integration frameworks for heritage adaptive reuse contexts. This study examines the spatial and environmental requirements for integrating decentralised wet AD systems within heritage urban settings, with reference to George Town, Penang. An analytical literature review was conducted to extract and categorise operational and biochemical parameters of wet AD systems, identifying their structural and environmental implications. This was followed by a comparative precedent analysis of three decentralised installations to evaluate spatial configuration, structural loading, and environmental control conditions. Through process-to-space mapping and cross-case synthesis, technical process requirements were translated into architectural integration criteria. The findings reveal consistent functional compartmentalisation across feedstock preparation, digestion, gas handling, energy conversion, and digestate management zones, each imposing specific structural, ventilation, safety, and service access requirements. The study proposes a structured set of spatial and environmental criteria that convert technical process demands into architectural considerations, enabling informed early-stage feasibility evaluation of decentralised wet AD integration within conservation-sensitive urban contexts.

Keywords: *Wet anaerobic digestion, heritage urban context, food waste-to-energy (FWtE), adaptive reuse, spatial and environmental requirements*

1 INTRODUCTION

The growth of food waste in cities due to rapid urbanisation and alteration in consumption habits has placed a growing burden on the available waste management systems. Food waste is one of the leading sources of greenhouse gases in the world, especially when it is disposed of in landfills (Food and Agriculture Organization of the United Nations, 2019; United Nations Environment Programme (UNEP), 2024). Food waste contributes a significant part of municipal solid waste in Malaysia and is still mostly handled by centralised collection and landfill, which leads to environmental overloads and unutilised resource potential (Solid Waste and Public Cleansing Management Corporation, 2022).

This model of linear waste management is particularly problematic in urban settings that have a strong density and a stronger impact on the environment.

In heritage cities like George Town, Penang, these issues are also compounded by conservation policies and high-density urban form. George Town, as a UNESCO World Heritage Site, is also typified by the reuse of the old shophouses to cafes, restaurants, and food-related businesses (George Town World Heritage Incorporated, 2022). Although such functions result in the continuous food waste streams, waste management is still externalised in a way that it further promotes the division of food production and waste recovery in the built environment.

Anaerobic Digestion (AD) system is the most commonly accepted type of food waste-to-energy (FWtE) technology, which has been highly praised due to its environmental advantages and the ability to handle high-moisture organic wastes (Mata-Alvarez et al., 2014; Khalid et al., 2019). Wet AD systems particularly apply to urban food waste since they operate as a slurry-based system, have a compact design, and may be decentralised (Li et al., 2022). The pilot implementation projects indicate that modular wet AD systems can be deployed in urban environments that are limited (Walker et al., 2017; Tiong et al., 2024).

Nevertheless, existing research on AD systems has predominantly focused on technical optimisation, environmental performance, and policy frameworks, with limited attention to their spatial and architectural implications within heritage adaptive reuse contexts. This absence is significant because the integration of decentralised wet AD systems directly affects structural loading, spatial zoning, ventilation requirements, and safety management factors that are critical in conservation-sensitive environments. Without translating operational parameters into architectural criteria, implementation risks structural incompatibility, regulatory conflict, and inappropriate intervention within protected heritage fabric.

The incorporation of decentralised wet AD systems introduces structural, environmental, and operational demands that influence spatial planning and building performance. These requirements are particularly consequential in heritage settings, where conservation principles emphasise minimal intervention, reversibility, and protection of character-defining elements (ICOMOS, 2013). Accordingly, this study examines the spatial and environmental requirements for integrating decentralised wet AD systems in heritage urban contexts, using George Town, Penang as a reference case. By synthesising technical literature and precedent analysis, the study establishes a process-based architectural framework to support feasibility evaluation within adaptive reuse environments.

2 LITERATURE REVIEW

2.1 Food Waste Management in Urban Context

The world has experienced rapid urbanisation as well as shifting consumption patterns, which have aggravated food waste production in urban areas. One-third of the food produced to be consumed by humans is lost or wasted globally, and when disposed of in landfills, these wastes emit a large portion of greenhouse gases (Food and Agriculture Organization of the United Nations, 2019; UNEP, 2024). Food waste represents a significant proportion of the municipal solid waste streams in Malaysia and remains a largely centralised collection and landfill waste management system. It has been reported that food waste in urban Malaysia is over 15,000 tonnes per day and that the largest part of municipal waste streams is organic (Solid Waste and Public Cleansing Management Corporation, 2022). This is a linear approach of waste management whereby mounting pressure is put on the landfill space as well as adding to the emission of methane and the degradation of the environment in the long-term.

The generation of food waste is usually centralised in commercial districts in a dense urban environment which are characterised by restaurants, markets and other food related businesses. In addition to the solid food residues, other related by-products like cooking oil used and organic slurry waste are also sources of environmental pressures when discharged inappropriately. Research in Malaysian urban settings points out that unregulated dumping of food-related waste into the drainage systems are among the factors that lead to blocked drainage systems, breeding of pests and water pollution. An example is an example of a community-based program where 86,000 ml of used cooking oil were collected by 172 households in a variety of urban areas, which demonstrates that despite the scattered but large amount of food-related waste at neighbourhood levels. (Merman et al., 2023).

In heritage cities like George Town, the reuse of historic shophouses into food-based enterprises has contributed to localised food waste generation (George Town World Heritage Incorporated, 2022). Nevertheless, the treatment of waste is externalised to the built environment, which strengthens the separation between consumption and the process of recovery. Such circumstances provide a systemic imperative of decentralised food waste-to-energy (FWtE) plans that can be executed in spaces with a high density of urban environments, especially in small heritage urban areas where infrastructural growth is restrained.

2.2 Decentralised Anaerobic Digestion in Urban Settings

Decentralised FWtE systems have emerged as alternatives to large-scale centralised waste treatment facilities, reducing transportation demands, enhancing local resource recovery, and enabling on-site energy generation by locating treatment processes near waste generation points (Mata-Álvarez et al., 2014). In high-density urban environments, where land availability and infrastructural expansion are constrained, decentralisation offers logistical and spatial advantages over conventional centralised models.

Among FWtE technologies, Anaerobic Digestion (AD) is well established as a biological conversion system that transforms organic waste into biogas and digestate, thereby recovering both energy and nutrient value. Wet AD systems are particularly suited to high-moisture urban food waste due to their slurry-based operation and controlled feeding processes (Khalid et al., 2019). Advances in mobile and containerised technologies have enabled the deployment of small- to medium-scale wet AD systems within compact urban footprints (Li et al., 2022), allowing installation in proximity to commercial food-generating premises.

However, the decentralisation of AD systems fundamentally repositions waste-processing infrastructure from remote industrial zones into the architectural domain of buildings and urban blocks. Unlike centralised facilities, decentralised wet AD systems require integration within existing structural frameworks, mechanical systems, and spatial hierarchies. Their implementation introduces demands related to structural loading, floor slab reinforcement, ventilation routing, fire safety zoning, acoustic control, service circulation, and segregation between technical and public areas.

These requirements expand the role of architects beyond formal or programmatic adaptation to infrastructural mediation. Architects must evaluate spatial allocation, structural feasibility, service integration, conservation compatibility, and regulatory compliance. In heritage urban settings, where adaptive reuse operates under principles of minimal intervention and reversibility, decentralised AD integration must be carefully positioned within non-character-defining zones to avoid compromising significant architectural fabric.

Therefore, decentralised wet AD systems should not be considered solely as environmental technologies, but as embedded building infrastructures whose feasibility depends on architectural planning, structural assessment, and conservation-sensitive design strategies.

2.3 Operational Process of Wet Anaerobic Digestion

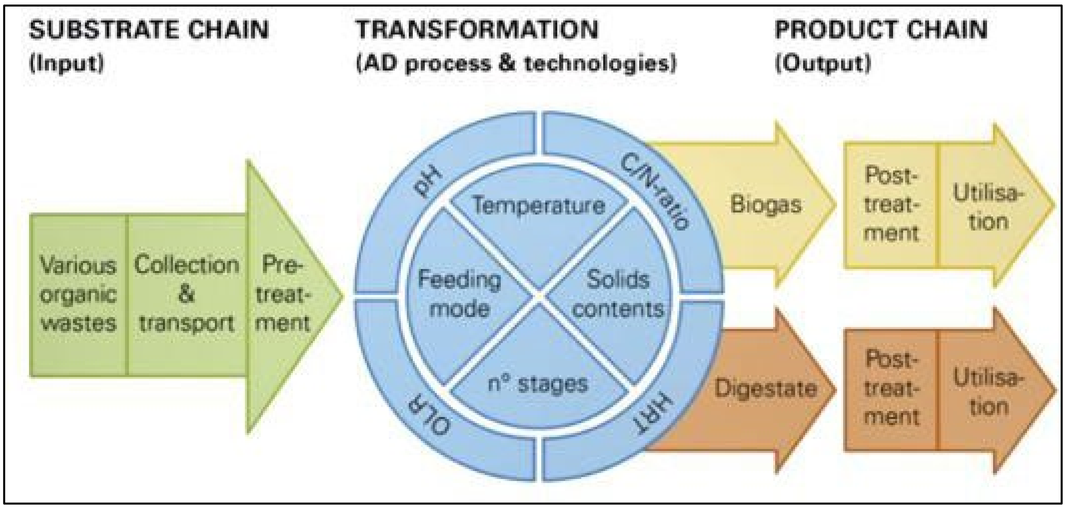


Figure 1 Overview of the anaerobic digestion process showing substrate input, transformation stages, and product outputs.
(Adapted from: Weiland, 2010).

AD is a controlled biological process in which microorganisms decompose organic material in the absence of oxygen, producing biogas and digestate as primary outputs. As illustrated in Figure 1, the AD process can be understood as a transformation chain linking substrate input, biochemical conversion, and product output. (Weiland, 2010; Mata-Álvarez et al., 2014)

2.3.1 Substrate Chain (Input Stage)

The process starts by the collection and preparation of organic waste. Under urban food waste, substrates are usually kitchen and restaurant waste with a high moisture content and a changing composition. The feedstock is pre-treated before the digestion by sorting, shredding, homogenisation and dilution to achieve uniform particle size and formation of slurry. This pre-treatment is essential to enhancing microbial accessibility and stabilisation of feed conditions. (Weiland, 2010; Karki et al., 2021)

2.3.2 Transformation Stage (Anaerobic Digestion Process)

The transformation step takes place in a closed digestion compartment in a non-aerobic environment. It is divided into four main stages of biochemical processes, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In hydrolysis, complex organic polymers are degraded into simpler soluble compounds. These compounds are further transformed into volatile fatty acids, hydrogen and carbon dioxide by acidogenesis and acetogenesis. The last stage involves the use of the methanogenic microorganisms to convert the intermediate products into methane rich biogas. The efficiency and stability of the digestion process are governed by several operational parameters, as indicated in Figure 1:

1. Temperature: Wet AD systems typically operate within the mesophilic range (approximately 30–40°C), requiring relatively stable thermal conditions.
2. Potential of Hydrogen (pH): Optimal methanogenic activity occurs within a neutral pH range (approximately 6.5–7.5).
3. Carbon-to-Nitrogen (C/N) ratio: A balanced carbon-to-nitrogen ratio supports stable microbial metabolism.

4. Hydraulic Retention Time (HRT): Determines the duration of substrate residence within the reactor.
5. Organic Loading Rate (OLR): Influences microbial activity and gas production rate.
6. Solids content and feeding mode: Affect reactor configuration and mixing requirements.

These parameters directly inform reactor design, equipment configuration, and environmental control requirements (Weiland, 2010).

2.3.3 Product Chain (Output Stage)

Biogas and digestate are the major products of wet AD (Weiland, 2010). Biogas generally comprises of methane (CH_4) and carbon dioxide (CO_2) and might need purification prior to use (Mata-Alvarez et al., 2014). It can be applied as a generator of electricity, as producing heat or as a combination of heat and power (CHP). The remaining semi-liquid by-product, called digestate, can be subjected to post-treatment and then used as a fertiliser or soil amendment (Khalid et al., 2019).

2.4 Urban Heritage Conservation Principles and Regulatory Context in George Town

Heritage urban areas represent layered cultural landscapes in which architectural fabric, spatial morphology, and socio-economic activities collectively contribute to cultural significance. In UNESCO-designated sites such as George Town, conservation extends beyond individual monuments to encompass streetscape continuity, scale, material authenticity, and intangible heritage practices (George Town World Heritage Incorporated, 2022).

International conservation doctrine, particularly the Burra Charter developed by ICOMOS (2013), establishes key principles including minimal intervention, retention of significant fabric, compatibility of new additions, and reversibility of change. These principles recognise that transformation within heritage environments is not prohibited; rather, it must be carefully managed to safeguard authenticity and integrity while accommodating contemporary needs.

Within George Town World Heritage Site, these international principles are operationalised through a structured governance framework administered by the Penang State Government, the George Town World Heritage Incorporated, and the Penang State Heritage Department. Development control is guided by the Special Area Plan (SAP) for George Town, which outlines conservation and alteration guidelines for buildings within the Core and Buffer Zones.

Although particular technical standards depend on the typology of the building and the conservation level, the heritage control systems in George Town typically demand that new insertions do not cause an irreversible change of the meaningful fabric, do not impose a significant visual impact on primary facades, and do not cause compatibility with the existing urban scale and materiality. Mechanical and service installations will be thus incorporated in a way that does not hurt streetscape integrity and architectural authenticity.

Structural modifications within heritage buildings may be feasible through the introduction of supplementary support systems; however, such interventions must be carefully evaluated to maintain the integrity and reversibility of significant fabric. Accordingly, the integration of decentralised infrastructural systems in heritage settings must operate within clearly defined conservation parameters, balancing technical feasibility with regulatory and ethical responsibilities.

2.5 Adaptive Reuse and Circular Urban Metabolism

Adaptive reuse has emerged as a central strategy in contemporary heritage conservation, extending the functional lifespan of historic buildings while reducing demolition waste and embodied carbon loss. Rather than replacing obsolete structures, adaptive reuse reprogrammes existing fabric to accommodate evolving socio-economic functions, thereby sustaining both cultural value and environmental performance (Bullen & Love, 2011).

In the context of sustainability, adaptive reuse is closely related to the principles of the circular economy that emphasises the preservation of resources, their reuse, and the regeneration of value instead of the extraction and disposal of resources (Geissdoerfer et al., 2017). In these regards, adaptive reuse can be seen as a kind of architectural upcycling, in which already existing built resources are revalorised and re-integrated into current urban metabolism, instead of being taken out of it.

The concept of urban metabolism further frames cities as systems of material and energy flows, in which waste streams represent potential resource inputs rather than terminal outputs (Kennedy et al., 2007). This perspective becomes particularly relevant in George Town, where historic shophouses and colonial-era buildings have been adaptively reused as restaurants, cafés, boutique hotels, and food-oriented commercial enterprises. These programmes generate continuous streams of organic waste, revealing an overlooked metabolic dimension within heritage districts.

AD is also a material upcycling process involving production of biogas and digestate out of organic waste. The comparison of the spatial upcycling (reuse of historic structures) with the material upcycling (reuse of food waste into energy) implies a consistent cyclical reasoning of the urban system. Nevertheless, in contrast to traditional building services, wet AD systems are managed technical infrastructure with specified spatial, structural and environmental imperatives.

The question is not whether adaptive reuse and decentralised AD are conceptually aligned however, but how infrastructural systems can be brought in as reversible and conservation-friendly layers in heritage buildings. The decentralised AD systems can also add to the circular urban metabolism without compromising the heritage integrity when properly incorporated in the non-character-defining spaces and appropriately supported by the structural and environmental controls.

2.6 Selection and Overview of Decentralised Wet Anaerobic Digestion Precedents

To examine the operational and spatial characteristics of decentralised wet AD systems in dense urban environments, three decentralised precedents were selected: the SEaB Flexibuster™ system, the Singapore Hawker Pilot system, and the Camley Street micro-scale AD facility in London. These precedents were chosen based on three criteria:

1. Decentralised deployment,
2. Availability of documented operational and spatial configuration data,
3. Implementation within constrained urban settings.

2.6.1 SEaB Flexibuster™

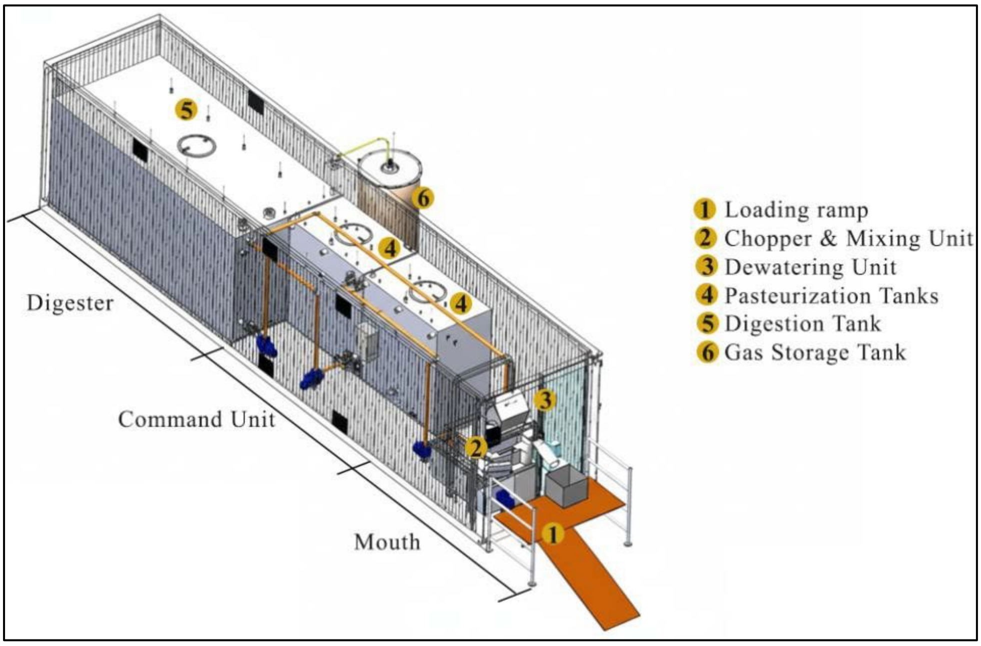


Figure 2 Spatial configuration of the SEaB Flexibuster™ containerised wet AD system (Adapted from: SEaB Energy, 2020).

SEaB Flexibuster^{TM} is a containerised wet AD system that is used to treat food waste in a decentralised, on-site manner. The system is spatially structured in a typical container module in a linear sequence of processes as shown in Figure 2. The setup starts with a loading ramp to a chopper and feedstock preparation mixing unit, dewatering and pasteurisation tanks. The main digestion tank is located in the middle of the container, and gas storage components are located at the end of the module. This structure depicts process-based zoning and safety distance on a small footprint.

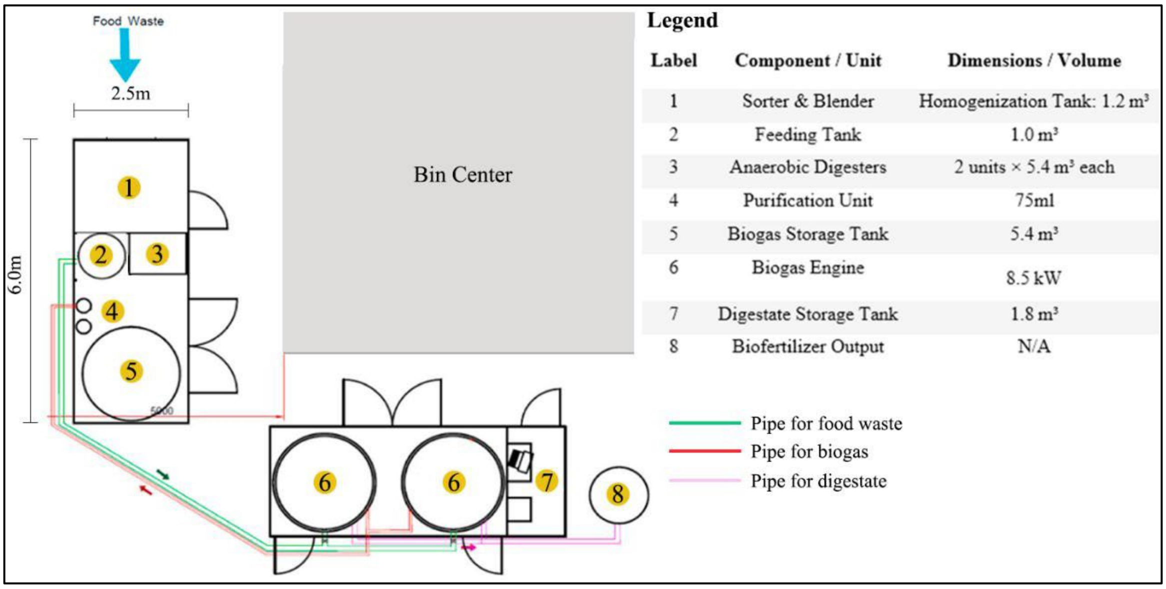
With a remotely monitored automated process of combining grinding, controlled feeding, AD and pasteurisation, the system transforms some 500-3000 kg/day of food waste into electricity, heat and digestate. The system can be run under mesophilic conditions with an approximate hydraulic retention time (HRT) of around 15-20 days, and it occupies about 20-40 m2 per container unit. The most important structural element of the module is the digestion tank, whereas the gas storage units must be enclosed and separated because of the generation of methane.

Figure 3 On-site Implementation of the SEaB Energy Flexibuster™ Wet AD System at a Continente Supermarket, Portugal.
(Source: SeaB Energy website, 2020)

The technology has been adopted in commercial purposes where it has been installed in the Continente supermarket in Portugal (Figure 3) where it takes food waste produced in the supermarket and turns it into electricity and heat which is used in the same supermarket. This is a closed-loop design that minimizes the use of external waste transport and allows on-site recovering of resources based on small commercial footprint. (SEaB Energy, 2020).

2.6.2 East Coast Lagoon Food Village (ECLFV), Singapore

Figure 4 Associate Professor Tong Yen Wah, who leads the NUS team, is pictured next to the anaerobic digester at the East Coast Lagoon Food Village.
(Source: News@NUS, 2024).



Legend

Label	Component / Unit	Dimensions / Volume
1	Sorter & Blender	Homogenization Tank: 1.2 m^3
2	Feeding Tank	1.0 m^3
3	Anaerobic Digesters	2 units × 5.4 m^3 each
4	Purification Unit	75ml
5	Biogas Storage Tank	5.4 m^3
6	Biogas Engine	8.5 kW
7	Digestate Storage Tank	1.8 m^3
8	Biofertilizer Output	N/A

Figure 5 Layout plan of the Singapore Hawker Pilot wet AD system.
(Adapted from: Tiong et al., 2024).

This Singapore Hawker Pilot system (Figure 4) represents a wet AD application which is decentralised and installed in a working urban hawker centre with about 60 food stalls that produces about 150 kg of food waste in a day. The system will be located next to the current bin centre such that the food waste can be collected and processed in the same commercial area.

As shown in Figure 5, the installation is modularised into two containerised modules which harbour the sequential steps of feedstock preparation, digestion, gas storage and energy conversion. The set up combines pre-treatment modules, closed digestion systems, gas management systems, and a biogas engine into a small service base. The spatial design is a linear process flow that is clearly functional with wet-processing areas and gas-handling clearly segregated.

The system is meant to handle mixed food waste produced by the hawker stalls, and it is operated under mesophilic conditions. Digestion of biogas is transformed into electricity and used to operate the facilities of the community in the hawker centre such as outdoor fans and mobile charging points. This arrangement is an example of a closed-loop model where food waste that is produced as a result of commercial affairs is processed into usable energy in the same urban environment. (Tiong et al., 2024)

Overall, the pilot installation illustrates the feasibility of decentralised wet AD deployment in dense commercial environments, particularly where food waste generation is concentrated and spatial integration must occur within constrained service areas.

2.6.3 Camley Street Micro-Scale AD Facility (London, UK)

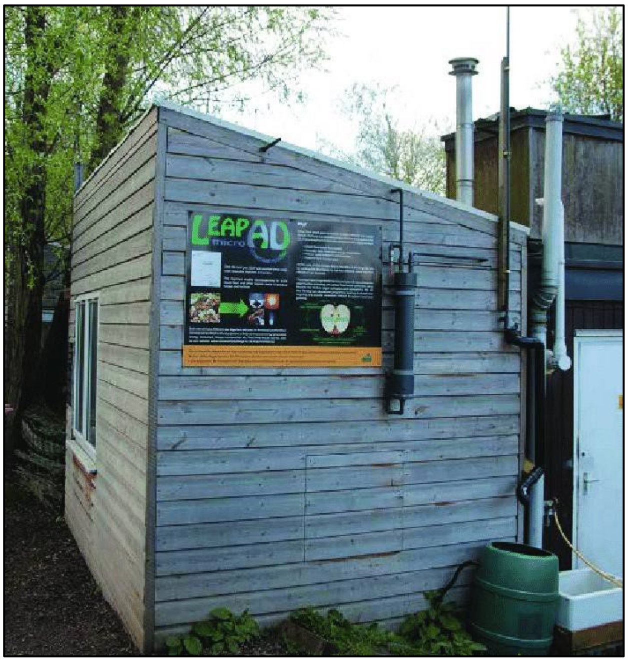


Figure 6 Camley Street Park, London (UK): Building hosting the micro-scale AD facility (Source: Pracucci & Zaffagnini, 2019).

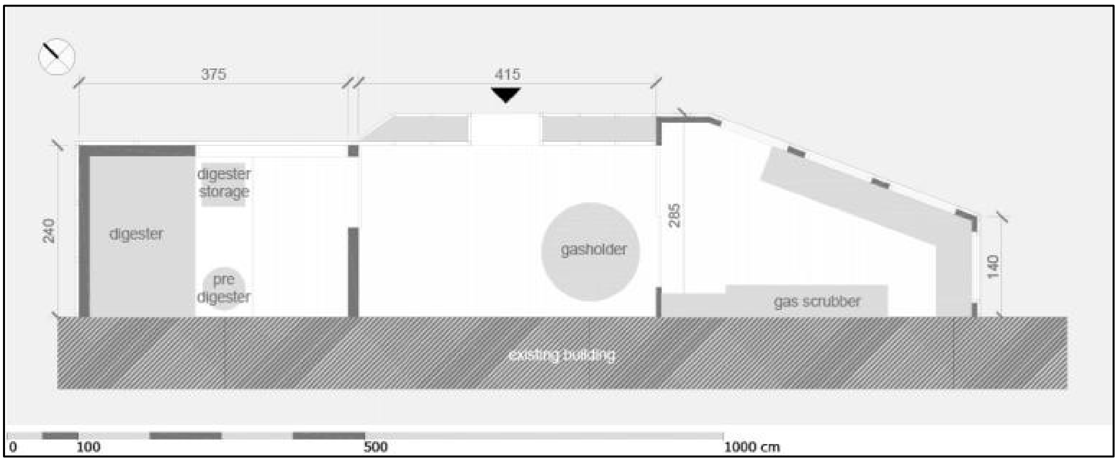


Figure 7 Layout plan of the Camley Street micro-scale anaerobic digestion facility. (Adapted from: Pracucci & Zaffagnini, 2019).

The Camley Street micro-scale AD plant in London (Figure 6) is a small-scale urban application in the form of a pilot installation monitored. This project, unlike a containerised commercial system, was an experimental demonstration of the concept of decentralised digestion on a limited urban site, which investigated the technical feasibility of recovering organic waste at the neighbourhood scale.

The system was fitted into the current site boundary and was arranged in sequential stages as shown in Figure 7 as primary digestion, gas storage, gas treatment and digestate handling. The small-scale layout is indicative of the linear process logic of wet AD systems but accommodates the space constraints of inner-city settings.

Over a 319-day monitoring period, the facility digested 4,574 kg of organic waste, and the average daily feed rate was about 14.3 kg/day. The documented hydraulic retention time was about 127.2 days which indicated low organic loading rates which is characteristic of micro-scale systems. These small-scale digesters are generally well adapted to small organic feeds and have low spatial demands with footprints that may vary between about 5-15 m 2 depending on the design. (Pracucci & Zaffagnini, 2019)

The biogas produced by the system was used in the local community cafe on site to cook and heat food, which was an example of direct localised energy recovery. Even though of limited scale, the pilot installation demonstrated empirically that even micro-scale wet AD systems can be run steadily in dense urban settings, when managed properly.

The Camley Street project therefore illustrates the experimental potential of decentralised digestion as a community-level waste management strategy, particularly in sites where organic waste volumes are relatively low but spatial constraints are significant.

Collectively, these precedents illustrate that decentralised wet AD systems can operate across varying scales while maintaining compartmentalised process zoning and controlled operational environments. These characteristics provide the empirical basis for analysing the spatial, environmental, and operational requirements of integrating decentralised wet AD systems within heritage urban contexts. (Walker et al., 2017).

3 METHODOLOGY

3.1 Research Design

This study adopts a qualitative analytical approach to examine the spatial and environmental implications of decentralized wet Anaerobic Digestion (AD) systems within heritage urban contexts. The research is structured in two sequential stages:

1. Literature-based analytical review of wet AD operational processes,
2. Precedent study examination of decentralised wet AD implementations.

This multi-layered approach allows technical process requirements to be translated into architectural and environmental criteria relevant to adaptive reuse settings.

3.2 Literature-Based Analytical Review

A structured review of academic and technical literature was conducted to synthesise the operational processes and technical parameters of wet AD systems. The review focused on:

- Process stages (feedstock preparation, digestion, gas handling, digestate management)
- Reactor configuration and scale
- Temperature requirements (mesophilic range)
- Moisture characteristics of urban food waste
- Gas production and safety considerations

The objective of this analysis was to establish the technical and biochemical basis that determines spatial and environmental requirements for decentralised wet AD integration within existing buildings.

3.3 Precedent Study Analysis

To examine spatial configuration in real-world deployment, three decentralised wet AD implementations were analysed. The cases were selected based on the criteria outlined in Section 2.6, including documented decentralised deployment, availability of spatial and technical configuration data, and implementation within constrained urban environments comparable to heritage settings.

The selected precedents represent variation in operational scale and typological context, encompassing containerised commercial systems, modular community-based installations, and micro-scale neighbourhood applications:

- SEaB Flexibuster™ containerised system
- East Coast Lagoon Food Village (ECLFV) modular pilot system (Singapore)
- Camley Street Micro-AD facility (London)

Layout diagrams, volumetric capacities, equipment dimensions, and structural loads were examined to identify:

- Functional zoning
- Spatial sequencing
- Structural implications
- Environmental control requirements

Cross-case comparison revealed consistent process-based compartmentalisation and spatial logic across varying scales and contexts. The recurrence of these patterns provided sufficient analytical depth and conceptual saturation to synthesise architectural integration criteria applicable to decentralised wet AD systems within heritage urban environments.

3.4 Integrated Spatial Synthesis

The literature-based analytical review and precedent analysis findings were integrated to come up with architectural spatial, environmental, and operational requirements. The synthesis codes the process based technical requirements into architectural requirements that can be applied to heritage adaptive reuse situations, specifically the spatial attributes of George Town, Penang.

4 RESULTS AND DISCUSSION

4.1 Integrated Spatial Synthesis

According to the literature analytical review, the urban food waste is highly moist and constantly generated, which means that wet Anaerobic Digestion (AD) is especially consistent with this type of waste. The wet AD systems are slurry-based processing and mesophilic and can be deployed in a decentralised manner in a modular or containerised system.

The analysis of precedents demonstrates that decentralised wet AD systems can be accommodated within compact urban footprints, without requiring extensive industrial-scale spatial allocation. The modular design of all the systems analysed provides integration in service domains of the existing buildings. These results indicate that wet AD can be technically applicable in decentralised food waste management in dense heritage urban areas, provided that the spaces and structures are viable.

4.2 Operational Process and Spatial Configuration

Across all precedents, wet AD systems exhibit consistent functional compartmentalisation into five primary zones:

1. Feedstock intake and pre-treatment
2. Digestion chamber
3. Gas handling and storage
4. Energy conversion (where applicable)
5. Digestate management

Sequencing of these zones indicates the route of transformation of organic waste starting with input of substrates to the production of energy and release of by-products. In precedents, the spatial organization is impacted by operational logic, safety demands and equipment specification. The feedstock intake and pre-treatment zone is always at the start of the order and comprises of shredding, homogenisation, or controlled feeding units. The digestion chamber is the centre of the system and usually takes up the greatest spatial and structural area. Gas handling and storage areas are separated into wet-processing areas, which implies safety-based spatial compartmentalisation. Energy conversion units are situated in service-based plant areas that need ventilation and acoustic management whereas the digestate storage is at the end of the process flow that can be removed under control.

The documented spatial and technical characteristics of each zone across the selected precedents are summarised in Table 1.

Table 1 Process-Based Spatial Characteristics of Selected Decentralised Wet AD Precedents

Operational Zone	SEaB Flexibuster™	ECLFV (Singapore)	Camley Street Micro-Scale AD Facility (London)
Feedstock Intake & Pre-treatment	3.1m container intake module	1.2m³ homogenisation tank, 1.0m³ feeding tank	Breaker mill for size reduction
Digestion Chamber	6.1m container, structural loads up to 24,000kg	Dual 5.4m³ digesters	2.0m³ and 0.65m³ digesters in enclosed chamber
Gas Handling & Storage	Integrated gas storage tank separated from digestion zone	Gas purification unit, 5.4m³ gas storage	Dedicated gas holder separated from digester
Energy Conversion (CHP)	On-site electricity & heat generation	8.5kW biogas engine	Biogas used directly in community cafe
Digestate Management	Output digestate tank with controlled discharge	1.8m³ digestate storage tank	Post-treatment and controlled removal

(Source: Omar Bakhri, 2026)

The recurrence of these compartmentalized areas in all the precedents proves that wet AD systems are controlled service infrastructure and not integrated habitable space. Process needs, equipment size, and safety are the major factors that define spatial organization as opposed to architectural flexibility. This consistent operational configuration provides the empirical foundation for synthesising spatial, environmental, and operational requirements in the subsequent section.

4.3 Synthesised Spatial, Environmental and Operational Requirements

Based on the reported spatial arrangement revealed in Section 4.2 and the operation parameters elaborated in Section 2.3, an integration of decentralised wet AD systems can be synthesised into three main requirement categories, namely spatial, environmental, and operational. These are not arbitrary architectural choices but are directly based on the conditions of the processes, equipment sizes and safety considerations of wet AD systems.

Spatial demands are found mainly due to the size of the reactor, structural loading and the sequence of the processes. The digestion chamber is always the most structurally challenging part where the reinforced floor slabs are used, and the foundations are to be stable to take the weight of a tank and dynamic loading during the mixing process. Pre-treatment areas require sufficient clearance of mechanical equipment and direct access of service to daily feedstock delivery. The compartmentalisation across zones implies both the functional and safety aspects.

The biochemical stability of wet AD processes and associated gas management conditions determine key environmental requirements, including thermally stable enclosures for mesophilic digestion, controlled ventilation, gas detection systems, and fire-rated separation of gas handling areas. Wet-processing spaces also require drainage systems and moisture-resistant finishes to maintain hygiene and prevent material degradation. These environmental demands are closely linked to operational requirements derived from the linear sequence of waste input, biological transformation, energy conversion, and digestate discharge. Safe and continuous operation necessitates clear circulation pathways, restricted access to technical zones, and buffer spaces for feedstock and digestate management. The integrated architectural implications of these environmental and operational requirements are summarised in Table 2.

Table 2 Synthesised Spatial and Architectural Requirements for Decentralised Wet AD Systems

Operational Zone	Integrated Architectural Criteria
Feedstock Intake & Pre-treatment	Enclosed wet-handling room; floor drainage, washable non-porous finishes, direct service access, buffering space, separation from public areas
Digestion Chamber	High load-bearing slab, stable foundation, insulated enclosed chamber, maintenance clearance, restricted access
Gas Handling & Storage	Mechanical ventilation, methane detection, fire-rated enclosure, safety clearance buffer; separation from wet zone
Energy Conversion (CHP)	Ventilated plant-room environment, acoustic mitigation, exhaust routing, integration with building MEP systems
Digestate Management	Floor drainage, moisture-resistant surfaces, containment edge, proximity to service exit, controlled handling zone

(Source: Omar Bakhri, 2026)

Collectively, the synthesis demonstrates that wet AD systems function as controlled technical infrastructure embedded within the built environment. Their architectural integration depends on accommodating structural loads, environmental control systems, and operational circulation patterns rather than aesthetic adaptation alone.

4.4 Discussion: Implications for Heritage Urban Integration

The findings show that the wet AD systems can technically be applied in the decentralised urban context, but their integration into the heritage context is heavily limited by building typology and structural capacity, as well as operational scale. In George Town where adaptive reuse of old buildings into food related programmes is becoming a common practice, the viability of wet AD systems needs to be evaluated in terms of spatial practicality as well as conservation constraints.

While food-oriented adaptive reuse generates consistent organic feedstock, spatial and structural characteristics vary considerably across heritage typologies. Traditional shophouses, which constitute a substantial portion of the historic urban fabric, typically feature narrow structural bays, limited-service zones, and timber upper-floor systems. The structural demands of containerised digestion modules may exceed the load-bearing capacity of upper floors, thereby restricting installation primarily to reinforced ground-level areas or secondary service spaces. Structural assessment therefore becomes a prerequisite for implementation within adaptive reuse projects. Such interventions must also align with conservation principles of minimal intervention and reversibility, as discussed in Section 2.4, ensuring that supplementary structural systems do not compromise character-defining fabric or permanently alter significant spatial configurations.

In addition to the structural issues, the compartmentalised and service-oriented structure of wet AD systems has an additional impact on spatial suitability. The separation between feedstock handling, digestion, gas storage, and energy conversion areas, which are required, are more compatible with back-of-house areas like rear yards, internal courtyards, or ancillary rooms compared to the main heritage interiors. This makes integration strategies to focus on non-character defining spaces to maintain architectural importance and allow infrastructural improvements. This supports the governance-based solution integrated into the Special Area Plan (SAP) according to which the new service insertions are supposed to be aesthetically secondary and spatially compliant in the heritage environment.

Operational scale introduces an additional layer of feasibility. Even though small micro-scale systems can be physically fitted into smaller heritage buildings, processing can be too small to produce significant energy recovery or even digestate reuse. The limited spatial capacity and relatively low waste volumes at single-shophouse scale may reduce operational effectiveness.

However, in comparison, bigger food-based typologies like public markets, food courts, hawker centres, and shopping complexes provide a more feasible setting to the decentralised wet AD integration. The typologies generate more consistent and substantial organic waste streams, offer stronger structural frameworks, and have less ambiguous service zoning. The concentration of wet AD systems in these environments will maximize resource recovery and minimise intrusive intervention to sensitive heritage interiors.

Operational logistics must also be carefully planned to ensure continuity within dense urban environments. Feedstock collection, maintenance access, and digestate removal should be coordinated through service circulation routes that do not disrupt pedestrian movement or compromise the visual integrity of heritage streetscapes. Integration therefore depends on synchronising technical infrastructure with existing spatial hierarchies and conservation priorities.

From a circular urban metabolism perspective (Section 2.5), decentralised wet AD integration represents a potential re-internalisation of waste recovery within adaptive reuse typologies. However, such metabolic closure must be balanced against conservation responsibility, indicating that sustainability objectives alone cannot supersede heritage protection imperatives.

Taken together, these results indicate technical compactness alone does not determine integration feasibility in heritage settings. Instead, successful implementation depends on aligning infrastructural demands with building typology, operational viability, and conservation requirements. Interdisciplinary and context-specific approaches to placement are thus necessary in order to reconcile sustainability goals and heritage protection.

5 CONCLUSION

This study examined the spatial, environmental, and operational implications of integrating decentralised wet anaerobic digestion (AD) systems within heritage urban contexts, using George Town, Penang as a reference case. Through analytical literature review and comparative precedent analysis, the findings demonstrate that while decentralised wet AD systems are technically viable for urban food waste recovery, their architectural integration depends on typological scale, structural capacity, and environmental control constraints. By translating operational parameters into spatial and environmental criteria, the study develops a set of spatial and environmental criteria to support conservation-sensitive integration and early-stage feasibility evaluation within adaptive reuse settings.

The findings reveal that wet AD systems function as compartmentalised service infrastructure requiring structural reinforcement, environmental control, and clear zoning separation. In heritage settings characterised by adaptive reuse, integration feasibility varies significantly across building types. Smaller shophouse typologies may face structural and spatial constraints that limit operational efficiency, whereas larger food-oriented sites such as markets, food courts, and hawker centres offer more viable conditions for decentralised deployment.

This study contributes to bridging the gap between technical food waste-to-energy (FWtE) research and architectural conservation practice by translating operational parameters into spatial criteria relevant to adaptive reuse contexts. It emphasises that successful integration is not merely a matter of technological compactness, but of aligning infrastructural demands with building typology, urban scale, and conservation responsibility.

5.1 Limitations

The research is limited to literature review and documented precedent analysis. No on-site structural assessment or simulation modelling was conducted for specific buildings in George Town. Operational data were derived from published case studies rather than primary measurements. Therefore, conclusions remain conceptual and indicative rather than implementation specific.

5.2 Recommendations for Architectural Practice

Architects involved in adaptive reuse projects should evaluate decentralised FWtE system integration at early design stages, particularly in relation to structural capacity, service routing, and ventilation systems. Installation should prioritise non-character-defining zones and back-of-house areas to safeguard heritage value while accommodating technical infrastructure.

5.3 Recommendations for Policy and Heritage Governance

Heritage governance frameworks may benefit from developing technical guidelines that support the integration of sustainable infrastructure within protected urban areas. Clear regulatory pathways for structural reinforcement, mechanical systems, and fire safety upgrades would facilitate environmentally responsive retrofitting while preserving architectural integrity.

5.4 Future Research

Future research may include structural feasibility assessments of specific heritage typologies in George Town, pilot implementation studies within larger food-based adaptive reuse sites, and lifecycle performance evaluations of decentralised wet AD systems in heritage contexts. Empirical case implementation would provide further validation of the spatial criteria developed in this study.

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All authors played equal contributions towards the production of this paper.

CONFLICT OF INTEREST

The author declares no potential conflict of interest with respect to the research, authorship, and/or publication of this article.

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