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Title: Emerging perspectives on environmental burden minimisation initiatives from anaerobic digestion technologies for community scale biomass valorisation

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Abstract

This paper provides an extensive review of anaerobic digestion (AD) systems, with a specific focus on community scale digesters for urban applications, processing either municipal organic waste exclusively or as mix feed. Emphasis is placed on reducing the systems scale environmental impact of AD technologies, including pre- and post-treatment stages, alongside biogas production. Developments to-date in AD system research in Europe and in the Asia region have been compared, providing a comprehensive evaluation of current practice, elucidating the areas of further potentials.

The scope of this review is two-fold – one, covering AD technologies including a cohort of simple and integrated wet and dry systems, which can be operated as continuous flow designs in single- or multi-stages. Two, focusing more on practices in digestate handling that minimise environmental impacts arising from their storage and land application. From an environmental perspective, we note the following trends emerging in the literature for processing urban waste that need further exploitation: dry AD (60-85% moisture) is suitable for low organic loads, mainly owing to resource savings in terms of water usage; co-digestion has shown better buffering capability, especially for two-stage digestion of food-based feed stocks; separating the digestate into liquid/solid fractions is effective for handling post-digestion emissions, mainly for mitigating ammonia volatilisation to air and phosphate leaching to soil.

We report responses to a survey, conducted for this review, highlighting the contemporary issues and challenges - with particular focus on the operational, social and management issues from an Indian perspective. There is need for follow-up of running plants to ensure their environmental performance. Such initiatives will have to consider managing of pollution footprints from AD, alongside the current drive for its widespread implementation for two incentives: greenhouse gas mitigation and fossil-fuel independence.

Keywords: *ammonia; anaerobic digestion; digestate; environmental burden; life cycle assessment; valorisation*

Highlights:

- Potentials for enhancing environmental sustainability of anaerobic digestion covered.
- Recent developments in burden minimisation from AD process to soil and water discussed.
- Taxonomical characteristics of AD environmental management practices considered.
- State of the art in AD operation in Europe and in the Asia region compared.
- Interventions for reducing environmental burdens from food waste AD system proposed.

Contents

1. Introduction

1.1. Anaerobic Digestion – an emerging model for community scale renewable energy sustainability

Mounting organic waste, produced mainly from ever-increasing human activities in confined urban settings globally, has put immense pressure on land and civic resources. As a consequence, modern infrastructure planning is increasingly yielding to development of inclusive, self-sustaining cities through adoption of a systems approach to integrated solid waste management - for both increased fuel security and better utilisation of waste [1, 2]. A recent study [3] introduced the concept of a Biomass Energy Conversion Park, and conducted a techno-economic evaluation of potentials for an integrated system of conversion technologies, primarily focussing on anaerobic digestion (AD). Over the years, AD has emerged as a new model in biomass valorisation and in the European Union (EU), for example, it is attracting increasing levels of investment, primarily driven by current issues such as global warming, demand for renewable energy, landfill tax on organic waste, demand for organic fertiliser, high fossil fuel prices, pollution of the environment and legislation relating to the treatment and disposal of organic wastes [4]. Subscribing to this notion, life cycle assessment (LCA) of different waste disposal strategies for utilisation of the organic fraction of the MSW (OFMSW[1]) have shown AD as inducing significant resource savings [5] and being the most environmentally favourable solid waste management option in terms of both greenhouse gas (GHG) saving and environmental toxicity to the terrestrial and aquatic environments when compared to aerobic composting, incineration or landfilling [6-9]. Further, AD has additional attributes, making it worthy of promoting renewable energy sustainability when compared to other bioenergy conversion technologies – a) it does not consume oxygen; b) has lower nutrient requirements and; c) it generates energy carrier (i.e. methane) through non-destructive means and enables reuse of the residual biomass in agriculture. Revenues for anaerobic digesters can come from energy (gas, heat, and electricity), tipping or service fees (landfill disposal offset), secondary products (digestate, liquid fertiliser, and feedstock for downstream processes), carbon offset credits, and government incentives (renewable energy tax credits and price supports).

AD of urban organic waste, typically comprising of OFMSW, waste oils and animal fat, energy crops and agricultural waste, manure and sewage sludge, has been reported to offer a positive valorisation pathway [10] with an overall positive balance (0.67MJ primary exergy inputs from nature per MJ electricity if heat is used and 0.86 MJ primary exergy inputs from nature if heat is not used [5]. Bio energy from AD has been considered as a dominant future renewable energy source, providing a steady supply of heat and power all the year round (*quasi* based load for a thermal power station on a fossil grid). The methane produced can even be stored in gasometers, and can be pumped, after some

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[1] OFMSW is defined by the European Commission as ''biodegradable park and garden waste, food and kitchen waste from household, restaurants, caterers and retail premises and comparable waste from food processing plants''[103].

further purification, into gas distribution systems as part of the renewable heat incentive[2] [11]. AD of bio-degradable organic residues (crop/animal/food) has been considered vital as a 'closed-nutrient cycle' system (i.e. where nutrients are not lost but re-utilised in the food cycle) along with recovery of bioenergy (**Fig 1**) [12]. This is an economic edge of AD over conventional aerobic systems, currently in operation for processing biodegradable waste, thereby offering authorities a multi-purpose technology option for fulfilling a cluster of policy needs [4]. Besides, it has potential buy-ins from small-scale industries by avoiding huge investments in managing their waste streams via discharge to Common Effluent Treatment Plant (CETP) facilities (or solid waste incineration), while offering energy recovery options.

1.2. Lateral issues of environmental concern for OFMSW digestion

The majority of AD literature to-date reports innovations in the following two areas from the view point of technology fool proofing - biogas production, primarily enhancing the energy conversion efficiency [13-16]; and, attaining process stability, either through process intensification [17-19] or through co-digestion using a combination of feedstock [20-24]. Evaluation of the environmental performance of these systems with due consideration to the lateral emissions (mainly discharge to air and water) is not extensively covered in the literature. For example, there is presently a lack of knowledge about the environmental impacts (typically for elevation in N-compounds, e.g. ammonia) of mixing of high energetic feedstocks during co-digestion - for example, OFMSW with animal manure [22, 25]. Given renewable energy production in the European Union, for example, is targeted to reach 20% of total energy production by 2020 [26] insight into environmental consequences of this transition is imperative [21]. The impact of AD on air quality can be at different stages – effluent storage and/or subsequent manure application on land. Apart from the greenhouse gas components (CH_4. N_2O and CO_2), the main constituents of AD operation for air quality implications are NH_3, N_2, H_2S, VOC emissions and for leaching to ground water through soil are PO_4^{3-} and NO_3^- (**Fig 2**). The emissions contributions from individual stages of AD and their interactions are described in more detail in **Section 2**.

AD has been considered a proven technology for stabilizing the OFMSW [27, 28]. However, typical OFMSW is high in proteins and amino acids that are transformed into ammonia-N (NH_3-N) through the ammonification process during AD. This gets aggravated during co-digestion with waste from food processing and slaughter houses [19, 29]. On average, an AD plant with 500 kW power generating capacity yields over 10,000 t of digestate per year with a dry matter content of about 10% [30, 31]. Its main components are water, nitrogen in ammonium form, phosphorus, potassium, magnesium, calcium, and non-decomposed lignocelluloses. For example, typical anaerobically

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[2] The Renewable Heat Incentive offers financial support for 20 years for biomethane injected into the gas grid at all scales, as well as heat produced from biogas plants with a thermal capacity up to 200 kW [11].

fermented pig slurry consist of (per l) 595 mg NH_4^+, 755 mg PO_4^{3-}, and 1.1–1.25 g K_2O [32]. An environmental impact assessment of digestate application has shown that it is a rich source of nutrients with often high dry matter content, making it useful as a fertilizer, but at the same time also inducing risks of pollution [4]. Digestate application on fields has been shown to enhance acidification and eutrophication potentials [5]. Acidification is mainly caused by ammonia emissions during application, while marine eutrophication occurs when nitrate leaks to the groundwater. Freshwater eutrophication is mainly caused by diammonium phosphate production. Ozone depletion and photochemical oxidant formation are mainly caused by transport, which results in the highest impact for the organic waste digestion due to a transport intensive waste collection step.

In principle, through technological advances informed by a whole system understanding, environmental burdens from enhanced acidification and methanation stages of OFMSW in an AD system, either on its own or as mixed substrate (i.e. material input to digester) during co-digestion, can be evaluated (see **Section 3.1**). However, as AD is primarily a bio-chemical procedure for conversion of multifarious substrates (i.e. organic feedstocks) with a diverse range of input nutrients and organic contents, this raises enormous challenges to efficient nutrient management – both during biogas production and during subsequent re-use of digestate (the nutrient rich slurry produced as a combination of liquor and solids, depending on the AD system). This is owing to many factors, such as public acceptance, input of pollutants, overload of nutrients and organisational as well as infrastructural constraints.

AD of OFMSW is generally a more energy intensive operation compared to the corresponding facility using agricultural feedstock, thereby aggravating its environmental implications. For example, two AD plants with similar power outputs operating on OFMSW and agricultural waste are respectively reported to use 36% and 6% of the produced electricity; this additional energy required in the former case mainly for the separation of non-fermentable/ compostable fractions [5]. On one hand, AD process reduces volatile fatty acids (VFAs) (and the associated odour) from the input feedstock (estimated reductions of Iso-butanoic, Butanoic, Iso-valeric and Valeric acids respectively of 350, 860, 480, 210 mg L^{-1} slurry [4, 33], while on the other it enhances, and concentrates, N-compounds [18, 34]. The latter is mainly attributed to the increased ammonia content of digested manure, combined with a slightly increased pH [35], which is further influenced by the alkalinity and buffering capacity and the cation exchange capacity, affecting the level of free NH_4^+ of the soil [36].

In order to maximise the benefits of bio energy installations as an affordable component of future energy mix there is a growing impetus on matching the size of the technology to energy demand, rather than the tonnage of waste [37]. Given renewable energy and GHG reduction targets are driving an acceleration in the use of bioenergy resources, the environmental impact of such national and regional development plans must be assessed in compliance with the EU Strategic Environmental

Assessment (SEA) Directive (2001/42/EC) [38]. This is of concern in the context that small size (albeit high-tech) AD systems processing OFMSW are deemed to be rising in demand - both for urban waste management and for valorisation [39, 40]. Therefore, to increase environmental sustainability through sound strategy in the production of renewable energy, it is necessary to minimise these environmental burdens in the biogas production chain [5]. This specifically applies to development of smaller, decentralised installations in a multiplicity of locations, which means even the small environmental burdens from individual installations, can pose huge potential impacts, if not dealt with at local source [41]. Alleviating such rebounds would be essential towards facilitating the transition of the bioenergy market in going from economy of scale to economy of numbers while maintaining its environmental benignity.

This paper provides an extensive review of available literature on AD systems suitable for urban applications, i.e. systems mainly designed for processing either OFMSW exclusively or a mix feed comprising of OFMSW (also known as biopulp) and farmyard residue or cattle/slaughter house waste. Greater emphasis is laid on reducing the systems scale environmental impact of AD technologies while promoting their diffusion into a low carbon energy infrastructure, including pre- and post-treatment stages alongside biogas production. It aspires to build the knowledgebase and bridge the gap between developments to-date in AD system research in Europe and in Asia region, mainly focussing on the merits of developing a more decentralised bioenergy infrastructure, suiting the agendas of both urban sustainability and green economy.

2. AD technology appraisal - potentials for enhancing environmental performance

2.1. Taxonomy of AD technologies for urban applications

Most modern AD plants are designed to accept mixed feedstocks for co-digestion (e.g. OFMSW, farm and livestock wastes); comparative performances of different digester configurations are available in the literature [23, 42-44]. Successful OFMSW digesters use extensive pre- and post-digestion processing units in a variety of configurations for handling high-solid and heterogeneous nature of feedstocks [45]. Typical AD technologies for urban applications include a cohort of simple and integrated wet and dry systems [46], which can be operated as continuous flow designs in single- or multi-stages (**Fig 3**). The Organic Loading Rate (OLR) of single-stage digesters is limited by the ability of methanogenic organisms to tolerate the sudden decline in pH that results from rapid acid production during hydrolysis and such reactors are reported to have problems in digesting readily degradable OFMSW, such as kitchen waste. This is mainly from accumulation of VFAs (mainly propionic acid) in the reactor, causing imbalances between the methanogenic and acidogenic populations, subsequently resulting in poor digestion and reduced methane production [44]. This is overcome in a two-stage acidogenic/ methanogenic AD system, providing better process control for the different stages of the anaerobic biochemical reactions and improved digestion. Thus, two-stage AD is reported to be biologically more stable, especially for accepting fluctuating feedstock types and organic loading rates, typically witnessed in urban situation. Despite this fact, about 90% of the installed AD capacity in Europe comprises of single-stage systems and only about 10% is composed of two-stage systems [45].

A recent evaluation of wet and dry digesters recommended that suitable AD operation in urban areas need to be integrated systems [46], i.e. incorporating the pre-treatment of the feedstock, especially for co-digesting OFMSW with supplementary feedstock for process stability and enhanced biogas yield (see **Section 6.1** for more details), as well as post-treatment of solid-liquid digestates. The latter involving both phase separation and required treatments for environmental compliance and for attaining the required stabilisation and portability for further application as biofertilisers (see **Section 2.4**). Typical integrated wet AD (>90% moisture) under mesophilic condition has been widely applied for food-based digestion, hence suitable for urban waste management. However, such systems are reported to have higher life cycle energy demands, mainly for additional equipment in both pre-treatment of feedstock and waste water treatment post-digestion [5, 46]. Further, wet AD of OFMSW often has tendency for scum formation, requiring adequate design interventions (such as homogenisation through continuous stirring) to mitigate serious environmental issues [45]. Another risk of wet AD processing of unsorted OFMSW is of toxicity from heavy metals and battery acids, which ultimately gets released to the environment post-digestion. On the other hand, dry AD (60-85% moisture, also referred as ‘plug-flow’ digester) has been considered environmentally more favourable for treatment of waste with low organic loads, mainly owing to resource savings in terms of water usage [46], lower number of pre-treatment steps in the input [47], reduced energy demand due to plug-flow movement of substrate (i.e. no mechanical devices required for mixing), substrate inoculation through digestate re-circulation [19], as well as reduced waste water generation [16, 29]. In particular, dry AD is reported to be more efficient for OFMSW digestion, owing to its composition and water content [48]. Further, to overcome the drawback of low biogas yield, reported for food-based digestion, more ‘advanced’ dry AD has been proposed for efficient treatment of OFMSW in urban areas, with long solid retention time and adaptability to regulate the moisture content of input waste by mixing paper waste [46].

AD technologies have been reviewed, mainly highlighting their role in GHG mitigation and renewable energy generation [49] and their potentials for treating municipal solid waste [45]. The majority of these AD plants are operated under mesophilic (30-40°C) conditions, barring some enhanced AD systems requiring thermophilic (50-60°C) conditions. As expected, thermophilic digesters have higher biogas production rates than mesophilic digesters, in particular dry digesters outperforming wet digesters. A matrix of current AD technologies (of global relevance) is developed, taking stock of the merits and the limitations of each in terms of their decentralisation potentials, especially on the grounds of their digestion stability, emissions from pre- and post-digestion stages and environmental consequences (**Table 1**). Relevant to urban application, staging of the AD process (typically two-stage) has been found effective for food-based digestion, owing to their positive impact on waste stabilisation and methane yield, compared to single stage reactors [23, 42, 44].

2.2. Pre-treatment losses

Pre-treatment techniques are applied in AD to optimise its performance, mainly for resource efficiency [50]. For OFMSW, pre-treatment is usually necessary to facilitate material flow, improve gas yield, reduce the amount of reactor volume occupied by inert material and improve quality of digestate. Several methods are attracting much attention for their suitability to alter the structure and composition of the biomass, essentially through disintegration. Particularly, for urban waste AD this has several purposes – to alter the feedstock composition to enhance the substrate; to allow operating the AD at higher OLR, i.e. increase the scale of operation [51]; to manage complex waste; to prevent the release of offensive odour [46], etc. The variations in pre-treatment approaches are geared to treating different characteristics of feedstocks, involving efficient processing of the input feedstock [13, 14, 23, 52] and/or, innovative mechanical/bio-chemical/ thermal/radiative treatments [15, 44, 53], the latter particularly useful for digesting longer chain lignocellulosic biomass and wooden fractions [54, 55]. However, any pre-treatment makes use of some form of energy (pressure, translational, rotational, thermal, or electrical) and/or chemicals and both resources can have diverse environmental implications.

LCA of different pre-treatments, especially in processing urban OFMSW, have shown the impact of additional equipment and resource application as inducers of both environmental impact and operational costs [46]. Another study, applied to two types of municipal wastes (kitchen waste and sewage sludge) account for their environmental burdens, suggesting all of them of bearing environmental cost which has to be accounted for while evaluating the environmental performance of AD technology. This is essentially from the use of additional resources (chemical and /or energy) during the pre-treatments, in particular the thermal, freeze-thaw and ozonation techniques have environmental burdens that surpass the benefits accrued from their incorporation into the AD system [51].

2.3. Production losses

AD plants generally produce biogas with a composition of approximately 50-70% CH_4 and 30-50% CO_2. There are often small amounts of other compounds such as molecular nitrogen (N_2), oxygen (O_2) and hydrogen sulphide (H_2S) amongst others. The overall composition (as well as the yield) is a function of the feedstock as well as operating conditions (including pH control value). Typical fugitive emissions from the biogas production site include methane, N-compounds, S-compounds and VOC (e.g. alkylthiols) (**Fig 2**). In particular, digesters operating on OFMSW exclusively, especially the source-segregated food waste component, have shown process instability from high loadings of protein and fat contents, leading to production of high concentration of both NH_3 and NH_4^+ from the degradation of proteins and amino acids [18]. In addition, fugitive emissions of methane can occur throughout the AD plant, from pipes, valves, over-pressure of the system and the storage facilities for waste and biogas. Two important sources of methane are the biogas reactor and leaks from upgrading facilities. Owing to the difficulty in estimating these emissions, mainly due to their variability from one site to another [56], only limited field data is available in the literature [57]. On average, 2% production losses of methane (expressed as percentages of the total methane in the biogas) is widely assumed for modelling purposes [7, 58], with further breakdown of 1% from the digestion plant and 0.5% from the gas engine assumed [21]. In addition, there have been concerns on the emissions from low-efficiency CHP engines (reported emission of N_2O from the biogas engine of 0.1 kg TJ^{-1} of electricity produced and NO_x of 0.42 g m^{-3} of biogas produced, [21]), which contributes to GHG and acidic emissions from energy conversion step [7]. The UK's policy emphasis on good quality CHP [59], i.e. with a high power/heat ratio, is an effort to minimise these environmental burdens.

2.4. Post-digestion losses

The residual biomass post-digestion, commonly referred as 'digestate' in the AD literature, comprises of left-over indigestible material, process intermediaries and dead micro-organisms. The content of digestate depends on both the feedstock and the hydraulic retention time (HRT) of the digester – usually longer HRT reduces the organic content owing to more effective methanogenesis [60]. With greater emphasis on strategies for diverting biowastes from landfill, and their sustainable re-utilisation through valorisation, the volume of digested materials is expected to increase significantly. At the same time, promotion of digestate as biofertiliser has grown over recent years, mainly for two reasons – one, as a low carbon substitute to fossil fertilisers as farmers and land managers are being encouraged to reduce product carbon footprint from their harvest [61, 62]; two, for restoring soil organic matter and for closed-loop nutrient recycling [56, 63, 64]. In the UK, the quantity of digestate recycled to land is expected to increase to around 5M tonnes (fresh-weight) by 2020 [65]. Further, land application of digestate is considered as a sustainable practice in the EU towards meeting the standards of the good agricultural and environmental condition (GAEC), which requires addition of organic materials to maintain and enhance soil organic matter levels [66]. However, as there are multiple types of digestates with varying degrees of inherent properties, including moisture, biological stability, microbial activity. etc., digestate is still considered a relatively new material and needs better characterisation. AD leads to carbon degradation to CO_2 and CH_4 and N preservation, and mineralization of organic-N; all the NPK nutrients present in the feedstock is retained in the digestate, and get concentrated owing to the nature of the process [67]. This is why the content of total ammonia nitrogen (TAN), the precursor of NH_3 emissions, tends to be greater in digested than in undigested manures [68]. For example, comparing the average nutrient composition over 52 weeks of feedstock and digestate from an AD treating dairy cow slurry under mesophilic conditions showed respective changes in dry matter, Total-N and RAN of -17.9%, +2.8% and +20% (negative and positive signs implying reduction and increment) [4, 69]. As a consequence, digestate is an emission source of NH_3, N_2, N_2O, CO_2 and some residual CH_4 (see residual biogas potential, RBP below) (**Fig 2**) to air; CO_2 emitted mainly from further degradation of organic matter in aerobic environment following land application of digestate [70]. Further, leaching of NH_4^+ and PO_4^{3-} occur to soil with potentials for eutrophication in the local environment [34].

Nutrients profile for food-based and manure-based digestates have been reviewed and compared showing their Nitrogen, Phosphorus and Potassium (NPK), content along with Magnesium (Mg) and Sulphur (S) (**Table 2**). Typical total-N content of food-based digestate ranges between 5-8 kg m-3, with about 60-80% of this present as ammonium nitrogen (NH_4-N, also refereed as 'readily available nitrogen', RAN) [62]. However, for digestate from kitchen waste feedstock RAN of as much as 99% of corresponding Total-N has been reported [71]. Food-based digesters, operating at high OLRs without ammonia stripping, are reported to produce digestate with high NH_3 content. This is because, while the total nutrients loading of the whole digestate and the original input feedstock remain conserved during AD [56], the majority of organic (slow release) nitrogen is transformed into RAN [72], specifically for protein-rich feedstocks, including OFMSW, dairy by-products and slaughterhouse waste [73, 74]. For example, RAN in food-based digestate is nearly 40% higher than manure-based digestate [62]. Further, for a field application rate of 25 m^3 ha^{-1} the RAN (in kg ha^{-1}) is found to be >140, 60, 55 and 30 respectively for food-based digestate, manure-based digestate, pig slurry and cattle slurry [34]. Sensitivity analyses conducted to assess the split share of digestate total-N (i.e. organic-N, NH_4-N and NO_3-N) on acidification potential have reported NH_3 and NO_3 as the main contributors to the enrichment of pollutants in direct air and water environments respectively [7, 75]. In the atmosphere, ammonia may oxidize and contribute to acid rain formation and acidification of the environment, as well as eutrophication by increasing the nitrogen available in aquatic ecosystems [25, 76]. NH_3 emission from field application of digestate is proportional to its TAN, hence often expressed from experiments as a % of TAN applied (**Table 3**). Additional N-losses to the environment occur from denitrification, mainly as nitrous oxide N_2O (a potent greenhouse gas) and Nitrogen (N_2) gas to the atmosphere. The N_2O emission from digestate soil application is considered longer lasting than NH_3 [72] and its emissions are estimated from both TAN and the longer term releases from the nitrified mineral N. Therefore, while considering N_2O emissions it is important to take account of the long term impact. N_2O emission from digestate application is expressed as percentage of total-N.

Depending on the biogas technology, the digestate could be a semi-solid (i.e. slurry) or a liquid material - with high nutrient and organic matter content. Generally, digestate is classified into three types – whole, liquid, fibre. Although some AD plants, as part of their post-processing, opt to separate the digestate into liquid and fibre fractions for management reasons (chemically/mechanically/physically using polymers, belt or screw-presses or excess heat respectively), whole digestate is most commonly available for land applications. Dry matter (DM) of the fibre fraction and the separated liquid fraction typically range between 20-40% and between 1-4% respectively. Both whole digestates and the separated liquid fraction are very good source of RAN (i.e. ammonium-N), potentially available for rapid crop uptake [61]. The liquid digestate contains less than 15% DM content, while the solid digestate contains more than 15% DM. Major properties of liquid digestates from different feeds, mainly their mineral nutrient content are reported in **Table 2** [77]. However, there is need for regular monitoring of digestate properties or agricultural applications, primarily owing to the alteration in the properties over the course of the digestion process.

The increased NH_4-N content of OFMSW digestate and pH elevation, mainly attribute to formation of $(NH_4)_2CO_3$ [77], which has dominating effect on ammonia volatilisation from the digestate compared to other factors, such as lower viscosity, lower dry matter content, etc. [56]. Further, the heavy metals and trace elements in the feedstock accumulate in the AD process, which exacerbate their concentrations in the digestate. For a standard application rate of 250 kg total-N ha^{-1} the typical soil loadings for zinc and copper from OFMSW digestate are respectively around 0.14 and 0.03 kg ha^{-1} whereas the corresponding metal additions from application of pig slurry would be about 2.5 and 0.8 kg ha^{-1} respectively. Literature values of mean heavy metal concentrations in food-based digestate are provided in **Table 4** [78], alongwith the corresponding values for livestock slurries and the PAS 110 guideline reference values [79] (see **Section 3.3**).

3. Recent developments in environmental best practice in AD

3.1. Review of AD monitoring applications

Emissions management along the AD process chain depends largely on the technology involved, its state of operation, availability of emissions inventory and emissions reduction techniques/ control strategies. This requires suitable monitoring/measurement techniques implemented along the whole process chain, best operating practices, and acceptable ranges of possible emissions. This would alleviate the risks of environment pollution and its resulting adverse effects on humans, animals or plants. Although the AD technology is well over a century old, stringent sustainability concerns over recent years have given rise to potentials for significant improvements in both operational efficiency of the digester and the handling of the process/products. As an AD best practice, this covers all three stages of the process chain: i) Input: maintaining tight record of specific input feed materials; ii) Operation: process management controls and operation monitoring; iii) Output: digestate sampling, testing, validation checks and information for end users. However, process modelling of AD operation to-date only had limited success, largely owing to the dynamic nature, non-linearity and lack of expert knowledge of the whole process [80]. Nevertheless, there has been renewed focus on adequate instrumentation, with rapid sensors/analytical features for reducing the uncertainty associated with the initial conditions and kinetics of the process. A detailed review of AD monitoring applications, highlighting the recent advances in Process Analytical Technologies (PAT)/ Theory of Sampling (TOS)/chemometrics approaches, which integrates utilisation of agricultural manure, biomass and industrial organic waste is presented for the Danish co-digestion concept [81]. Besides, there is emphasis on novel application of the soft-sensor concept[3], for development of model-based estimators to reliably predict unavailable measurements based on less expensive online estimates of unmeasured inputs for an AD system [80]. Albeit, owing to lack of availability of a perfectly instrumented AD facility, monitoring key variables at the necessary sampling rate, most approaches for soft sensor development to-date rely on simulation data for modelling the inherent AD parameters, mainly for quality assurance of the process model. This has been the major limitation for successful application of this concept in monitoring the performance of real AD plants.

Apart from non-availability of online instrumentation there is also dilemma over the user group of these different stages of AD monitoring. While the process monitoring can be handled by trained lab technicians, utilising a Programmable Logic Controller system for automation of electromechanical processes, the monitoring of digestate has to be conducted taking into the environmental factors and soil conditions. Evidently, there is need for further automation of these monitoring protocols. One suggested approach would be to allow on-field quantification of nutrients applied to farmlands using different application methods over the fertilisation seasons. This aspect is currently being researched for developing specially designed ‘manure analysers’ for widespread deployment [81].

Robustness, simplicity, accuracy, precision, and reliability are some of the key parameters desired of AD monitoring equipment/ hardware [81]. PAT with chemometric multivariate data analysis has been identified as a tool for ensuring optimal performance of the AD process. While online monitoring of process has been the focus of AD research community, commercially motivated to attain optimisation (process stability and optimum biogas yield), there is still a strong need for a robust instrumentation and better control systems for digestate management. Whereas a number of multivariate data analysis protocols using advanced sensor technologies have become available, the majority of these are currently limited to AD process monitoring and there is still a lack of dedicated digestate analysers.

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[3] This approach employs a combination of a hardware sensor and an estimation algorithm (software) to provide an online estimate of an immeasurable variable utilising good quality process data [152].

Currently (2014), there are limited approaches for digestate quality monitoring and they are all based on offline instrumentation [80]. Albeit, PAS 110 Clause 10 provides guidance on obtaining representative samples of all three types of digestates (whole, fibre, liquor) via one or more sampling access points appropriately located in the digestate production/storage system prior to its use [79]. It is recommended that separated fibre undergoes a maturation step before sampling, aiming to achieve significant loss of the free ammonia during the separation process. The following section deliberates upon some of the recent advances in evaluation of the key AD attributes.

- Volatile solids (VS): VS provide an indication of the stability of the digestate and may infer the stability of the process. VS has so far been mainly monitored offline according to APHA Standard Protocols [23, 82], but there has been growing interest for developing a soft sensor for online monitoring of volatile solids for its merit. This would overcome the drawbacks of offline monitoring, often marred by low and irregular sampling rates. It is reported, measurement procedure for VS are relatively simpler than for conducting offline VFA, RBP [80]. This makes VS an important digestate quality attribute (among the list of attributes identified in the PAS 110).

- Volatile Fatty Acids (VFA): The digested slurry is considered as a biomass low in VFA content (estimated to be a factor of 10 less) compared to the untreated slurry [4, 33], primarily owing to its utilisation and conversion into CH_4 during methanogenesis. However, monitoring traces of VFAs in the digestate has been considered important for preventing residual biogas production, which is essential to eliminate additional CH_4 release. Detailed protocols for offline VFA detection are provided in the literature [18, 23], while comparing digester performances using different AD configurations, organic loading rates, etc., which generally uses gas chromatography (e.g. Shimadzu, GC-2014 with a flame-ionization detector).

- Nitrogen (N-compounds): Onsite ‘rapid’ N measurements, taken using a Quantofix, or Argos N meter has been shown to be in good agreement with lab analysis data [61]. Several field experiments have been undertaken in the UK to determine the crop available N supply of digestate [83, 84]. However, in majority of literature the RAN is estimated by the conventional Kjeldahl method [85] and the ammonia N-losses from field applications using by wind tunnel experimental setup with gas bubblers [86], where the ammonia content is analysed from titration and colorometric analysis in the lab [34, 35]. Field measurements of N_2O have been made using static chambers for gas extraction, followed by spectral analysis through gas chromatography for quantitation [34].

- Volatile organics (VOCs, including thio-sulphates): Although detailed characterisation of VOCs are still not extensively reported in the AD literature, *in situ* monitoring, using a direct injection mass spectrometric technique has been developed applying Proton Transfer Reaction Time-of-Flight Mass Spectrometry (PTR-ToF-MS) [48]. Typically biogas produced from AD of OFMSW is found to contain trace amounts of VOC [87]. These emissions are affected by two different processes, one volatilisation (or oxidation) of the biomass-inherited organic compounds; two, microbial degradation of organic substrates, hence exhibiting a double-peaked emission pattern [48]. The VOC emissions are more prominent in dry digestion of OFMSW, owing to pre-oxidation step that may affect the dry anaerobic digestion parameters e.g. oxygen consumption (i.e. partial aerobic conditions), adaptation time of anaerobic bacteria and the time needed for the accomplishment of methanogenesis.

Interventions adopted to minimise the environmental burdens from AD technologies are not explicitly listed in the available literature, and possible techniques involve a combination of process modifications, resource management, post-treatments (**Table 5).** For example, separation and utilisation of nitrogen in the wet part of the digestion residue is made possible with a number of technologies which decreases environmental impact drastically, however to a substantial cost in some cases. However, our study could not provide estimated cost implication for these interventions, owing to lack of adequate data in the literature so additional cost evaluation is required.

3.2 Pre-treatments

Environmental burden minimisation strategies for the pre-treatment stage mainly involve feed-dependent process enhancements. AD being a biochemical process, the lack of adequate quality control of incoming raw materials (i.e. feed) into a digester has been identified as a crucial gap [81], which has implications for both performance of digestion and the quality of digestate. To maintain high quality feedstock control and management of physical impurities, sorting at the source or by more automated onsite separation, typically using mechanical/magnetic separation or supplementary installations of physical barriers like sieves, stone traps or protection grills in the pre-storage tanks, have been recommended More advanced techniques involve biochemical and thermal treatments. Of relevance to OFMSW processing, environmental performances of pre-treatments to two types of municipal solids (kitchen waste, sewage sludge) were evaluated for seven different techniques, including - alkaline, acid, thermal, thermo-acid, freeze-thaw, pressurize-depressurize, ozone treatment [88]. On the basis of additional resources use (chemical and/or energy), among the seven options tested, the mechanical (e.g. pressurize-depressurize) and chemical (acid or alkaline) pre-treatments are preferred to thermal treatments in terms of their life cycle environmental burdens [51]. In general, pre-treatment using energy has higher environmental impact than those using chemicals. Where imminent, thermal pre-treatments (for their merits on the improvement of waste stabilization), are recommended using waste residual heat. Among energy-using pre-treatments, mechanical disintegration (i.e., pressurize- depressurize) is preferred over thermal methods due to the lower energy demand without compromising the increase in biogas production. Even, among the chemical treatments, different LCA impact categories have preferences between acid and alkaline methods – the former performing better in terms of the GHG reduction while the latter having reduced toxicity potentials [51].

Typical biochemical pre-treatments include facilitating substrate mixing/hydrolysis and leachate recirculation. For example, there is a scope to improve/ fasten the degradation of the waste feedstock characterised by high volatile solids and low total solids (especially food waste - including raw fruit and vegetables and cooked food) through adequate hydrolysis and addition of alkaline buffer to enhance digestion [23, 52]; recirculation of a proportion of leachate into the digestion process (up to 50%, recommended in the literature [13]); recirculation of effluent (process water) [14, 42]. However, process water must be recycled with care (with appropriate treatment) to avoid the accumulation of soluble inhibitory compounds such as ammonia and salt. Although quite energy intensive but more efficient methods for waste disintegration, such as microwave heating [89], specifically for OFMSW with greater proportion of less biodegradable components [44], in presence or absence of hydrogen peroxide (H_2O_2); autoclaving of food waste to reduce ammonium radical and H_2S formation [15] are considered in recent studies.

3.3. Post-digestion best practice

The main concern for food-based AD, be it OFMSW exclusively or as a mixed feed, is mineralisation of proteins into RAN in digestate, with potentially adverse environmental implications post-digestion. Over the past decade, several methods have been developed to alleviate this phenomenon, including ammonia stripping [90, 91]; *in situ* ammonia removal through biogas re-circulation [18]; biological denitrification [92]; precipitation with cations, effective in reducing NH_4-N by up to 90%, as calcite and struvite [36, 93, 94]; electrochemical conversion [95]; microwave radiation [96] and ultrasound [97]. Evaluating the environmental benefits against the costs involved, the *in situ* stripping method has been reported as more sustainable [18], especially in comparison to chemical precipitation route, which introduces new pollutant from addition of reagent [96]. The majority of these interventions are applied to wet AD systems; pilot study on thermophilic dry AD have found increasing the C/N ratio from 27 to 32 enabling up to 30% reduction in NH_4-N in digestate [19].

There are further potentials for minimising environmental burdens from both storage and handling of the digestate. However, the requirement for storing the digestate until the growing season is a huge challenge, as in most plants, digestate is produced regularly throughout the year. Some countries have specified a set number of months for compulsory digestate storage prior to their application on fields, typically in a temperate climate, these ranges between 6-9 months of digestate production [4]. Unlike raw cattle slurry, digestate does not form a surface crust during storage so storing in open tanks releases NH_3 and CH_4 gases, which can be mitigated by covering the liquid surface with a protective layer (e.g. a natural crust 10-20 cm thick; a floating layer of inert material like plastic pieces or clay pebbles). Alternative approaches include covering the storage tanks with air tight membranes or using flexible sealed storage bags. However, in order to avoid any further CH_4 emission during the storage, it is recommended that the higher dry matter and fibrous fraction be stored without disturbance, or even composted. Another important issue is standardising the digestate composition suitable for land application, mainly owing to the very nature of AD being a technology capable of processing almost all sorts of organic feed. More recently, several countries have brought forward guidelines to overcome this challenge, with the general intention of maximising the commercial returns from digestate land application while minimising potential issues of environmental pollution and odour. For example, in the UK an independent Biofertiliser Certification Scheme provides assurance to consumers, farmers, food producers and retailers on the digestate quality post AD, in terms of safety for human, animal and plant health [62]. Another UK regulation, specifically applied to manure-based AD, requires pasteurisation of either the cattle slurry prior to digestion or the digestate before export from the farm [79]. Likewise, the new German biowaste ordinance requires mandatory sanitation of digestate, ensuring inactivation of Salmonella senftenberg, tomato seeds and *Plasmidiophora brassicae* (club root) after digestion [4]. Further, potential for chemical contamination of digestate from inorganic materials (e.g. heavy metals introduced through the diet of animals) and persistent organic compounds can be minimised by secured storage and routine monitoring of the content of the contaminants, both in the feedstock and in the digestate [4].

The volatilisation of NH_3-N from digestate depends on the following key factors – method of soil application [4], application timing [61] and subsequent weather conditions [86, 98]. This can be mitigated by minimising the surface area of digestate exposed to air after application through different modes of spreading which lower the air velocity above the digestate and ensure rapid incorporation into the topsoil by binding gaseous ammonia to soil colloids and soil water [4, 35]. Based on the reviewed literature, ammonia volatilisation risk for different soil application methods show the following trends: splash plate > trailing hoses > trailing-shoes > shallow injection (**Table 6).** For example, compared to splash plate (surface broadcast) application, typical NH_3 reduction from tailing hose, trailing shoe and shallow injection are respectively 30%, 30-60%, up to 70%. Splash plate application, despite being widely used in a large number of countries as cost-effective mineral fertiliser and slurry application method, seems to be worst performer in terms of environmental risks arising from digestate land application whereas a band spreader (trailing hose/trailing shoe) or shallow injector have comparable environmental benefits. For example, as shown in this Table, comparison between splash plate and trailing hose application for food-based digestate shows clear reduction in

NH_3-N loss to the air and NO_3-N leached to the soil. The UK Fertiliser Manual (RB209) provides some recommendations for minimising air losses of ammonia during digestate spreading. For liquid biofertiliser, reported ammoniacal loss reductions from 20-35% (of TAN) for surface application to 2-3% using disc coulter injection (into 5-7 cm depth) [99].

Separating the digestate into liquid/solid fractions has been identified as another best practice for effective handling of post-digestion losses, mainly for mitigating phosphate overloads as up to 90% of the phosphorous content is retained in the fibrous fraction while the liquid portion is applied as N-fertiliser with reduced ammonia emissions potentials to air [4]. The latter attributed to more rapid infiltration into soil, especially for digestate with low volatile solids applied to porous soils [86]. On the other hand, higher dry matter slurries remain on the soil/crop surface for longer leading to greater losses. Losses are also higher when slurries are applied to dry soils under warm weather conditions. Minimum quality requirements for whole digestate, separated liquor and separated fibre have been prescribed as part of PAS 110 standards in the UK [79]. Though at present this applies only to source-segregated biodegradable inputs i.e. those that have been collected separately from non-biodegradable inputs, and does not allow the use of sewage sludge or its derivatives). Further, digestates with different dry matter contents may need to be handled individually based on a nutrient analysis of the material and spread with different equipment as described above.

For preventing soil and water run-off, the land application method and time of the year are crucial. For example, the Canadian Government Technology Assessment Programme Research at the Ontario Rural Wastewater Centre [33] reported spring application (when plant nutrient uptake is high) having least pollution run-off to ground water compared to winter and autumn; the UK digestate and compost in agriculture (DC Agric) project [100] reported higher N-efficiency for food-based digestate (as % of total N applied) for Spring over Autumn to be around 60% [34]. Further, the potential for nutrient leaching is found to be higher on sandy soils with poor water retention capacity compared to clay and loam. To avoid risks of water pollution, digestate application should not be made to soil during waterlogging, freezing, snow events, when soli is cracked down to field drains or backfill, heavy rain over 24-48 hours. As a precaution, digestate applications should not be made within 10m of any ditch, pond or surface water; within 50m of any spring, well, borehole or reservoir that supplies water to human and cattle; on a very steep slope with high risk of surface run-off all year round [61].

Another important emissions abatement practice is reducing methane losses, termed as residual biogas potential (RBP), which is also considered a proxy for digestate stability. Co-digestion of different organic materials has been reported to yield more stable digestate with lower environmental impact [56, 101]. In the UK, for digestate to be compliant with PAS 110 the RBP must be below 0.25 $L\ g^{-1}$ of volatile solids (below which the material can be considered stable and suitable for land application);

typical RBP for food-based digestate is reported as 0.22 L g^{-1} of volatile solids [102]. However, the draft EU end-of-waste document [103] has proposed an alternative methodology for assessing digestate stability through measurement of the organic acid concentrations. There is potential for avoiding the air emissions from digestate by utilising the digestate effluent as replacement of freshwater and nutrients for bioethanol production and recent reports suggest enhanced ethanol production by as much as 18% compared to utilisation of fresh water only [104]. Another suggested post-processing involves liquid-solid separation of digestate, and using the liquid fraction rich in high N and K for irrigation and re-utilising the solid fraction, rich in volatile solid and P, as a co-ferment for anaerobic digestion [77].

4. AD operation in Europe

4.1. Current trends

In Europe the AD treatment capacity evolved largely over the past 20 years in response to EU policies, primarily aimed at reducing disposal of biodegradables [45, 105]. AD has been established as a win-win technology in Nordic countries, both in terms of recovery of energy (biogas) and nutrient (digestate) resources. Until recently, the majority of AD was applied to wastewater treatment (for sludge stabilisation and odour reduction) or farm manure management. Current emphasis is on extending this to biowaste management - biogas production, solids reduction, and pathogen reduction, shifting from conventional disposal-based solutions (such as landfill) to process-based solutions for recovery and recycling [3]. The European Commission has given particular importance to develop waste as an alternative energy source and in this context AD has gained central ground in utilisation of organic waste for production of energy. High-tech digesters of various kinds are implemented Europe wide in the agricultural and in the industrial sector. At least 25% of all bioenergy in the future can originate from biogas, produced from wet organic materials such as animal manure, whole crop silages, wet food and feed wastes, etc. [5, 106] and the digestate, the second most abundant product of digestion, is being commercialised as biofertiliser (see **Section 3.3**). Currently there is drive in the UK to promote AD plants, primarily waste based, with use of farm residues kept to the optimal level to maintain the operational performance and efficiency of the plant [107]. The most economically attractive AD plants (IRR >15%) are usually food waste-based systems, due to the gate fee attracted by the food waste [72]. However, there is a degree of uncertainty around technology, economics and environmental issues related to AD plants processing food wastes, drawing more research into process optimisation and potential environmental impacts of process/products. Nevertheless, the volume of digested materials is set to increase significantly as industry responds to the latest UK strategies for diverting biowastes from landfill, as well as other policy initiatives and measures geared to renewable energy, climate change mitigation and soil enrichment (mainly carbon restoration). Based on a waste hierarchy[4] approach, AD is recognised as generally the best option available for dealing with separately collected food waste [39]. The European AD landscape is rapidly changing year on year, but based on recent International Energy Agency report on biogas plants in Europe [108], Germany has more than 7000 small- and large-scale biogas plants, Switzerland 560, Sweden 230 (majority large scale). In the UK there are 110 AD plants processing organic feedstock, the majority of them are processing waste feed stocks of urban origin, complemented by the remainder farm-scale AD plants processing agricultural feed stocks [39]; in addition, there are 146 AD plants operated exclusively by the water industry for treating sewage sludge [109].

4.2. Environmental compliance

Regulatory framework of waste management in Europe is fairly developed, including the Revision of Waste Framework Directive (17/06/08): waste hierarchy and the Communications of the European commission on bio-waste management. Within the EU, use of animal by-products that are not intended for human consumption and used as AD feedstock is governed by EC Regulation No 1774/ 2002, which also applies to digestate containing industrial residues and animal by-products. Development of quality assurance and quality characteristics of digestate is currently on going in several EU member states to address the environmental concerns, mainly compliance with the EU Nitrates Directive and Water Framework Directive. For instance, digestate applications to agricultural land must comply with the EU Animal By-Products Regulations [110]; cattle grazing following digestate application should be avoided for three weeks (for pigs up to eight weeks) [111]; prescribed field N-limit for nitrate vulnerable zone (NVZ) not to exceed 250 kg total-N ha^{-1} (within 12-month period) [61];. mandatory closed spreading requirement for liquid digestate during autumn/ winter (owing to their high RAN content, exceeding 30% of its total-N content) [112]. Broad quality control criteria include, periodic sampling and analysis of feedstock to determine its biogas potential (e.g. dry matter, nutrients and volatile solid content and pH levels) and digestate to determine the nutrients [79].

The European Commission is developing end-of-waste criteria, i.e. criteria that a given waste stream has to fulfil in order to cease to be waste [103], for digestate (and compost) at an EU level, building upon the work in individual EU countries. For example, the UK has developed a publicly available specification[5], PAS 110 [79] – for the processing and end of waste status for digestate; and, an Anaerobic Digestate Quality Protocol (ADQP) [113]. PAS 110 ensures fitness for purpose of digestate suitability by requiring producers to undertake hazard analysis and critical control point

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[4] Article 4 of the revised EU Waste Framework Directive sets out 5 steps for dealing with waste (prevention, reuse, recycling, recovery and disposal), ranked according to environmental impact - the ‘waste hierarchy’, which has been transposed into UK law through The Waste (England and Wales) Regulations 2011.

[5] A Publicly Available Specification (PAS) is a sponsored fast-track standard driven by the needs of the client organisations and developed according to guidelines set out by British Standard Institute [79].

(HACCP) for a set criteria. ADQP sets out criteria mainly for quality assurance of digestate produced from source-segregated biodegradable waste (such as vegetable processing wastes or household food waste), eliminating the need for further scrutiny under Environmental Permitting Regulations [114]. In the UK, farmers using digestate need to adhere to the Biofertiliser Certification Scheme and follow the guidelines proposed in the Biofertiliser Matrix. This matrix differentiates between pasteurised (e.g. batch heated at 70°C for 1 hour) and un-pasteurised digesters. In Hungary, the digestate is regarded as other non-hazardous waste when the feed is not sewage or sewage sludge [77]. Existing national standards for digestate include, SPCR 120 Biowaste digestion residues in Sweden. RAL GZ 245 and 246 respectively for digestate from biowaste and from energy crops respectively in Germany. Further, in Germany the origin of the input materials determines the quality label of digestate product by biowaste and renewable energy crops. Digestates have to fulfil the minimum quality criteria for liquid and solid types (controlled by "Bundesgütegemeinschaft Kompost e.V" (BGK) [115]), which determine the minimum of nutrients and the maximum of pollutions (includes toxic elements, physical contaminants and pathogen organisms) in the digestate.

4.3. Operational issues

To realize the real potential for AD to contribute to the circular economy — by making the best use of finite resources and recycling nutrients back into food production, energy and food security, climate change, air quality and the economy — there are still barriers that the industry must overcome. There are wider sustainability issues, mainly arising during storage and handling of the digestate towards maximising the profits from the AD value chain. AD's multiple benefits can sometimes act as a handicap given the need for government policy to be joined up across policy areas as diverse as waste, bioenergy, transport and agriculture. In the UK, the anaerobic digestion and composting research network (ADCORN-UK) lists a number of government supported initiatives currently looking into promoting viable markets for digestate. The DC-Agric project (www.wrap.org.uk/dc-agri) is one such example with extensive field trials to understand the soil and air discharges of N-compounds (mainly NH_3 and N_2O) on digestate application. Likewise, research innovations are also underway for maximising digestate re-utilisation in landscaping, regeneration, sports turf and horticulture sectors.

The non-acceptability of biogas applications Europe wide is attributed to a number of structural, financial, attitudinal and awareness constraints. For example, operational, economical and technical reasons forced many of plants to close in Portugal in the past, and most of the others kept a low level of maintenance and poor operation and exploration of the systems. This was mainly due to lack of technical information for plant operators, lack of support during the start-up of the plant, low quality equipment and poor technology [12]. In spite of these limitations from previous experiences there is optimism in Europe about the future of AD, as a sustainable technology for valorisation of biowaste. In countries such as Austria, Switzerland and the UK, AD is the preferred technology for processing food waste from supermarkets, catering establishments and households [4]. In European countries with a developed biogas sector (e.g. Germany, Denmark and Austria) there are now financial incentives to establish covered digestate storages, with the main objective of reducing emissions. The UK government has set up 56 actions in its Anaerobic Digestion Strategy and Action Plan to tackle barriers to the increased uptake of AD [39]. Some of the challenges identified in this action plan, pertinent to reducing their environmental impacts include - improving understanding of the AD baseline; building safe and secure markets for digestate; encouraging localism through promotion of community AD. The latter is currently being addressed through the Driving Innovation in AD (DIAD) programme [116]. Further, in the UK there is increasing effort in co-digesting food waste with other organic wastes that would allow the PAS 110 requirements to be met.

5. AD operation in the Asia region

5.1. Current trends

AD has a long history in the Asia region, with the first digester built in 1859 in India [117] while hydraulic digesters have been widely used in China for nearly a 100 years [118]. Since the 1930s an estimated 40 million and 4.3 million bio-digesters, i.e. domestic plants (<1000 m^3 biogas day^{-1}), have been installed in China and India respectively [118, 119]. However, the majority of these plants are processing cattle slurry and farm residues, with huge potentials for recovering the embedded energy from organic waste, including OFMSW. The pressing demand for sustainable remedy, overcoming the ever-increasing fossil energy costs and environmental issues, are significant challenges driving AD innovation in Asia. Entwined is a looming crisis in these countries of efficiently managing organic waste (primarily composed of food) in the megacities, which is rapidly increasing day by day owing to increasing population, urbanisation and solid waste mis-management [120]. On the other hand, in most of the smaller Asian cities the waste management infrastructure is inadequate or is still at its infancy [121]. In response, some of the recent literature from Asia have focused mainly on biogas generation from AD of MSW [122-124] and other organic feed stocks, for example pulp/paper and tanneries [121, 125] identifying huge potentials for exploitation of OFMSW through organised AD infrastructures.

The clean development mechanism[6] (CDM) has promoted development of medium-sized biogas plants across Asia [126, 127]. Further, AD operations have been promoted under waste-to-energy (WTE) initiatives in a number of Asian countries under the auspices of financial and supervisory support from multilateral donor agencies, including the United Nations Development Program

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[6] An arrangement under the Kyoto Protocol allowing industrialised/developed countries with a greenhouse gas reduction commitment (called Annex B countries) to invest in projects that reduce emissions in developing countries as an alternative to more expensive emission reductions in their own countries [126].

(UNDP), the United Nations Industrial Development Organization (UNIDO) and from the Global Environmental Facility (GEF). In this context India gained a centre stage in developing a decentralised, ‘off grid’ waste-to-energy infrastructure from AD technologies and has led a mission of deploying one of the largest renewable energy programmes in the world over the last decade [128], through formulation and implementation of a number of innovative policies and programmes promoting bioenergy technologies, focusing on AD [129]. Small-scale high-tech biomethanation facilities for the treatment of solid waste (municipal bio waste or agricultural solid waste) are currently being implemented in large numbers by municipal authorities in India, geared to both waste minimisation and energy grid-independence. For example, there has been push for large-scale implementation of AD plants with power generation capacity in close proximity to the existing 1500 small dairy plants, with two-fold results – one, establishing large number of biogas plants; two, initiating world-class R&D activities, spearheading development of new technologies and constant enhancement of the performance of some of the established ones [130].

5.2. Environmental compliance

Environmental sustainability of AD operation in Asia is mainly scoped in terms of its renewable energy recovery potential as biogas. Currently, plants processing different feedstocks at difference capacities, and put to different end-use, are mushrooming in the absence of a stringent compliance regime. The operators mainly tend to subscribe to the notion of rate of economic return on the basis of biogas recovery; there is a lack of consolidated environmental best practice and a comprehensive regulatory framework covering the entire AD operations, including emphasis on sustainability of the supply chain, technology and efficient management of the effluents and solids left post-digestion. The priority on environmental compliance is bare minimum, mainly to clear the pollution control regulations for the discharge thresholds for air and water emissions [for example, the prescribed effluent standards of Central Pollution Control Board in India and Japan of respectively 250 and 160 mg-COD L^{-1}; the Law on Renewable Energy in China, requiring improved environmental protection from renewable energy exploitation [118]; the Law for the Promotion of Utilisation of Biomass in Japan [46]].

5.3. Operational issues

Despite being familiar with the principles of recovering energy from bio-waste for a considerable period of time its successful implementation has been a challenge in Asia. This is fostered through lack of skilled management of biogas digesters and follow-up expertise, often leading to failure of a number of biogas projects. Therefore, despite the suitability of warm climates for AD operation a number of urban AD projects in Asian countries are either underperforming, or have failed. Inappropriate technologies, lack of ownership and responsibility of operators, lack of markets for biogas and digestate, and weak business models are largely to be blamed for such failures [131].

Feedbacks/responses from AD operators to a survey questionnaire, conducted as part of this paper, show the concerns and challenges, particularly reflecting the technical, social and environmental issues from an Indian perspective **(Table 7)**; the majority of the issues in the Asia region seem to be related to digestate handling and management with negligible concern for environmental impacts. This has direct fall back on the protocols developed to overcome similar operational hurdles in the European context (**Section 3.3**). There is need for follow-up of running plants to ensure their environmental performance. There is a gap between aspiration and ground realisation of level of success in AD operation in Asia. While, in principle, AD has been considered ideal solution for biodegradable waste valorisation, the lack of skilled workforce is resulting in gross underperformance - both in terms of underutilised feedstock and increased emissions from processes and post-digestion [46]. The latter is leading to exacerbation in the environmental burdens beyond the levels estimated theoretically.

The majority of the AD operations in Asia are currently based on small digesters, for example, over 200,000 small size biogas plant uptake from the Ministry of New and Renewable Energy (MNRE) of the Government of India (GOI) initiative [132]. This involves dispersed waste water pollution and solid waste management issues with cost-intensive management interventions [133]. The management challenges have been further augmented by non-cooperation of government to support decentralised pollution abatement initiatives.

6. Discussion

6.1. Balancing co-digestion trade-offs

Co-digestion of feedstock has been extensively recommended in the AD literature for attaining superior digestion and higher biogas yield; reported studies cover food waste with cattle slurry [20], farm residue with animal slurry [25, 134], pig slurry with agricultural biomass [21], energy crops with wastes [83, 135], etc. The outcomes have been encouraging, specifically offering major advantages in terms of resource conservation, pollution abatement and management costs – the latter based on the reported finding that co-digestion can potentially improve the process, since using food waste as a sole feedstock can lead to longer-term stability problems from accumulation of VFAs in the digestion tanks, occasionally leading to complete seizure of the gas production [24]. Co-digestion has shown better buffering capability, especially for two-stage digestion of food-based feedstocks [23]. However, there are following impending issues with co-digestion that have to be dealt with prudence to consider this as win-win.

- The lack of knowledge about the environmental impacts (typically for elevation in N-compounds, e.g. ammonia) of mixing of high energetic feedstocks during co-digestion - for example, OFMSW with animal manure [22, 25].

- Adhering to the standard protocols for maintaining digestate quality control gets complicated. For example, the mandatory requirement for listing the characteristics of the constituent waste feeds (e.g. PAS 110, [79]) during co-digestion it is very important that the dry matter and nutrient concentrations of each input feedstock are known beforehand. If a feedstock originates from agri-food processors or other sources, its delivery and use should be accompanied by the appropriate quality assurance declarations, i.e., those that are legally required in the respective countries.

- Optimising the location of co-digestion AD plants is driven by both market incentives and regulatory requirements. For example, recovery of food waste through anaerobic digestion is subject to the Animal By-products Regulation (ABPR) (EC 1774/2002), which is designed to protect both animal and human health by preventing the spread of animal disease. Further, when off-farm material (e.g. industrial organic residues, biodegradable fractions of municipal solid waste, sewage sludge etc.) is co-digested, the digestate can contain various amounts of hazardous matter – biological, chemical and physical – that could pose risks for animal and human health or cause environmental pollution [136]. These contaminants can include residues of pesticides and antibiotics, heavy metals and plant and animal pathogens. The latter may result in new routes of pathogen and disease transmission between plants and animals if appropriate and stringent controls are not enforced (for example, the EU trans-national EC Regulation 1774/2002).

- Enhancement of total GHG emissions from using purpose-grown crops as substrate – mainly from two stages, one, CO_2 from the use of automated machinery along with fuel and lubricant consumption and; two, N_2O from digestate use in agriculture (estimated as about 65% and 25% respectively of the total GHG [134]) .

6.2. Handling multiplicity of AD operation

The major benefits of AD are that it can provide a local solution to locally arising waste and is a scalable solution. Large scale plants treating municipal and commercial food waste have been reported to be working just as well as smaller, on site treatment solutions. The concept of a centralised anaerobic digester receiving and treating biowastes is well developed in Europe with potential of enhancing the financial returns of this approach by economies of scale [20]. The UK has a large potential to increase biogas production through centralised, larger scale plants with food waste being the main feed [7]. However, the sheer scale of operation may lead to lateral material handling issues, for example the bulk of digestate from large plants and the resource investment to meet environmental compliance requirements of smaller plants. Some of the actual AD technologies discussed above seem promising, but in order to have a real impact on the waste problem, and to produce a significant amount of clean energy, the systems need to be improved and numerously implemented for converting indigenous UK waste to energy [37]. Further, increasing agricultural application of ammonia-rich digestate can potentially serve as precursors to enhancing the regional aerosol concentrations [137], inadvertently generating additional environment impacts.

6.3. Conducting integrated AD assessment

Ensuring systems scale sustainability of AD for mass deployment, catering to the green waste-to-energy infrastructure development with least transportation requirements, require an integrated assessment framework. Given renewable energy production in the EU, for example, is targeted to reach 20% of total energy production by 2020 [26] the transition requires insight into environmental consequences of producing renewable energy [21]. We propose the following rigorous evaluation steps for environmental burden minimisation: Step 1: the environmental impact/s from status quo substrate management and digestate handling procedures of individual AD technologies. Step 2: potentials for environmental burden reduction using process enhancement techniques/strategies as described in **Section 3**. From the AD process chain this can be assessed by analysing the potentials for minimisation of environmental burdens from pre- and post-treatment activities (**Fig 4**). For example, there is ongoing research to identify future raw materials that can be introduced into the AD, with particular focus on algal feed. However, their complex lignocellulosic structure demands for advanced pre-treatment steps (in order to guarantee a feasible yield from the AD process) [81] and for adequate post-treatment (in order to ensure environmentally benign digestate reutilisation). For example, the nutritive values of the digestate can be retained while avoiding direct emissions to air and soil through adequate drying prior to application to the field [79]. Another potential area of reducing environmental emissions from post-treatment is in the gas cleaning procedures [48] but this is outside the scope of our paper and thus would not be included in the discussion. Step 3: the potentials for systems scale environmental compliance for distributed AD installations (going beyond process level from Step 2), suitable for both community and industrial deployment. For example, the features of strategic environmental assessment can be used to assess the potentials for installing small-scale decentralised AD plants [38], serving the local energy needs while reducing the adverse impact from transportation emissions involved in moving feed and waste procurements to conventional centralised AD.

LCA has been considered an appropriate methodological framework to investigate the systems scale environmental benefits of AD [58, 138, 139]. An extensive LCA study of integrated AD plants, both wet and dry systems, has evaluated the GHG and environmental impacts of the process chain, and provide an extensive review of the methane yields of modelled and experimental studies, typically representing the data from Japan, covering a range of processes from pre-treatment to the production of recycled products or final disposal as waste [46]. Likewise, a number of recent LCAs evaluating the potentials of AD system as biomass valorisation technology for Europe have been conducted, for example in the UK [7, 140, 141], in Belgium [5], in Denmark [25, 142], in the Netherlands [21], in Sweden [75, 143]. Besides, application of multi-criteria decision making (MCDM) in evaluating the potentials of integrated bioenergy schemes have been separately reviewed [144]. Almost all these studies endorse the positive contribution of AD by inducing significant resource savings, however, to increase AD's environmental sustainability potentials, it is necessary to control emissions in the biogas production chain [5, 7].

Multi Criteria Decision Analysis have been adopted for feasibility assessment of urban AD operations, integrating the technical, environmental, financial, socio-cultural, institutional, policy and legal framework for developing countries [64, 131]. Based on similar principles, a multi-criteria decision support (MCDS) tool has been developed to select the optimal type, scale and locations of AD plants by examining feedstock mix combinations, technologies and use of the digestate based on scenarios related to economic and environmental issues, including GHG saving, air quality and water quality [72]. The latter two have specific focus on diffuse losses to air and water. This tool facilitates wide scale application of AD in England and Wales with specific aims of – assessing the economic and environmental performance of different AD co-digestion mixes, according to location, feedstock availability and use of digestate; quantify the net GHG impacts of these AD mixes to include products generated, feedstock production and application to land; quantifying the implications of the range of AD systems identified on water/air quality, biodiversity and impacts through land use change; identifying the best practice use for the digestates generated by the co-digestions mixes. The integrated assessments, made using the above criteria, identify a Pareto-optimal set of solutions to the problem of optimal location for AD plants based on system inputs and outputs. The model calculates NH_3 emission due to digestate in each grid and uses this as the basis for judging relative impact on air quality.

7. Conclusions

AD is better known for the economic return derived from biogas for energy rather than for its environmental impacts. Environmental assessment of small-scale biomass AD facilities is vital for sustainable organic waste management and cleaner energy generation by embedding diffused installation capacity. There is a need to evaluate the fitness for purpose of the available AD technologies in overcoming the inter-continental barriers in terms of environmental compliance. Thus, to realise the real potential for AD to contribute to the circular economy as visualised in **Fig 1** — by making the best use of finite resources and recycling nutrients back into food production, energy and food security, climate change, air quality and the economy — there are still barriers that the industry must overcome. Anaerobic digestion's multiple benefits can therefore act as a handicap given the need for government policy to be joined up across policy areas as diverse as waste, bioenergy, transport and agriculture.

This paper highlights the needs for furthering the research in facilitating the role of AD in cross-sectoral transition of bioenergy market in going from economy of scale to economy of numbers while maintaining the environmental benignity of future waste management - linking economic growth with energy self-sufficiency potentials of future domestic and industrial waste management. While the merits of AD have been widely established in the literature in terms of biogas production and wet waste management system this review highlights the need for effective digestate re-utilisation through concerted research and development efforts in advancing the protocols for digestate monitoring and control, especially ensuring the abatement of environmental burdens to soil and air prior to its field applications. We acknowledge that generating this awareness through proof-of-concept pilot studies is essential for its long term environmental sustainability alongside its growing application globally as a suitable biomass valorisation technology.

This would potentially lead to numerous pathways in addressing the underpinning environmental issues in municipal (and industrial) waste/biomass valorisation for energy self-sufficiency through assessment of a range of environmental management options and their promotion, thereby contributing to development of a robust AD system as a sustainable solution to future waste and energy crises.

8. Further research challenges

There remain challenges and barriers to be overcome if this growing industry is to achieve its potential in producing renewable energy, treating our organic waste, and creating new sources of renewable bio-fertiliser. Current AD technologies are not sufficiently efficient to recover usable energy at a cost compatible to fossil fuel. Further, the dispersed sources of feedstock raise enormous challenge for sustainable procurement of feedstock on one hand and ensuring the collection, transport and pre-treatment to remain environmentally benign on the other, given the majority of these activities are still fossil-driven and not cost-efficient. Further work may examine full-scale experience and a more integrated and energy-efficient scheme of waste management with the inclusion of subsequent digested solids treatment processes (dewatering, transportation, spreading) and biogas utilization pathways along with efficient pre-treatment and biogas production methods. Overcoming some of the issues raised above, it is envisaged future AD plant concepts will most likely be radically different from the concepts that are prevailing today. For example, serial digestion, where several reactors with varying operating conditions are connected, has shown promising results compared to the conventional design, where only one main reactor is considered [81]. This is applicable to future AD with limited availability of easily digestible organic waste. There is also significant potential of bringing new, previously unused waste feedstocks, for AD treatment towards commercialising the know-how for industrial application. The recommendation is for proper application of modern sensor technology and multivariate data analysis the process can be kept within specifications even at significantly higher loads. The possibility for expanding the use of closely related specially designed manure analysers to also allow on-field quantification of nutrients applied to farmland during fertilising seasons presents another huge unexploited market worldwide.

Along with the technological advancement towards environmental burden minimisation, from the pre- and post-digestion stages reviewed in this work, there is also potential for attaining wider sustainability of an AD system. This would involve developing a more sustainable structure for source-segregated waste disposal and collection and linking it with local AD network. There is need to identify the important data gaps in this process and develop a framework towards minimising the environmental impacts of AD while promoting its long term viability in sustainable urban metabolism as an efficient waste processing technology.

The price of tipping fees received by AD facilities could be influenced by adequate environmental burden characterisation of individual loadings – with further implications for upstream transportation costs, environmental restrictions and land pressures, as well as competition between facilities accepting OFMSW, especially as the sector expands. Public policy will also have an influence (i.e., mandatory landfill waste reduction and OFMSW pre-treatment requirements, economic incentives, and air quality regulations. This warrants an economic study of the interactions between tipping fees, public policy, and the development of OFMSW treatment industries, complementary to environmental sustainability of AD presented in this review. While the pollution avoidance from direct AD operations has been the plus point of extending its application as a sustainable technology (for example, an Australian study valued the environmental cost avoidance for AD at 4.3 $ t−1 in 2007 US dollars , see Rapport et al., 2012 for discussion), there are potentials for further fool proofing of AD as an environmentally benign technology by adapting the mitigation measures for the issues discussed in this study. Such initiatives will have to consider managing of pollution footprints from AD, alongside the current drive for its implementation towards GHG mitigation and attaining fossil-independence.

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TABLE CAPTIONS

Table 1. AD technologies for urban application.

Table 2. Nutrient content for whole and liquid digestates from different feedstocks (the corresponding units are provided in brackets).

Table 3. Nutrient loading for N-compounds for digestates from different feed stocks (Adapted from DEFRA report [39]).

Table 4. Mean heavy metal concentrations in digestates and in some common AD feedstocks (mg kg^{-1} dry matter).

Table 5. Snapshot of interventions applied to AD technologies in different countries for environmental burden minimisation.

Table 6. Qualitative comparison between different digestate application methods for environmental burden minimisation potentials.

Table 7. Survey responses highlighting the concerns and challenges to AD operation from Indian perspective.

FIGURE CAPTIONS

Fig 1. Waste-to-resource conservation loop for Anaerobic Digestion (AD) technology. (Adapted from the European Anaerobic Digestion Network [12]).

Fig 2. Emissions contributions to air and soil from different life cycle stages of AD operation. (Adapted from [25]).

Fig 3. Schematic diagrams of prevalent AD systems employed in treating OFMSW – (a) Single-stage, dry digesters commonly found in European countries (Dranco, Kompogas, and Valorga respectively from left to right [45]). (b) Two-stage, wet digesters commonly employed in Asia (with and without leachate recirculation in the acidogenic reactor respectively from left to right [14])[note: 1 - acidogenic reactor; 2 - methanogenic reactor; 3 - peristaltic pump; 4 - wet gas meter].

Fig 4. Schematic of potential environmental burden minimisation from the pre- and post-treatment stages of an AD system.

TABLES

Table 1

AD technology	Comments	Operational features	Environmental performance evaluation	Literature source
Continuously-stirred-tank reactors (CSTR) [Microbial operating temperature range: Mesophilic: 30-40°C Thermophilic: 50-60°C]	Available as both single- and two-stage digesters but mostly operated as single digesters under 'wet' conditions with total solids (TS) content in the digestion body below 100 g kg^{-1} (w.w.) in the mesophilic range. However, thermophilic operation has shown to fasten the reaction kinetic, reducing the digester volume.	Involves biogas induced mixing arrangement (BIMA), which is at the heart of the process of producing biogas with uniform consistency of methane (CH4). Usually the feed is diluted with re-circulated digestate	Thermophilic operation requires a heat source and associated insulation.	[23, 145]
In-storage psychrophilic anaerobic digestion (ISPAD) [Microbial operating temperature range: Psychrophilic: 10-25°C]	Suitable for AD of sewage and livestock wastes under temperate climatic zones with predominantly low ambient temperature, performing even under winter and autumn conditions.	Low maintenance cost requirements,, enabling operators with minimum technological know-how to run the facility. By definition, requires large, air-tight storage facility.	Minimises biogas NH3 content during production stage, compared to mesophilic systems. However, the conserved total available nitrogen (TAN or NH4 + and NH3) is released to the atmosphere during land application, resulting in a net loss of nitrogen.	[36, 146]
Dry digester	More advantageous AD system for processing OFMSW, owing to its composition and water content. Typically involves transition from	Reduces the required reactor volume; minimises the losses of organic matter during pre-processing operations.	Lower water and thermal demands and lower number of pre-treatments make it as efficient technology for resource savings. However, higher VOC emissions (mainly alkylthiols	[46, 48, 53]

	partially aerobic conditions (~13% v/v of oxygen) in the initial phase to full anaerobic conditions	However, usually lower biogas yield is reported compared to wet digestion.	and carbonyl compounds) reported during the dry anaerobic digestion of OFMSW	
Upflow anaerobic sludge blanket UASB reactor	Widely popular as methanogenic part of two-stage AD process, for treatment of sewage water with low total solids, or for treating the liquid leachate obtained from the acidogenic reactor (characterised by dense sludge bed in the bottom of the reactor).	Provides stable performance even at high organic loading rates. Suitable for maintaining high sludge retention.	Requires fresh water for waste simplification (hydrolysis and acidification) in the acidogenic stage and subsequently generates effluents that require discharging to waste stream. Generally involves additional pre-treatment steps for enhancing the biodegradability of feedstock/ reducing particle size.	[14, 23, 44, 53]

Table 2

Feedstock type	Digestion process	Total-N	RAN (NH_4-N)	Total-P (P_2O_5)	Total-K (K_2O)	Total-Mg (MgO)	Total-S (SO_2)	Literature source
Whole digestate								
OFMSW	mesophilic	7.35 *(5.0)* [kg m^{-3}]	5.94 *(4.0)* [kg m^{-3}]	0.48 *(0.5)* [kg m^{-3}]	1.81 *(2.0)* [kg m^{-3}]	0.06 *(0.05)* [kg m^{-3}]	0.44 *(0.4)* [kg m^{-3}]	[62] *[61]*
Cattle manure	mesophilic	4.40 [kg m^{-3}]	2.55 [kg m^{-3}]	1.35 [kg m^{-3}]	3.49 [kg m^{-3}]	0.74 [kg m^{-3}]	1.28 [kg m^{-3}]	[62]
Liquid digestate								
Swine manure	mesophilic	2.93 [g L^{-1}]	2.23 [g L^{-1}]	0.93 [g.L^{-1}]	1.37 [g.L^{-1}]	-	-	[147]
Liquid cattle slurry	mesophilic	4.27 [%DM]	52.9 [‰ Total-N]	0.66 [%DM]	4.71 [%DM]	-	-	[56]
Energy crops, cow manure and agro-industrial waste	thermophilic	105 [g kg^{-1} TS]	2.499 [g L^{-1}]	10.92 [g kg^{-1} TS]	-	-	-	[148]
OFMSW, cow manure energy crops and agro-industrial waste	thermophilic	110 [g kg^{-1} TS]	2.427 [g L^{-1}]	11.79 [g kg^{-1} TS]	-	-	-	[148]
Offal, cow manure, and plant residues	mesophilic and thermophilic	0.2013 [%m m^{-1} FM]	0.157 [%m/m^{-1} FM]	274.5 [mg kg^{-1} FM]	736.45 [mg kg^{-1} FM]	-	-	[77]
Silage maize and Clover/grass	mesophilic	0.253 [%m m^{-1} FM]	0.176 [%m/m^{-1} FM]	0.62 (%DM)	18.5 (%DM)			[101]

RAN - Readily available nitrogen; DM - dry matter; FM – fresh matter; TS – total solids

Table 3

Feedstock type	**DM (%)**	**Total-N (kg tonne^{-1})**	**RAN (NH_4-N) (kg tonne^{-1})**	**N_2O-N* (% of Total-N)**	**NH_3-N loss** (% of RAN)**
OFMSW[a]	4.3	7.4	5.9	1.17	21.17
Maize silage	7.4	4.2	3.0	0.87	25.40
Dairy cattle slurry[b]	4.2	3.0	1.8	0.89	13.33
Beef cattle slurry[b]	4.2	2.3	1.3	0.87	13.04
Pig slurry[c]	2.0	4.0	2.8	1.08	13.33

RAN - Readily available nitrogen; DM - dry matter

[a] *based on Taylor et al. (2010) [102].*

[b] *assumes 30% reduction in DM + 10% enhancement in RAN (as percentage of total-N).*

[c] *assumes 50% reduction in DM + 10% enhancement in RAN (as percentage of total-N).*

* *Gaseous release to air.*

** *Volatilised to air.*

Table 4

Feedstock type	Zn	Cu	Cd	Ni	Pb	Cr	Hg	Literature source
Digestate								
Food-based	104	21.5	0.9	19.7	6.1	10	<0.05	[102]
Animal feedstock								
Dairy slurry (UK study)	196	137	0.1	3.4	4.8	2.9	NA	[61]
Dairy slurry (German study)	176	51	0.2	5.5	4.8	5.13	NA	[4, 153]
Pig slurry (UK study)	870	279	0.3	3.9	3.5	2.3	NA	[61]
Pig slurry (German study)	403	364	0.3	7.8	<1.0	2.44	NA	[4, 153]
Poultry (egg layers)	423	65.6	1.03	6.1	9.77	4.79	NA	As above
Crop feedstock								
Grass silage	38-53	8.1-9.5	0.2	2.1	3.0	NA	NA	As above
Maize silage	35-56	4.5-5.0	0.2	5.0	2.0	0.5	NA	As above
Agri-food feedstock								
Dairy waste	3.7	1.4	<0.25	<1.0	<1.0	<1.0	<0.01	
Stomach contents	4.1	1.2	<0.25	<1.0	<1.0	<0.15	<0.01	
Blood	6.1	1.6	<0.25	<1.0	<1.0	<1.0	<0.01	
Brewing wastes	3.8	3.7	<0.25	<1.0	0.25	<1.0	<0.01	
PAS 110 guideline values (upper limits for the United Kingdom)	400	200	1.5	50	200	100	1	[79]

NA – not available

Table 5

Current practice of AD technology applied	**Sector (Municipal/ Commercial)**	**Type of waste**	**Reported scale of operation (daily)**	**End product (raw biogas/ biomethane/ CHP)**	**Process efficiency [%]**	**Emissions handling practice (pre/post digestion)**	**Study location [Literature Source]**
Slurry separation technology	Commercial	Pig Slurry	Biogas: 24.4 Nm^3	CHP	Heat: 46 Power: 40	slurry acidification to reduce CH_4 and NH_3 emissions from in-house slurry storage.	Denmark [135]
Source-segregated food waste digestion	mixture of commercial and municipal sources	Poultry litter				*in situ* ammonia removal by ammonia stripping.	UK [149]
Biogas induced mixing arrangement (BIMA)	Cooperative/Commercial	Dairy	Power: 18000 kWh	Power (IC generator)	Power: 27	successful adaptation of European technology (Entec) using sulphur adsorption from biogas to protect engines from corrosion.	India [150]
Advanced dry digestion	Urban/ Municipal	Food waste (70%)+ Paper(30%)	Biogas: 4920 Nm^3 Power: 9912 kWh	Power (IC generator)	Power: 33	Adding waste paper to food waste and enhancing the solid retention time (attained by returning the total solids back into the reactor after water extraction	Japan [46]
Hybrid anaerobic solid-liquid system (HASL)	Municipal/Experimental	Food waste	Biogas: 4.6 L	Biogas	Gas production efficiency: 140 (relative to BAU)	Leachate recirculation in acidogenic reactor; enhanced biogas production, water re-use and effluent reduction	Singapore [14]
Inclined thermophilic dry anaerobic digestion system (ITDAR)	Municipal/Experimental	Food waste, FVW, Green waste, Office papers	Biogas: 770-1155L	Biogas		adjusting the carbon to nitrogen (C/N) ratio by mixing of feedstock and digestate recycling achieved 30% reduction in ammonia-N in digestate.	Thailand [19]

Table 6

	Trailing hose	**Trailing shoe**	**Shallow injection**	**Splash plate**
Qualitative [4, 151]				
Ammonia volatilisation	Medium	Low	Low (negligible)	High
Crop contamination	Low	Low	Very Low	High
Wind drift	Minimal	Minimal	Negligible	High
Odour	Medium	Low	Very Low	High
Air exposure	Low	Low	Very Low	High
Application cost	Medium	Medium	High	Low
Quantitative [34] *(as % total N applied)*				
NH_3-N loss NO_3-N leached	48 13	- -	- -	63 15

Table 7

AD category	Drive for AD adoption	Management concerns	Operational challenges
Poultry	• Environmental concern – odour management • Electricity generation	• Digestate management – liquid effluent handling and transportation issues • Acceptability of liquid manure by farmers – potential for weed germination hampering wide acceptance.	• Feedstock characteristics – high N-toxicity requiring pre-treatments, e.g. nitrogen-stripping. • Limited number of success stories to benchmark the standard practice.
Fruit and Vegetable Waste (FVW)	• Reducing solid waste	• Irregular supply of feedstock owing to seasonality • Supplementary feedstock procurement (for co-digestion) • Stabilisation of digestate to minimise residual biogas formation during storage and/or land application.	• Maintaining a continuous AD operation. • Overcoming rapid acidification of the reactor from high volatile solids content. • Enhancing biogas yield by controlling inhibition of methanogens
Organic Fraction of Municipal Solid Waste (OFMSW)	• Reducing demand for landfilling • Extraction of embedded energy for heating and power • Compliance with pollution control norms	• Heterogeneity of the waste feedstock – results in varying organic loading rate • Stable AD operation (nutrient imbalance). • Digestate management – processing the solid manure and marketing. The latter mainly from issues of weed germination. • Stabilisation of digestate to minimise residual biogas formation during storage and/or land application.	• Source-segregation of the organic fraction • Adapting the technology to waste profile • Remediation of scum formed in digester tank • Online monitoring of the emissions profile from digester and digestate storage.
Slaughterhouse waste	• Environmental compliance • Potential for embedded energy recovery • Sustainable waste management and pathogen elimination	• High HRT requiring longer processing time and larger digester • Waste handling and management –social acceptance • Digestate management – processing the solid manure and marketing • Social acceptance of digestate application as bio-fertiliser	• Design challenges in reducing the energy demand by reusing waste heat within the system for pasteurisation and thermophilic digestion. • Feedstock processing and protein management (high N-toxicity), requiring pre-treatments, e.g. nitrogen-stripping.

Dairy (liquid waste)	• Environmental compliance • Potential for embedded energy recovery • Sustainable waste management and pathogen elimination	• Managing high-volume feedstock on regular basis • Low biogas yield per unit volume of substrate • Need for a co-operative waste management approach for sustainable AD operation	• Achieving low rate of return over short period, owing to high volume operation infrastructure required. • Effective policy for promoting co-operative waste management culture among societal groups.
Cattle manure	• Manure management • Reduce GHG (CH_4) emission • Local air pollution abatement (mainly wastewater and solid waste) • Recovery of energy for local heating and electricity.	• Needs immediate processing within 2-3 days • low biogas yield, requiring high volume processing with overall low economic returns • Manure handling, processing (e.g. decanting, scum removal) and storage requirements	• Additional water requirement for preparing homogenous slurry • Improvement of digestion efficiency through co-digestion of organic feed requires careful nutrient management • Removal of heavy metals from digestate (introduced through animal diet)
Waste water sludge	• High nutritive feedstock • Odour reduction • Provision of regular feedstock, suitable for co-digestion, • Complying with pollution control norms	• Storage and pre-treatment requirements • Additives from waste water treatment (coagulants, flocculants) tend to settle at the bottom of digester, impeding digestion, and over time reduce the HRT • Stabilisation of digestate to minimise organic loads prior to land application.	• Energy intensive operation (heavy duty sludge pumps, stirrers) for slurry handling • Nutrient recovery from biowaste • High sulphur content, requiring additional costs for post-digestion gas cleaning, specifically removal of H_2S.

FIGURES

Fig 1

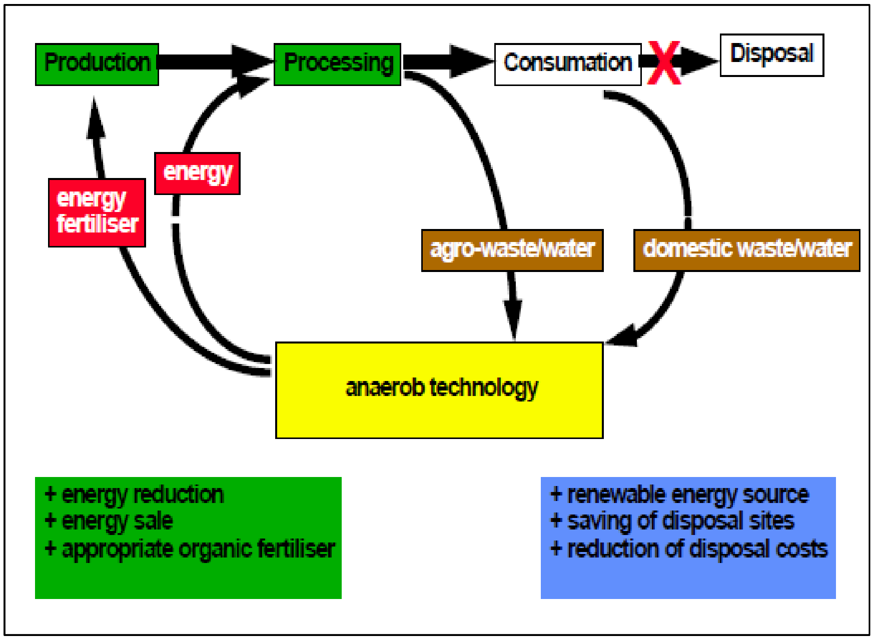
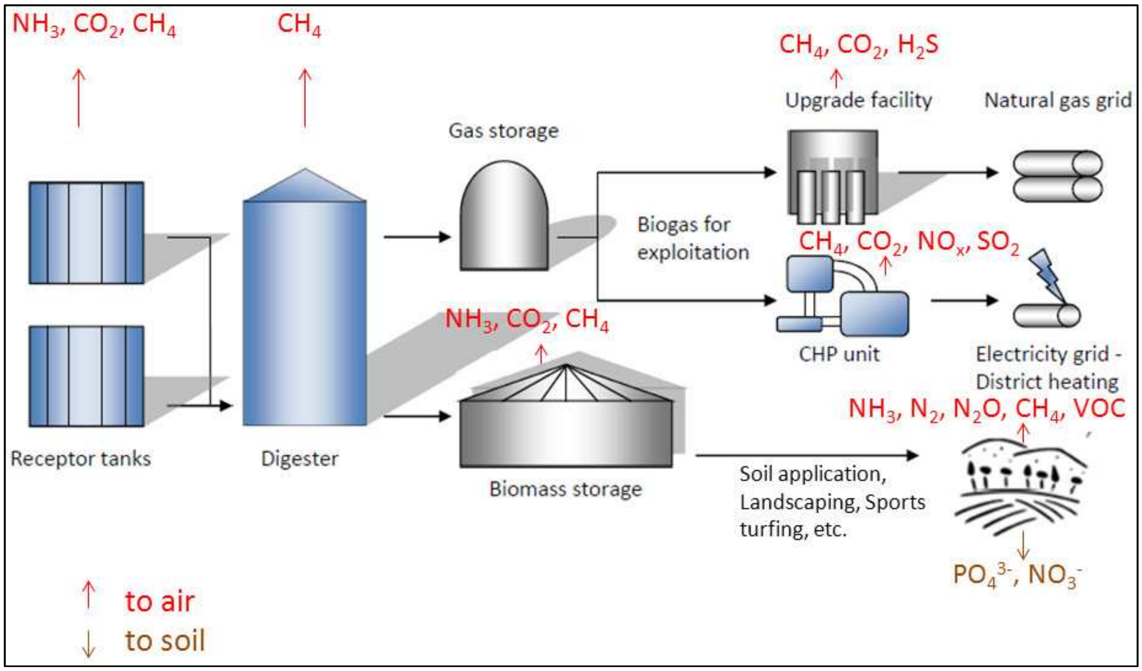


Fig 2



NH3, CO2, CH4
CH4
CH4, CO2, H2S
Upgrade facility
Natural gas grid
Gas storage
Biogas for exploitation
CH4, CO2, NOx, SO2
NH3, CO2, CH4
CHP unit
Electricity grid - District heating
NH3, N2, N2O, CH4, VOC
Receptor tanks
Digester
Biomass storage
Soil application, Landscaping, Sports turfing, etc.
PO4 3-, NO3 -
↑ to air
↓ to soil

Fig 3

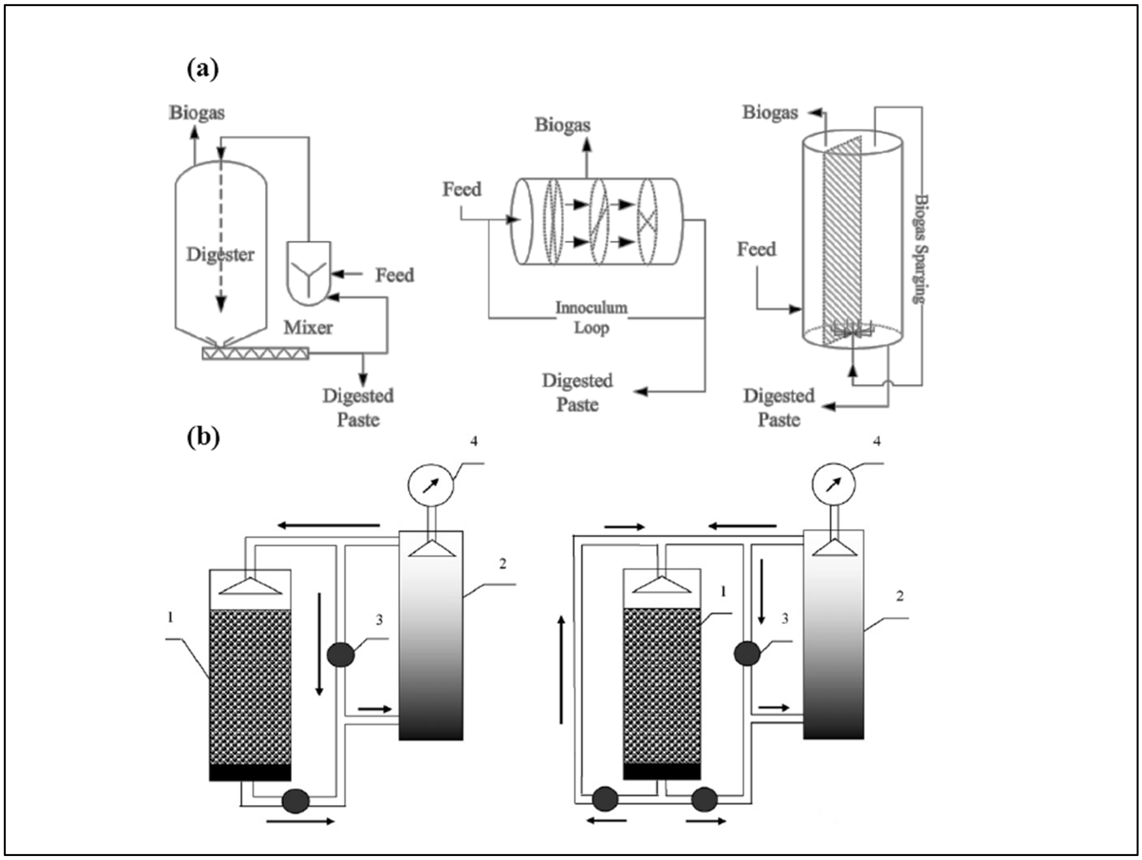
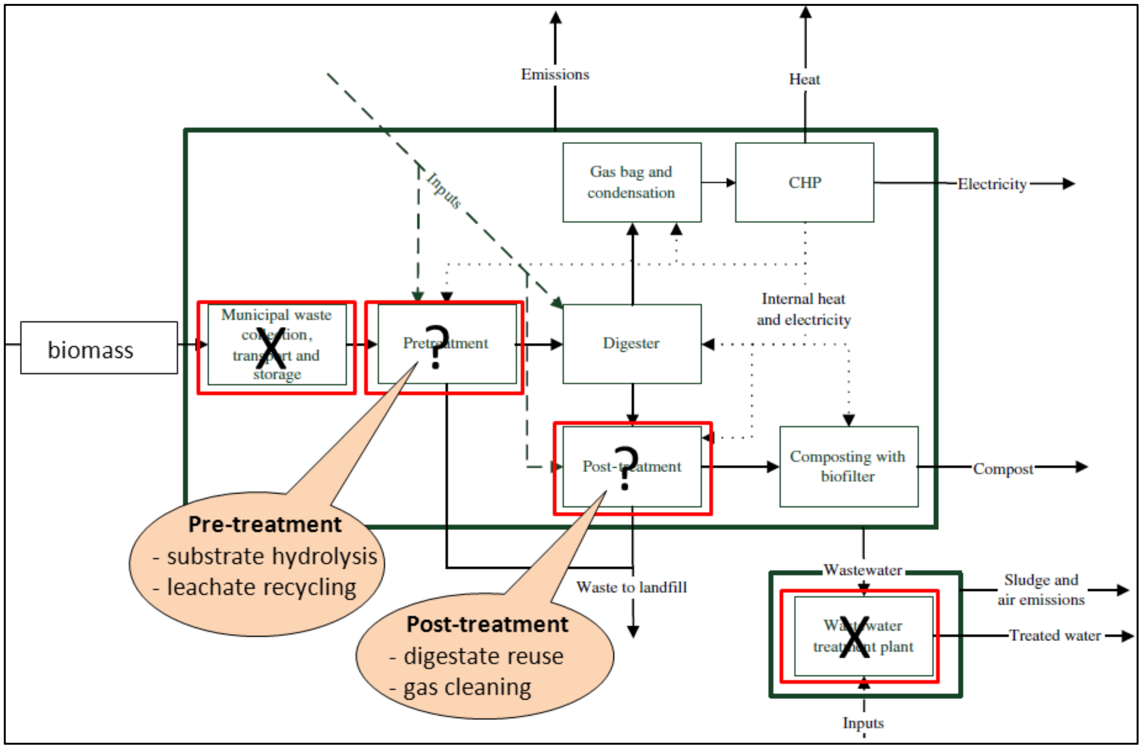

(a)
Biogas
Digester
Feed
Mixer
Digested
Paste
Biogas
Feed
Innoculum
Loop
Digested
Paste
Biogas
Biogas Sparging
Feed
Digested
Paste
(b)
4
2
1
3
4
1
3
2

Fig4


Emissions
Heat
Gas bag and condensation
CHP
Electricity
Inputs
biomass
Municipal waste collection, transport and storage
X
Pretreatment
?
Digester
Internal heat and electricity
Post-treatment
?
Composting with biofilter
Compost
Waste to landfill
Wastewater
Sludge and air emissions
Wastewater treatment plant
X
Treated water
Inputs
Pre-treatment
- substrate hydrolysis
- leachate recycling
Post-treatment
- digestate reuse
- gas cleaning