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Full scale co-digestion of wastewater sludge and food waste: Bottlenecks and possibilities

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ABSTRACT

Wastewater treatment plants in many countries use anaerobic digesters for biosolids management and biogas generation. Opportunities exist to utilise the spare capacity of these digesters to co-digest food waste and sludge for energy recovery and a range of other economic and environmental benefits. This paper provides a critical perspective for full-scale implementation of co-digestion of food waste and wastewater sludge. Data compiled from full-scale facilities and the peer-reviewed literature revealed several key bottlenecks hindering full-scale implementation of co-digestion. Indeed, co-digestion applications remain concentrated mostly in countries or regions with favourable energy and waste management policies. Not all environmental benefits from waste diversion and resource recovery can be readily monetarised into revenue to support co-digestion projects. Our field surveys also revealed the important issue of inert impurities in food waste with significant implication to the planning, design, and operation of food waste processing and co-digestion plants. Other pertinent issues include regulatory uncertainty regarding gate fee, the lack of viable options for biogas utilisation, food waste collection and processing, impacts of co-digestion on biosolids reuse and downstream biogas utilisation, and lack of design and operation experience. Effort to address these bottlenecks and promote co-digestion requires a multi-disciplinary approach.

1. Introduction

Energy security, resource depletion, and pollution prevention are three of the most vexing challenges of our time. They often manifest themselves in the form of climate change, economic crisis, and geopolitical instability [1,2]. These challenges call for a fundamental paradigm shift in resource and environmental management, which has resulted in the emergence of the circular economy concept. In a circular economy, products at the end of their service life or waste materials are turned into resources for another purpose, thus closing loops in industrial ecosystems and minimizing waste [3]. It is estimated that by shifting to a circular economy, several European countries can potentially reduce their national greenhouse-gas emissions by 70%, grow their workforce by 4%, and decrease their dependency from resource and energy import [4].

The transformation toward a circular economy can be already seen in the wastewater servicing sector. Traditionally, wastewater treatment plants (WWTPs) have been designed with the end-of-pipe treatment philosophy of meeting discharge standards to receiving water bodies while waste produced during treatment is destined for landfill or incineration. Conventional WWTPs typically include activated sludge treatment of wastewater and anaerobic digestion of the produced sludge. Most WWTPs adopting anaerobic digestion for sludge treatment face similar problems namely low organic loading and biogas (methane) yields due to the low biodegradability of wastewater sludge. In addition, WWTPs are often designed with spare capacity to cater for variation in the wastewater flow and future population growth [5]. Recent progress in water conservation and slow or even declining population growth in many developed countries have left many wastewater treatment facilities with spare digester capacity that is not and will not be utilised in the future.

Wastewater treatment is vital for environmental protection, but it is also an energy intensive activity. The treatment of municipal wastewater accounts for about 3% of global electricity consumption and 5% of global greenhouse gas emission [2,6]. Thus, it is not surprising that the wastewater industry has actively explored options to move toward energy-neutral operation.

A typical energy demand for biological wastewater treatment is in the range of 20–30 kWh per person equivalent per year [7]. On the other hand, given the current engineering limitations, energy recovery

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via anaerobic digestion of wastewater sludge is only about 15–18 kWh per person equivalent per year. In other words, under an optimal condition, WWTPs can potentially achieve up to about 65% energy self-sufficiency by fully utilising their sludge for energy recovery [7,8]. In practice, a typical WWTP can currently offset 20–30% of the energy consumption and greenhouse gas emission [7,9]. Thus, a viable and pragmatic approach is to co-digest municipal organic wastes in combination with municipal wastewater sludge using the spare digestion capacity at WWTPs to increase biogas production [10–12]. This approach does not only allow WWTPs to be energy-neutral but also reduce the cost of municipal organic waste management [13] while facilitating nutrient recycling [14,15].

Waste disposal options by landfilling or incineration are expensive and not compatible with the concept of a circular economy. Ongoing leachate management and extensive monitoring for potential groundwater and air pollution are required during active landfill operation and even up to 50 years post-closure [16]. On the other hand, extensive air pollution control is required for the waste incineration. Incineration of waste materials also results in significant greenhouse gas emission. In addition, both landfilling and incineration options offer very limited possibilities for resource recovery. Contrary to the traditional end-of-pipe treatment philosophy, in a circular economy, waste materials in general and the organic wastes in particular are a rich vein of resources in terms of energy and nutrient waiting to be tapped.

The opportunity to utilise spare capacity at WWTPs for municipal organic waste co-digestion is immense. Nevertheless, co-digestion at WWTPs also faces many significant hurdles that must be resolved through the dissemination of full-scale operation experience in both waste separation and biogas technology. Indeed, despite the rapid increase in the number of co-digestion studies at laboratory scale in the literature over the last couple of years [17], the number of pilot- and full-scale studies (particularly those dealing with operational issues) is still very limited. Of a particular note, waste materials can be highly variable in composition and data from laboratory-scale experiments using a small sample are not readily transferable to full-scale operation.

It is noteworthy that the bulk of organic waste from municipal origin is essentially food waste or food related waste, thus, the term food waste can be broadly used to refer to municipal organic waste. In this study, food waste materials include both avoidable (such as food scraps, unsaleable produces from supermarket, unusable beverage, and waste milk) and unavoidable streams (such as food processing waste, coffee ground, tea leaves, dairy processing waste, and fat oil and grease (FOG)).

Based on visits of full-scale facilities and collaboration between authors and plant operators, this paper discusses the current state of wastewater sludge and food waste co-digestion. Operation and design experience at four co-digestion plants using wastewater sludge and food waste in Italy and Germany are described in detail to reveal potential lessons for future projects. Key bottlenecks in the integration of co-digestion to WWTPs are identified and delineated. This paper provides useful background information for the formulation of a systematic roadmap for future development of co-digestion using experiences from existing resource recovery facilities promoting the concept of a circular economy.

2. Key drivers of co-digestion

Anaerobic co-digestion of food waste and wastewater sludge provides a range of economic and environmental benefits (Fig. 1). These include the diversion of putrescible waste from landfills and the ability to recover essential resources in a circular economy. Both of these are key environmental and social drivers of co-digestion. There are also financial benefits in the form of gate fee and revenue through renewable energy production. While financial consideration is essential to justify the commercial viability of a co-digestion project, only a portion of the environmental benefits from waste diversion and

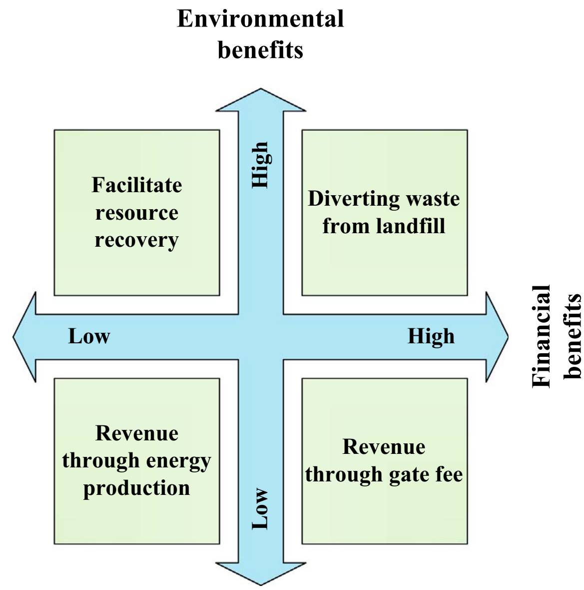

Fig. 1. Key drivers for co-digestion.

resource recovery can be monetarised. In fact, the economic benefit of co-digestion is often seen as a side effect and some full scale co-digestion projects have to rely at least partially on government subsidies [18,19].

Environmental benefits of diverting food waste from conventional disposal methods such as landfilling and incineration are significant. The high water content (typically 80–90% of the total weight [20]) of food waste renders incineration an energy intensive and costly option. Food waste accounts for 25–60% of municipal solid waste (MSW) [21,22]. Thus, by removing food waste from MSW, landfilling space can be saved for inert waste materials with significantly less environmental impact during landfilling operation and post-closure maintenance. Food waste is readily biodegradable. As a result, after deposition in landfills, food waste is the most significant contributor to methane gas production. According to Eriksson et al. [23], each kg of food waste can ultimately generate up to 0.1 m^3 of methane gas. About 15% of this methane gas is captured for beneficial use or flaring [23]. Thus, fugitive greenhouse gas emission from landfilling of food waste could amount to 3.1 gigatonnes CO_2-eq/year based on the global figure of 1.6 gigatonnes of food waste each year [24]. Co-digestion, on the other hand, allows for complete capturing and beneficial utilisation of methane gas from food waste. In addition, the contents of chemical oxygen demand (COD) and ammonia (NH_3-N) in landfill leachate are directly linked to the fraction of putrescible organic carbon (which is essentially food waste) in MSW [22]. During anaerobic co-digestion, the COD is transferred into energy-rich methane while nitrogen is converted into ammonium in the aqueous phase and can be effectively removed in the WWTP by conventional nitrification/denitrification processes or energy-saving nitrogen removal processes such as deammonification. Hence, the removal of food waste from landfilling materials can lessen the risk of environmental damage due to leakage of leachate into groundwater and the cost of leachate management.

Food waste can be a resource with great potential for energy production and nutrient recovery. Energy production from food waste is an attractive proposition and the subject of numerous recent reviews (see for examples [21,25–29]).

In addition, food waste contains important nutrients for crops including phosphorus and nitrogen. Anaerobic co-digestion provides an excellent platform for nutrient recycling either through nutrients extraction from the sludge centrate (also known as reject water) and/or biosolids reuse via land applications as a fertilizer. Several commercial systems have recently been developed to recover nutrients from sludge

Table 1
Comparison between Australia, Germany, and Italy in terms of number of anaerobic digestion plants for bioenergy, incentives for renewable energy production, and waste management policies.

Country	Population (million)	Biogas plants[a]		Incentive for bioenergy (€/kWh)	Biodegradable waste to landfill
		Wastewater sludge	Biowaste		
Australia	25	49	4	0.03[b]	Levied
Germany	81	1,400	180	0.18[b]	Banned
Italy	60	68	346	0.23 (max)[c]	Banned

[a] From www.iea-biogas.net/country-reports.html.
[b] From [19] as of 2013; feed in tariff is only available in the state of Victoria (Australia) at 0.05 €/kWh additional to the rebate value.
[c] From Biogas & Biomethane Report 2015 (European Biogas Association).

centrate via struvite precipitation [30,31]. They include the Pearl® Technology (Ostara, Canada), Seaborne (Seaborne Environmental Research, Germany), AirPrex (Berliner Wasserbetriebe, Germany), and Phosnix (Unitika Ltd., Japan). Nevertheless, it is noteworthy that these commercial systems have been primarily applied to WWTPs to prevent struvite blockage [30] and the revenue from struvite recovery is still a secondary consideration.

Phosphorus recovery from food waste is particularly important. Phosphorus is a mineral nutrient essential for food production and is currently extracted from phosphorus containing rocks through mining [32]. Because of its non-gaseous environmental cycle, phosphorus is a non-renewable resource. Peak phosphorus is expected within the next two decades with significant global ramifications for food security [32]. Nevertheless, the financial value of a sustainable supply of phosphorus for food production cannot be realised until the global reserve of phosphorus rocks has been severely depleted. Thus, once again, the environmental value of phosphorus recovery from food waste cannot be readily monetarised under the current economic condition.

As in the case of phosphorus recovery, the gap between environmental benefits of co-digestion and what can be monetarised to commercially support co-digestion is significant and varies widely depending on national policies for MSW and energy management [19]. Where organic waste is managed indifferently from inert waste, the economic value of diverting food waste away from landfills is negligible. Similarly, the economic value of biogas production from anaerobic digestion is intrinsically linked to the national energy security and climate change policy. Indeed, the marked difference in the number of full-scale biogas plants between Australia, Italy and Germany for instance, is reflected not only by the population, but also by the contrast in their MSW and energy management policies (Table 1).

In the EU, lack of land, environmental protection and human health consideration, as well as population density have resulted in the Landfill Directive (LD) in 1999 which enforces mandatory targets to prevent or reduce as far as possible any negative effects to the environment from landfilling of waste. The EU Landfill Directive provides EU member nations with the necessary legal framework to minimise and phase out biodegradable waste from landfills. For example, Germany has banned all biodegradable waste from entering landfills since 2005. Levy is another mechanism to divert biodegradable waste from landfills. The UK introduced a landfill levy in 1997 at 9 €/t and it has risen to over 98 €/t in 2014 [19]. Overall, the EU Landfill Directive is arguably the most significant driver for anaerobic digestion of food waste via co-digestion.

In Australia, landfill levies have been introduced at the state level. These levies vary widely from state to state. In several states, there are no levies or the levies are not sufficient as a major driving force to divert biodegradable waste from landfills [33]. In 2014, the landfill levy in the state of New South Wales was 76 €/t, which is slightly lower than that of the UK. By contrast, in 2014, the landfill levy in the state of Western Australia was only 23 €/t [19] while there were no landfill levies in Queensland, Tasmania and the Northern Territory [33]. The lack of a clear, robust and nation-wide policy to minimise biodegradable waste from landfill is one of Australia's most significant hurdles for co-digestion implementation.

Similar to MSW management, the EU also has the Renewable Source Directive (2008/0016 EU) that mandates member nations to set renewable energy targets. Thus, financial incentives for biogas production in the form of feed-in tariffs or rebates (e.g. the Renewable Obligation Certificate) available within the EU are in general more generous than those in Australia. In Australia, wastewater treatment facilities account for the majority of biogas plants in the country (Table 1). Most of them aim to utilise the generated electricity for internal consumption, thus, allowing them to realise the produced energy at market price which is much higher than the government rebate.

In addition to the range of benefits shown in Fig. 1, there are also several technical factors that favour the co-digestion of food waste and wastewater sludge. Existing anaerobic digestion plants in most sewage treatment facilities operate at an organic loading rate (OLR) of below 1 kgVS/(m^3·d). This is because even thickened wastewater sludge still consists of about 95% of water. By contrast, anaerobic digestion plants using organic-rich feed stock can operate at an OLR of 3 kgVS/(m^3·d) or even higher [17]. Food waste is rich in organic content. Thus, the co-digestion of food waste with wastewater sludge can significantly increase the OLR while resulting in a marginal decrease in the hydraulic retention time. In other words, the free digestion capacity in terms of OLR at existing sewage treatment facilities can be utilised by co-digestion. Co-digestion can also result in a more balance C:N ratio and helps to dilute any inhibitory substances from individual co-substrate [17,34]. The C:N ratio of wastewater sludge is low [34] and is typically well below the optimal range of 15–30 for anaerobic digestion [35]. Since food waste is rich in carbon, improving the C:N ratio is also a key driver for co-digestion of food waste with wastewater sludge.

3. Co-digestion practice around the world

3.1. Co-digestion of wastewater sludge and organic wastes

The utilisation of available OLR capacity in WWTPs to co-digest food waste with wastewater sludge has gained significant momentum in the last decade. Examples of co-digestion at WWTPs can be readily found in many parts of the world (Table 2). The fundamental science behind co-digestion can be directly adapted from the agricultural sector. Indeed, in the agricultural sector, co-digestion (mostly between manure and crop residual) has been a standard practice for several decades [36–38]. However, co-digestion of food waste and wastewater sludge presents a new set of challenges particularly at full-scale level.

Much of the early experience in co-digestion at WWTPs is from the EU, where MSW and energy management policies are most supportive. A large number of WWTPs in North America have also implemented co-digestion in their operation to become energy-neutral. A list of 19 full-scale WWTPs with co-digestion in the US is available from Shen et al. [11]. As a notable example, in 2012, the East Bay Municipal

Table 2
Examples of co-digestion plants around the world (data about the East Bay MUD plant is from [39]; all other data are from the authors through their visits to the plants or correspondence with the operators; PS=primary sludge, WAS=waste activated sludge, OFMSW=organic fraction of municipal solid waste, FOG=fat oil and grease, OLR=organic loading rate, and SRT=solid retention time).

Plant	Main substrate (loading rate)	Co-substrate (loading rate)	OLR (kgVS/(m^3·d))	SRT (d)	Temp (°C)	Gate fee (€/t)	Electricity generation (kW)
Rovereto – Italy	PS and WAS (90 t/d)	Food waste (10 t/d)	1.3	45	35	86	400
Camposampiero – Italy	OFMSW and other biowaste (82 t/d)	WAS (27 t/d)	2.9	21	55	75	400
Treviso – Italy	WAS (100 t/d)	Food waste (up to 20 t/d)	0.78	22	35	70	125
Moosburg – Germany	PS and WAS (100 t/d)	Pre-treated food waste (22 t/d), dairy & lacto rich waste (18 t/d), others	2.7	25	35	Varies[a]	380
Glenelg – Australia	PS and WAS	Liquid trade waste (e.g. unusable soft drink and waste milk) (28 t/d)	na[b]	na[b]	35	0[c]	na[b]
Kurobe – Japan	PS and WAS (80 t/d)	Coffee ground (8 t/d), septic tank sludge & other biowaste (up to 5 t/d)	na[b]	na[b]	55	0	95
East Bay MUD – USA	PS and WAS (2,650 t/d)	Food waste and FOG (40–120 t/d)	na[b]	18	35	na[b]	11,000

[a] The Moosburg plant pays the transportation cost of 3 €/t of pre-treated food waste; Gate fees for dairy and lacto rich wastes are from 17 to 30 €/t.
[b] Data not available.
[c] Gate fee is exempted due to a government grant.

Utility District WWTP was the first in the US to be energy-neutral through co-digestion of food waste.

Co-digestion has also been practiced by numerous WWTPs in other parts of the world including Japan and Australia. Although little information can be found in the English speaking peer-reviewed literature, the authors have been able to visit some of these plants. The Kurobe plant (Japan) was constructed and commissioned by Swing Corp in 2011. Municipal wastewater sludge is co-digested with coffee ground which is trucked from a local beverage production facility to the Kurobe plant approximately twice a week. Another example is the Asahi plant (Japan) which was constructed by Swing Corp shortly after Kurobe with a similar design. The plant was designed to co-digest 100 t/d of wastewater sludge with 10 t/d of coffee ground and tea leaf from the production of iced coffee and green tea by Asahi Soft Drink Co. Ltd. According to the operators, no gate fees are levied against coffee ground and tea leaf to the Kurobe and Asahi plants.

The concept of co-digestion at WWTPs is relatively new to Australia. Since July 2013, a full-scale trial has been commissioned at the Glenelg WWTP (South Australia), where wastewater sludge is co-digested with mostly solids free liquid waste such as unusable soft drink and waste milk. With support from the South Australia State Government, during this trial, there were no gate fees for approved liquid high strength organic wastes, no administration costs associated with permits, and no fees for initial analysis to encourage participation from trade waste customers. Since about July 2014, Sydney Water has conducted a full-scale trial to co-digest wastewater sludge with crude glycerol to boost biogas production at the Bondi WWTP (New South Wales) [40]. The prudence in co-substrate selection by WWTPs in Australia highlights the challenges of implementing co-digestion, where full-scale operation experience is still limited.

3.2. Co-digestion examples in Italy and Germany

Table 2 shows several co-digestion examples around the world involving wastewater sludge and food waste. The first four plants in Table 2 have been strategically selected to demonstrate the flexibility and diversity in process arrangement. A brief description of each of these plants is available here to facilitate further discussion on the pros and cons of each approach in subsequent sections.

The Rovereto plant (Italy) accepts food waste from urban areas in the province of Trento on a daily basis (Fig. 2). Most of the food waste is in plastic bags and is unloaded into a large stainless steel tray equipped with live bottom feeder screw conveyor. The stainless steel tray allows for visual inspection of food waste materials before they are fed into a hammer mill via an inclined screw conveyor. In the hammer mill, food waste is ground into small particles of less than 10 mm and water (approximately 1 m^3/t of food waste) is added to form a slurry with a TS content of about 12%. The drum sieve in the hammer mill is able to separate inert materials (e.g. plastics, animal bones, broken ceramic and glass, seashells) which are transferred into a container for landfilling. Inert materials account for about 20% of the food waste to the plant in mass. The food waste slurry, after passing an hydrocyclone for fine inert removal, is kept in two cylindrical tanks working in parallel (HRT < 12 h) prior to co-digesting with wastewater sludge in two digesters under *meso*philic (35 °C) condition. Digestate from the Rovereto plant is dewatered and dried for subsequent incineration at a different facility.

In contrast to the Rovereto plant, the primary function of the plant in Camposampiero (Italy) is to treat organic waste. Thus, the digester has been specifically designed for organic-rich substrate. Wastewater sludge is a co-substrate and only constitutes to less than 25% by volume. Waste materials to the Camposampiero plant is mainly the separately collected organic fraction of municipal solid waste (OFMSW) from urban areas. OFMSW is first loaded to a bag cutting machine and then exposed to a magnetic separator, before entering a pulper. The shredded OFMSW material is then mixed with process water and organic waste leachate to form a slurry. Heavy solid particles (e.g., bones, shells, metal caps, broken ceramic and glass) are removed from the slurry by sedimentation. The food waste slurry is pre-hydrolysed for approximately one day before being co-digested under thermophilic conditions (i.e. 55 °C) with thickened waste activated sludge from an adjacent WWTP. Biosolids from the Camposampiero plant is composted and finally used as fertilizers or soil conditioners in agricultural land.

The WWTP plant in Treviso (Italy) had been accepting solid food waste for co-digestion with wastewater sludge since 2006. A detailed process description of the Treviso plant prior to 2016 is available from Bolzonella et al. [41] and Cavinato et al. [13]. Food waste processing at the WWTP is rather complicated given the need for man power, space, and economics of scale. Thus, in early 2016, the plant has redesigned the co-digestion process to only accept liquid food waste from separately collected OFMSW that has been processed off-site. The dewatered sludge from the Treviso plant is subsequently composted and finally utilised as fertilizer.

Co-digestion has been implemented at the WWTP plant in Moosburg (Germany) for more than 10 years. The plant is equipped with storages for accepting up to six different co-substrates. Pre-treated liquid food waste is provided from the Oberding plant, which is a centralised food waste processing facility (see Section 3.3). This pre-treated liquid food waste makes up approximately 22 t/d while other

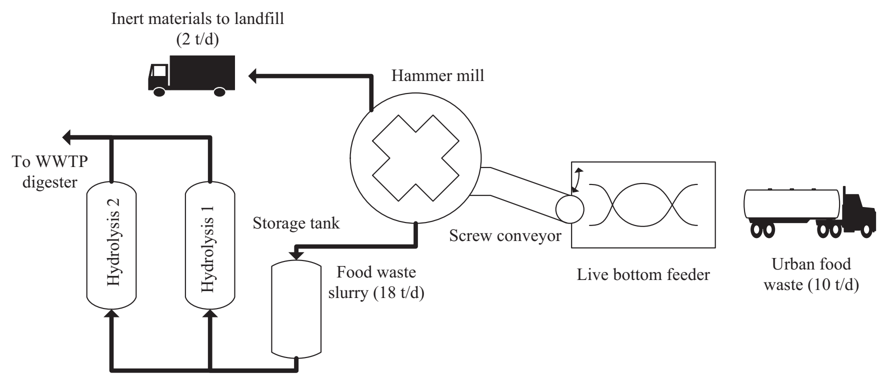

Fig. 2. Food waste processing at the Rovereto plant.

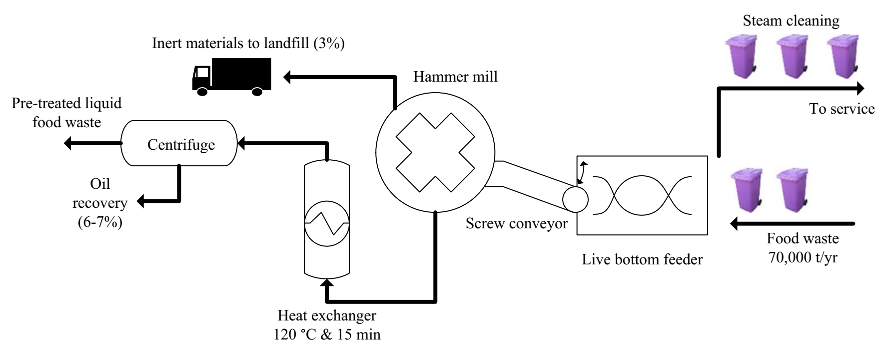

Fig. 3. Food waste processing at the Oberding plant.

co-substrates including contaminated milk, lacto-rich waste, FOG, dissolved air floatation sludge, and cleaning water from dairy processing can vary significantly in quantity, quality, and delivery time. The liquid food waste is hygienized and is trucked to the plant at 90 °C in a specially designed tanker. Thus, an insulated tank is used for liquid food waste storage at the plant. All liquid wastes undergo laboratory analysis prior to co-digestion with a mixture of 50%/50% primary and waste activated sludge from the plant. Any co-substrate that fails to meet the required specification on COD, nitrogen and salinity can be returned to the supplier. Gate fees at the Moosburg plant vary depending on the actual co-substrate. According to the plant operator, prior to 2011, the plant could get liquid food waste for free. Since 2011, the plant has had to pay for the delivery cost of 3 €/t. On the other hand, the Moosburg plant charges a gate fee of 17–30 €/t for all other liquid wastes depending on their quality and volume. The digestate is dewatered, thermally dried and trucked for incineration. Due to the high ratio of co-substrates, the energy and heat production is much higher than the internal demand at the Moosburg plant. Therefore, excess energy is fed into the power grid, while excess heat is also applied to dry dewatered waste sludge from other WWTPs as pre-treatment prior to incineration.

3.3. *Centralised food waste processing*

Food waste can be sorted and processed either onsite or delivered in a pre-treated liquid form. In addition to sorting and processing equipment, onsite processing also requires several auxiliary facilities including weighing bridge and even airlock passage to the receiving bay (e.g. in the Rovereto plant). Thus, onsite processing of waste materials is mainly suitable for large plants such as the Camposampiero facility. For a small plant, onsite waste processing can be inefficient in terms of equipment and manpower utilisation. In fact, the low rate of equipment and manpower utilisation has been cited as a major reason for the Treviso plant to change its operation from onsite processing to only accepting pre-treated liquid food waste in an arrangement similar to that of the Moosburg plant.

A notable example of centralised food waste processing is the plant in Oberding (Germany). The Oberding plant was commissioned in 1940, initially for the treatment of slaughter house waste. In 1995, it started accepting food waste for the production of ‘porky power’, which is a fodder for pig farming. Since 2001, due to the foot and mouth disease outbreak in the UK and subsequently the rest of Europe, the Oberding plant has diverted all pre-treated food waste to anaerobic digestion. Each year, about 10,000 t of expired food and 60,000 t of food waste from commercial customers (e.g., restaurants, canteens, supermarkets) are collected within a catchment of up to 200 km from the plant. The gate fee is 30 €/t on average (in 2016). The pre-treated liquid food waste is then delivered to co-digestion plants (including the Moosburg plant described above) free of charge. The cost of transportation is paid by the receiver. In some cases, the transportation distance from the Oberding plant to the end-user is over 200 km.

The Oberding plant is arguably a leading example of a modern food waste processing facility (Fig. 3). The plant has a fleet of specialised collection trucks that can accommodate three different bin sizes (i.e., 120, 240, and 1,000 L). The customer can opt to exchange for clean bins or to a bag-based system with additional on-site high pressure water cleaning fitted to the truck. At the plant, food waste is unloaded to a live bottom feeder using customised fork lifts equipped with a tilting rack that can accommodate several bins together. The bins are automatically cleaned with high-pressure water, then steam-cleaned on a conveying belt before returning to service. The mixture of water and food waste is macerated by a hammer mill. Plastic materials are removed by a drum sieve while other heavy inert materials (e.g., broken glass and ceramic, bones, metals) are removed by gravity. The plant operator estimates that inert materials account only for about 3% of the input. After maceration, the food waste slurry is transferred into a pressurised vessel where it is heated to 120 °C by steam for at least 15 min (Fig. 3). The heated liquid food waste is then centrifuged for oil recovery. Some canteens and restaurants do not separate FOG from food waste. Thus, oil recovery by centrifugation accounts for 6–7% of the total food waste input (Fig. 3). The pre-treated liquid food waste is stored in insulated reservoirs and delivered to a number of co-digestion plants (including agricultural biogas plants) using tankers with insulation capacity to maintain a temperature of at least 90 °C.

4. Challenges and opportunities

4.1. Available feedstock

The potential for co-digestion at WWTPs is immense. A broad range of co-substrates is available with sufficient quantity and supply security. Examples of these include food waste from urban areas (e.g., canteens and restaurants), organic waste from food processing, expired food from supermarkets, market waste, dairy waste, and FOG. Of a particular note, energy recovery through co-digestion is arguably being underutilised even in Germany, which is a global leader in biogas technology with several hundred biogas plants using mainly organic biowaste currently in operation. Germany currently generates about 13 million tonnes of biowaste (mainly food waste) each year [42], of which, about 4 million tonnes remains as the organic fraction in MSW [42]. Of the remaining 9 million tonnes of biowaste that is separately collected, only 2 million tonnes is currently used for biogas generation and the rest is composted without any energy recovery [42]. Thus, there is potentially about 11 million tonnes of biowaste co-substrate that can be tapped into for biogas production in Germany alone.

4.2. Inert impurities and feedstock handling

Food waste contains up to 20% of inert materials. Some of these inert materials, such as seashells and bones, are legitimate food waste, although they are not digestible. Other materials, such as glass, porcelain, plastic, and cutlery, are inherently associated with food waste. The disposal of inert (or reject) materials can incur a significant cost. As an example, at the Rovereto plant, the cost of reject material disposal in solid form is higher than the gate fee on tonnage basis. In other words, revenue from gate fee can be significantly offset by the cost of disposing inert materials. Moreover, only a fraction of inert materials can be removed during sorting. The remaining fraction is ground into small particles as part of the food waste slurry. It is possible to regularly remove these fine inert materials by sedimentation (for high density materials such as seashells, glass, and metals) or floatation (for low density materials such as plastics). However, this practice attributes to significant losses of biodegradable materials and the disposal of reject materials as slurry is even more expensive.

Some inert materials particularly seashells and bone fragments are very abrasive. They can exert excessive wear and tear to pumps and other equipment at a much faster rate than the standard design allowance. Slurry pump replacement in the first two years of operation was reported at the Camposampiero plant. Plastics are another cumbersome impurity. Even the presence of small plastic particles in biosolids can jeopardise any beneficial reuse for land application.

Food waste collection practice can also impact its digestibility, co-digestion operation and equipment utilisation. Separate food waste collection from individual households has been implemented in several countries such as Germany, Italy, and Japan. For practical reason, food waste is often collected weekly or even less frequently. Thus, some digestible materials can be lost due to biodegradation and the formation of leachate already in the biowaste bin. In addition, variation and irregularity in the supply of food waste can result in rather inefficient operation, particularly for a small plant. For example, occasionally food waste delivery to the Rovereto plant can be as little as 500 kg and two operators are still required for food waste processing. Moreover, collection curfew due to concerns over malodour, noise, and aesthetical impression means food waste can often be delivered only in the early morning over a short time window. Given the lack of storage capacity at most small plants, equipment for food waste processing can only be used for a few hours each work day, resulting in a low financial return on capital investment.

Separate food waste collection is still an emerging concept. In Australia, there is no separate food waste collection from individual households and the only source of food waste available for co-digestion is from commercial collectors such as PulpMaster [43]. Food waste from these commercial collectors only accounts for a few percentages of food waste generated in the country.

While co-digesting food waste with wastewater sludge is generally more complex, the utilisation of liquid substrates such as FOG and dairy waste is not problem-free. FOG can solidify at low temperature (e.g., 10 °C or less), rendering it unpumpable. Thus, FOG storage tank must be heated to prevent solidification during cold climate conditions. Some dairy wastes, particular those from whey processing, can be very salty. High concentration of inorganic salts is a major inhibitory factor to anaerobic digestion [44,45].

4.3. Additional processes and monitoring requirement

Co-digestion at WWTPs allows for the utilisation of available OLR in existing anaerobic digesters. However, co-digestion may also entail requirements for auxiliary facilities for waste processing and storage, inert solids removal, off-gas treatment, sludge centrate treatment, biosolids drying, and enhanced biogas purification. The extent of most of these requirements depends on the types of co-substrate, local requirements, and current facilities at the plant.

Some of the above mentioned auxiliary facilities are prominent features in all co-digestion plants. Provision for the removal of settling (and sometime floating) solids is a notable example. Given the content of inert materials of about 20% in food waste, their accumulation via sedimentation in the digester can be problematic. Thus, all European co-digestion plants treating raw (not pre-treated) food waste listed in Table 2 have a mechanism to remove inert materials from the storage tank on a regular basis (usually fortnightly) thus preventing them from entering the anaerobic digester. The removal of these inert materials can be achieved by a drainage valve at the bottom of the storage tank.

Co-digestion of nutrient rich substrate may also entails the need for additional treatment capacity for sludge centrate management. Due to a high nutrient loading in the sludge centrate, two sequencing batch reactors (SBRs) have been built specifically for the treatment of sludge centrate at the Moosburg plant. Nitrogen is removed by the SBRs via nitrification and denitrification with lacto-rich liquid waste as a carbon source. Phosphorus is also removed by chemical precipitation. A similar approach has been evaluated and proven to be particularly effective at pilot scale at the Treviso plant [46].

Requirements for substrate characterisation and monitoring vary considerably. In the Rovereto plant, visual inspection of food waste materials is used to remove large objects that may damage plant equipment as they are transferred by the live bottom screw conveyor feeder into the hammer mill. In the Moosburg plant, all co-substrates are visually inspected before they are accepted into a storage tank. Each co-substrate is then analysed onsite for COD, nitrogen and salinity prior to co-digestion. The Moosburg plant has a number of storage tanks and can simultaneously receive up to six different co-substrates. The exact cost of co-substrate monitoring at the Moosburg plant cannot be specified. Given the requirement for an onsite laboratory and skilled personnel for the analysis, it can be a significant cost component. On the other hand, there are no specific monitoring requirements at all other plants listed in Table 2.

4.4. Biosolids management

Food waste and other co-substrate contain a higher fraction of volatile solids, which is also more biodegradable than that of wastewater sludge. Thus, their contribution to biosolids production is not significant. Several recent studies have demonstrated the synergy of co-digesting wastewater sludge and a readily biodegradable co-substrate due to faster hydrolysis kinetics and the priming effect [43,47–50].

According to some of these studies [43,48,49], co-digestion may enhance volatile solids destruction and result in less biosolids production than mono-digestion with only wastewater sludge, especially for liquid solid waste. Limited full-scale operation data have also emerged to validate synergistic effects [34]. Although the contribution of co-substrates to biosolids production is dependent on its properties and digestibility and is usually rather small, the implication of co-digestion on biosolids management might be still significant. Indeed, biosolids management is another challenge to practical implementation of co-digestion.

The two most common approaches for biosolids management are land application and incineration. The former is environmentally friendly since it is cost effective and allows for nutrient recycling. The latter is an option regardless of the characteristics of the produced biosolids. Composting is another option for biosolids disposal although it can also be considered as part of land application. It is noteworthy that the criteria for biosolids management vary widely around the world. For example, in Europe, high population density, lack of space, and concern about possible contaminant release into soil and groundwater (such as heavy metals and emerging trace organic chemicals) have opened up incineration as a socially and economically acceptable option for biosolids disposal [51]. By contrast, in Australia and the USA, land application for beneficial reuse remains the predominant biosolids management approach [51].

The presence of inert impurities (especially plastics) that are originated from food waste can render the produced biosolids unsuitable for land application. For example, the German fertilizer regulation has a specific definition on the amount of inert impurities (plastics, cardboard, glass and metals) in the final digestate or biosolids applied to agriculture land. Not more than 0.4% w/w of these impurities in the final product is allowed. For plastics of more than 2 mm in size, the threshold is even lower at 0.1% w/w. Plastic and metal film lining is widely used for food packaging. Thus, despite significant effort to phase out plastic shopping bags, the presence of plastics in the final biosolids from food waste co-digestion is still a pervasive issue and has been reported at all three co-digestion plants in Italy in Table 2 especially when handling expired packaged food. It is noteworthy that plastics fragments and most other inert impurities can be removed from the digestate by a steel mesh prior to dewatering. The installation cost of such steel mesh is insignificant if it is included in the initial design. Nevertheless, it is also necessary to consider the on-going cost of removing inert impurities from the digestate in the overall economic evaluation of co-digestion.

Concern about offensive odours and disease risks from pathogens is also a major hurdle for biosolids reuse [52]. Odorous biosolids is usually rejected by farmers as offensive odour is an indication of unsafe materials. It is hypothesized that the addition of food waste as a co-substrate can increase the content of sulfur and nitrogen in biosolids. In Australia, where land application is the predominant mode of biosolids management, odorous product can only be used away from agriculture land such as for mine site rehabilitation with significant transportation cost. Food waste co-digestion can potentially increase biosolids odour. Although this hypothesis has not been systematically validated, any increase in biosolids odour can negatively impact the overall economic benefit of co-digestion. Co-substrates that may carry disease vectors such as contaminated milk (e.g., milk from a sick cow) present another obstacle for biosolids reuse. As an example, the Moosburg plant is capable of accepting contaminated milk as a co-substrate since biosolids from the plant is incinerated. Otherwise, biosolids hygienisation is compulsory prior to any form of land application (including composting).

Of a particular note, the regulatory framework for co-digestion is still in its infancy. The mixing of waste materials during co-digestion means that the produced digestate or biosolids is subject to the most stringent and conservative set of regulations. Depending on the final use of the digestate, additional hygienization of co-substrate prior to or of the digestate after co-digestion may be necessary. Alternatively, hygienization can also be achieved by the process temperature (i.e. thermophilic conditions) guaranteeing a defined retention time of any particle in the system.

Water content in the final biosolids product is an important factor governing the cost of transportation for land application or fuel consumption for incineration. The dewaterability of biosolids is strongly dependent on its characteristics (e.g., the content of VS, extra cellular polymeric substances, and soluble microbial products). It is possible that co-digestion can alter biosolids dewaterability, although this hypothesis has not yet been validated.

It is noteworthy that co-digestion plants often produce excess thermal energy, which can be utilised for biosolids drying. Biosolids drying is an effective strategy to address both biosolids odour and biological stability. As a notable example, excess thermal energy from biogas utilisation is utilised by the Moosburg plant to produce non-odorous biosolids with only 10% water content from its own digestate as well as from digestate from other WWTPs. The Moosburg plant is still able to meet its obligation to provide 1,100 MW/year of thermal energy to the local hot water network.

4.5. Biogas utilisation

The potential biogas production from wastewater sludge is significant, and if fully utilised, can allow a typical WWTP to achieve energy neutrality [9]. With co-digestion, significantly larger biogas production can be realised. Thus, biogas utilisation presents both opportunities and challenges. For a small WWTP, co-digestion is a viable pathway to achieve the required biogas production threshold that can justify the maintenance cost and capital investment of biogas utilisation equipment such as combined heat and power unit. By contrast, managing a large and variable flow of biogas can be an issue if storage facility is not readily available. At the Moosburg plant, since the COD content of all co-substrates is determined prior to co-digestion, COD input to the digester is regulated to maintain stable biogas production. Hydrolysed co-substrates can also be fed to the digester at specific intervals. This practice of regular-intermittent feeding does not require substrate characterisation but can result in highly variable biogas production as have been reported at the Rovereto plant. Without adequate storage facility, variable biogas production increases the risk of underutilisation as excess biogas must be flared. Increasing the demand for thermal energy for example for sludge drying and heat provision to a local hot water network is a viable approach for efficient biogas utilisation as practiced by the Moosburg plant.

In addition to electricity and heat generation, biogas can be further purified to produce town gas, transport fuel, and even raw materials for plastic production. The conversion of biogas to transport fuel has recently been implemented in several EU countries including Germany, Italy, and Sweden [53–55]. Successful production of bioplastic from biogas has also been demonstrated at proof-of-concept experimental levels [56]. Further research and development are needed to diversify biogas utilisation options and increase their cost-effectiveness.

In general, biogas purification involves the removal of CO_2 and other impurities such as water vapour, H_2S and siloxane. The infrastructure requirement for biogas purification is a major consideration, thus, opportunities for these value added utilisation of biogas increase as the production scale increases. Shen et al. [11] provides a comprehensive review of biogas utilisation from WWTPs in the US. On average, 10% of WWTPs with capacity of 378,000–3,780,000 m^3/d currently inject purified biogas directly to natural gas pipeline [11]. This figure reduces to 4%, 1%, and 0% for WWTPs with capacity of 37,800–378,000, 378–37,800, and less than 378 m^3/d, respectively [11]. Direct injection of purified biogas to natural gas pipe is also a common practice for large agricultural biogas plants in Germany [55].

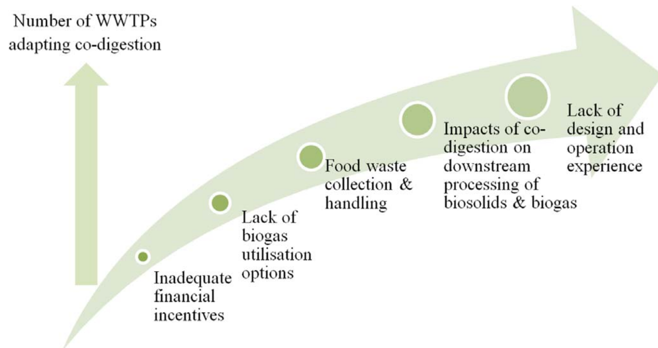

Fig. 4. Key bottlenecks in the integration of co-digestion to existing WWTP facilities.

4.6. Financial incentives and regulations

The development of any co-digestion project is ultimately an economic decision. Given the significant gap between environmental benefits and actual monetarised values as discussed in in Section 2, financial incentives remain one of the most important drivers for co-digestion. Although generous feed-in tariffs such as those available in Europe are helpful, it is the consistency in bioenergy and waste management policy that underlines long-term support to embrace co-digestion. For example in 2014, the amendment to the German Renewable Energy Law was initiated to alleviate the renewable energy tax burden. However, the amendment has also led to a significant reduction in feed-in tariff revenue from bioenergy production. As a result, the Moosburg plant has expressed concern that it may have to cease co-digestion operation when governmental supports are no longer available given the increasing financial pressure. Considering the high investment cost for establishing co-digestion at WWTPs, a consistent policy is required to ensure sufficient time for amortization.

As noted in Section 2, financial incentives for co-digestion are essentially gate fees and revenue from renewable energy production. The former is directly governed by landfill levies or costs of alternative organic waste disposal options while the latter is influenced by a range of factors such as energy price, renewable energy and green house emission target as well as energy security [19,33].

In Europe, the Landfill Directive from 1999 has been a major driver for the significant development of co-digestion. In Australia, future uptake of co-digestion application is likely to be uneven given the variation in landfill levies in different states. In the states of New South Wales and South Australia, landfill levies are adequately high to provide the necessary basis for the introduction of gate fees to support co-digestion. Not surprisingly, co-digestion studies at full-scale level have recently been conducted in these states (Section 3).

Wastewater and to a large extent MSW management services are natural monopolies. In other words, water utilities can have monopoly power over wastewater service by virtue of their ownership of the only available network structure. Although the regulatory framework for wastewater services varies from each jurisdiction, in general, their pricing structure is regulated by an independent authority. Co-digesting wastewater sludge with organic wastes using spare capacity of WWTPs is still an emerging practice. There is currently an uncertainty if gate fee can be independently set by water utilities. Thus, clarity and transformation of the current regulations governing wastewater services are necessary to support co-digestion.

In addition, a common feature amongst the current regulations is the lack of competition, which is attributed to limited spare treatment capacity that exists locally and the high cost and difficulty associated with long distance transportation of organic wastes. A study by the Office of Fair Trade (a regulatory body in the UK) has identified the economic potential of co-digestion [57]. The study also highlights the importance of competition within and between industries engaging in co-digestion to increase efficiency and innovation [57]. An adequate level of competition is essential to maximise the utilisation of existing assets and ensure that waste does not have to be transported over a long distance at high greenhouse gas emission and financial cost [57].

Revenue through energy production from co-digestion is directly driven by the national energy policy. In general, net energy importing countries such as Germany and Italy often provide generous subsidies to diversify their energy supplies and increase energy self-sufficiency. As a result, co-digestion projects in these countries are supported by more favourable feed-in tariffs. Nevertheless, any government subsidies are temporary and most WWTPs aim to utilise the produced energy for internal consumption thus realising the generated electricity at market price which is often higher than the government imposed feed-in tariff. Thus, provided that there are consistent and transparent market mechanisms for energy trading, financial incentives through energy production can also be realised even without favourable feed-in tariffs [19].

4.7. Challenges and opportunities

Anaerobic co-digestion of wastewater sludge and food waste has gained significant momentum in recent years. Given the volume of both avoidable and unavoidable food waste and the geographic distribution of WWTP facilities in urban area, co-digestion remains a largely untapped potential for simultaneous renewable energy production and sustainable food waste management. Although the fundamental science of co-digestion is already well established, there are still a number of key bottlenecks centering around the practical integration of co-digestion to existing WWTP facilities. These bottlenecks include the discrepancy between environmental benefits and true economic values of co-digestion, regulatory uncertainty regarding the collection of gate fee, the lack of flexible and cost-effective options for biogas utilisation, issues related to food waste collection, processing and handling, impacts of co-digestion on biosolids reuse or disposal, and lack of design and operation experience (Fig. 4).

The bottlenecks in Fig. 4 are inter-related. Adequate monetarisation of all environmental benefits is the most critical precursor to further facilitate full-scale applications of co-digestion and to resolve the remaining bottlenecks. More importantly, resolving these bottlenecks is not a challenge solely to wastewater or waste services. Indeed, it requires concerted efforts from several other disciplines and all stakeholders involved. The few examples described in this paper are an important first step. The experience detailed in this study should foster wastewater sludge and food waste co-digestion projects in the future.

5. Conclusion

Drawing from the authors' research experience and collaborations with full-scale facilities, this paper describes the current status of wastewater sludge and food waste co-digestion for simultaneous waste management and renewable energy production. Co-digestion of food waste with wastewater sludge is advantageous where spare digestion capacity of WWTPs is available to deliver significant environmental benefits. However, not all of these environmental benefits can be readily monetarised into revenue from energy production and gate fees. Thus, co-digestion applications concentrate mostly in countries or regions where there are significant incentives as well as favourable energy and waste management policies. Current operation at four co-digestion plants in Italy and Germany was discussed to reveal potential lessons for future projects. Several bottlenecks for further integration of co-digestion to existing WWTP facilities have been identified and discussed. In particular, attention should be given to the issue of inert impurities in food waste during the design and planning phase. Other issues include regulatory uncertainty regarding gate fee, the lack of viable options for biogas utilisation, issues related to food waste collection and processing, impacts of co-digestion on biosolids reuse and biogas utilisation, and lack of design and operation experience. A multi-disciplinary approach is necessary to address these bottlenecks to promote food waste and wastewater sludge co-digestion as a key technology of a circular economy.

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References

[1] Umbach F. Global energy security and the implications for the EU. Energy Policy 2010;38(3):1229–40.
[2] Li WW, Yu HQ, Rittmann BE. Chemistry: reuse water pollutants. Nature 2015;528(7580):29–31.
[3] Webster K. What might we say about a circular economy? Some temptations to avoid if possible. World Future: J Gen Evol 2013;69(7–8):542–54.
[4] Stahel WR. The circular economy. Nature 2016;531(7595):435–8.
[5] Tchobanoglous G, Burton FL. Tchobanoglous G, editor. Wastewater engineering: treatment, disposal, and reuse / Metcalf & Eddy, Inc. McGraw-Hill series in water resources and environmental engineering. New York: McGraw-Hill; 1991.
[6] Gude VG. Energy and water autarky of wastewater treatment and power generation systems. Renew Sustain Energy Rev 2015;45:52–68.
[7] Bodík I, Kubaská M. Energy and sustainability of operation of a wastewater treatment plant. Environ Prot Eng 2013;39(2):15–24.
[8] Jenicek P, Bartacek J, Kutil J, Zabranska J, Dohanyos M. Potentials and limits of anaerobic digestion of sewage sludge: energy self-sufficient municipal wastewater treatment plant?. Water Sci Technol 2012;66(6):1277–81.
[9] McCarty PL, Bae J, Kim J. Domestic wastewater treatment as a net energy producer-can this be achieved?. Environ Sci Technol 2011;45(17):7100–6.
[10] Hao X, Liu R, Huang X. Evaluation of the potential for operating carbon neutral WWTPs in China. Water Res 2015;87:424–31.
[11] Shen Y, Linville JL, Urgun-Demirtas M, Mintz MM, Snyder SW. An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: challenges and opportunities towards energy-neutral WWTPs. Renew Sustain Energy Rev 2015;50:346–62.
[12] Xie S, Hai FI, Zhan X, Guo W, Ngo HH, Price WE, Nghiem LD. Anaerobic co-digestion: a critical review of mathematical modelling for performance optimization. Bioresour Technol 2016;222:498–512.
[13] Cavinato C, Bolzonella D, Pavan P, Fatone F, Cecchi F. *meso*philic and thermophilic anaerobic co-digestion of waste activated sludge and source sorted biowaste in pilot- and full-scale reactors. Renew Energy 2013;55:260–5.
[14] Da Ros C, Cavinato C, Pavan P, Bolzonella D. Winery waste recycling through anaerobic co-digestion with waste activated sludge. Waste Manag 2014;34(11):2028–35.
[15] Cavinato C, Da Ros C, Pavan P, Cecchi F, Bolzonella D. Treatment of waste activated sludge together with agro-waste by anaerobic digestion: focus on effluent quality. Water Sci Technol 2014;69(3):525–31.
[16] Bilitewski B, Härdtle G, Marek K. Waste management. New York: Springer; 1997.
[17] Mata-Alvarez J, Dosta J, Romero-Güiza MS, Fonoll X, Peces M, Astals S. A critical review on anaerobic co-digestion achievements between 2010 and 2013. Renew Sustain Energy Rev 2014;36:412–27.
[18] Balussou D, Kleyböcker A, McKenna R, Möst D, Fichtner W. An economic analysis of three operational co-digestion biogas plants in Germany. Waste Biomass- Valoriz 2012;3(1):23–41.
[19] Edwards J, Othman M, Burn S. A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. Renew Sustain Energy Rev 2015;52:815–28.
[20] Wen Z, Wang Y, De Clercq D. What is the true value of food waste? A case study of technology integration in urban food waste treatment in Suzhou City, China. J Clean Prod 2016;118:88–96.
[21] Pham TPT, Kaushik R, Parshetti GK, Mahmood R, Balasubramanian R. Food waste-to-energy conversion technologies: current status and future directions. Waste Manag 2015;38:399–408.
[22] Iacovidou E, Ohandja D-G, Gronow J, Voulvoulis N. The household use of food waste disposal units as a waste management option: a review. Crit Rev Environ Sci Technol 2012;42(14):1485–508.
[23] Eriksson M, Strid I, Hansson P-A. Carbon footprint of food waste management options in the waste hierarchy – a Swedish case study. J Clean Prod 2015;93:115–25.
[24] FAO, Food wastage footprint: Impact on natural resources. 2013.
[25] Girotto F, Alibardi L, Cossu R. Food waste generation and industrial uses: a review. Waste Manag 2015;45:32–41.
[26] Karmee SK. Liquid biofuels from food waste: current trends, prospect and limitation. Renew Sustain Energy Rev 2016;53:945–53.
[27] Thi NBD, Lin CY, Kumar G. Waste-to-wealth for valorization of food waste to hydrogen and methane towards creating a sustainable ideal source of bioenergy. J Clean Prod 2016;122:29–41.
[28] Uçkun Kiran E, Trzcinski AP, Ng WJ, Liu Y. Bioconversion of food waste to energy: a review. Fuel 2014;134:389–99.
[29] Xu C, Shi W, Hong J, Zhang F, Chen W. Life cycle assessment of food waste-based biogas generation. Renew Sustain Energy Rev 2015;49:169–77.
[30] Kataki S, West H, Clarke M, Baruah DC. Phosphorus recovery as struvite from farm, municipal and industrial waste: feedstock suitability, methods and pre-treatments. Waste Manag 2016;49:437–54.
[31] Mehta CM, Khunjar WO, Nguyen V, Tait S, Batstone DJ. Technologies to recover nutrients from waste streams: a critical review. Crit Rev Environ Sci Technol 2015;45(4):385–427.
[32] Cordell D, Jackson M, White S. Phosphorus flows through the Australian food system: identifying intervention points as a roadmap to phosphorus security. Environ Sci Policy 2013;29(0):87–102.
[33] Edwards J, Burn S, Othman M. Anaerobic digestion at wastewater teratment plants: opportunities with and without policy support. Water 2015:83–8.
[34] Koch K, Plabst M, Schmidt A, Helmreich B, Drewes JE. Co-digestion of food waste in a municipal wastewater treatment plant: comparison of batch tests and full-scale experiences. Waste Manag 2016;47:28–33.
[35] Anzola-Rojas MdP, Gonçalves da Fonseca S, Canedo da Silva C, Maia de Oliveira V, Zaiat M. The use of the carbon/nitrogen ratio and specific organic loading rate as tools for improving biohydrogen production in fixed-bed reactors. Biotechnol Rep 2015;5:46–54.
[36] Xie S, Lawlor PG, Frost JP, Hu Z, Zhan X. Effect of pig manure to grass silage ratio on methane production in batch anaerobic co-digestion of concentrated pig manure and grass silage. Bioresour Technol 2011;102(10):5728–33.
[37] Seppälä M, Paavola T, Lehtomäki A, Pakarinen O, Rintala J. Biogas from energy crops - optimal pre-treatments and storage, co-digestion and energy balance in boreal conditions, in. *Water Sci Technol* 2008:1857–63.
[38] Herrmann A, Taube F. The use of maize for energy production in biogas plants - Is research up to date with agricultural practice? In: Handbook of environmental chemistry, vol. 5: Water Pollution. p. 165–97; 2006.
[39] Hagey P. Utility district ramps up food waste to energy program. BioCycle 2011;52(11):39–41.
[40] Nghiem LD, Nguyen TT, Manassa P, Fitzgerald SK, Dawson M, Vierboom S. Co-digestion of sewage sludge and crude glycerol for on-demand biogas production. Int Biodeterior Biodegrad 2014;95:160–6.
[41] Bolzonella D, Battistoni P, Susini C, Cecchi F. Anaerobic codigestion of waste activated sludge and OFMSW: the experiences of Viareggio and Treviso plants (Italy). Water Sci Technol 2006;53:203–11.
[42] Strippel VF. Aktueller stand der Abfallvergärung in Deutschland. Biogas J 2016;2:45–7.
[43] Wickham R, Galway B, Bustamante H, Nghiem LD. Biomethane potential evaluation of co-digestion of sewage sludge and organic wastes. Int Biodeterior Biodegrad 2016;3–8:3–8.
[44] Liu Y, Boone DR. Effects of salinity on methanogenic decomposition. Bioresour Technol 1991;35(3):271–3.
[45] Song X, McDonald J, Price WE, Khan SJ, Hai FI, Ngo HH, Guo W, Nghiem LD. Effects of salinity build-up on the performance of an anaerobic membrane bioreactor regarding basic water quality parameters and removal of trace organic contaminants. Bioresour Technol 2016;216:399–405.
[46] Frison N, Katsou E, Malamis S, Bolzonella D, Fatone F. Biological nutrients removal via nitrite from the supernatant of anaerobic co-digestion using a pilot-scale sequencing batch reactor operating under transient conditions. Chem Eng J 2013;230:595–604.
[47] Koch K, Helmreich B, Drewes JE. Co-digestion of food waste in municipal wastewater treatment plants: effect of different mixtures on methane yield and hydrolysis rate constant. Appl Energy 2015;137:250–5.
[48] Astals S, Batstone DJ, Mata-Alvarez J, Jensen PD. Identification of synergistic impacts during anaerobic co-digestion of organic wastes. Bioresour Technol 2014;169:421–7.
[49] Aichinger P, Wadhawan T, Kuprian M, Higgins M, Ebner C, Fimml C, Murthy S, Wett B. Synergistic co-digestion of solid-organic-waste and municipal-sewage-sludge: 1 plus 1 equals more than 2 in terms of biogas production and solids reduction. Water Res 2015;87:416–23.
[50] Xie S, Wickham R, Nghiem LD. Synergistic effect from anaerobic co-digestion of sewage sludge and organic wastes. Int Biodeterior Biodegrad 2017;116:191–7.
[51] Christodoulou A, Stamatelatou K. Overview of legislation on sewage sludge management in developed countries worldwide. Water Sci Technol 2016;73(3):453–62.
[52] Witherspoon JR, Adams G, Cain W, Cometto-Muniz E, Forbes B, Hentz L, Novack JT, Higgins M, Murthy S, McEwen D, Ong HT, Daigger GT. Water Environment Research Foundation (WERF) anaerobic digestion and related processes, odour and health effects study. Water Sci Technol 2004;50:9–16.
[53] Patrizio P, Leduc S, Chinese D, Dotzauer E, Kraxner F. Biomethane as transport fuel - a comparison with other biogas utilization pathways in northern Italy. Appl Energy 2015;157:25–34.
[54] Lönnqvist T, Sanches-Pereira A, Sandberg T. Biogas potential for sustainable transport - a Swedish regional case. J Clean Prod 2015;108:1–10.
[55] König A. Cost efficient utilisation of biomass in the German energy system in the context of energy and environmental policies. Energy Policy 2011;39(2):628–36.
[56] Van Loosdrecht MCM, Brdjanovic D. Anticipating the next century of wastewater treatment. Science 2014;344(6191):1452–3.
[57] Charlotte M. Co-digestion charge: is waste water's new best friend?. Water Wastewater Int 2012;27(4):40–2.