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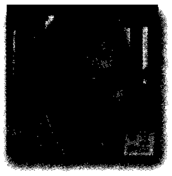

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Food waste is the most difficult waste fraction of household waste to manage because it is wet and putrescible. It becomes odorous and it attracts flies and scavengers. When it sticks to other wastes, it reduces the yield of dry recyclables. Home composting has the benefit of proximity but many are unwilling or unable to practise it. Source segregation and storage for kerbside collection and treatment works for many households but not for all, participation is especially low among households in flatted properties. The in-sink food waste disposer (FWD) is used extensively in Australia, New Zealand and the USA but it has been relatively underutilised in Europe. Using data from the published literature, the global warming potentials for landfill, incineration and centralised composting were calculated to be respectively +743, +13 and −14 $kgCO_2e$/t food waste; anaerobic digestion was approximately −170 $kgCO_2e$/t food waste irrespective of whether the food waste is delivered by truck or by FWD and the public sewer. Surahammar in Sweden has provided a unique opportunity to assess the impacts of FWD at community scale and compare them with results from laboratory studies and field trials. Over 14 years, FWD installation went from zero to 50% of households voluntarily; 4-weekly influent monitoring data from the wastewater treatment works of the town show that biogas increased by 46% but flow (water use) and chemical and biological load did not change significantly.

1. Introduction

Quantifying the amount of domestic food waste produced can only really be accomplished by sampling and bin analysis. Quested and Johnson (2009) estimated that 5·8 million t/year of food waste are collected by local authorities in the UK. (Note that in the current paper 't' is used to denote tonne (1000 kg) fresh waste unless shown as dry solids (DS).) It is mainly in the residual waste stream (general bin). They reported that in addition 0·69 million tonnes are home composted or fed to animals. The Office of National Statistics reported there were 24·9 million households (hhd) in the UK in 2006. This equates to 233 kg food waste per hhd.year collected by local authorities mainly as residual waste. Food waste collection for feeding to pigs was practised for centuries but was banned in the UK and then in the whole European Union (EU) following an outbreak in 2001 of foot and mouth disease after the original infection had been attributed to infected meat that had not been cooked in the legally required manner. It might have been better to tighten enforcement of the cooking requirements, which would be easy with modern sensors and telemetry, but we are where we are.

Europe has given emphasis to separate (kerbside) collection of biowaste for many years but even so a large proportion of biowaste is still in mixed waste, which makes resource recovery more difficult. The European Commission's Green Paper (CEC, 2008) on biowaste says that only 30% of biowaste is separately collected and treated biologically.

Data from the 2001 UK census and household waste statistics for England (the data for Scotland and Wales are not comparable) (Defra, 2010) show that the correlation coefficient between the percentage of flatted properties and NI192 (the percentage of household waste sent for reuse, recycling or composting) for all the London boroughs and the City of London is −0·529 (Figure 1); that is the data confirm anecdotal evidence of waste managers that a smaller percentage of household waste is sent for reuse, recycling or composting by households in flatted properties than households that are not in flatted properties. Flatted properties comprise 49% of London's housing and 71% in inner London. Even for all 325 waste collection authorities in England, the correlation is −0·368 (where 0 is unrelated and +1 or −1 is a perfect linear relationship with all points on the line). To be successful, any waste strategy must address this conundrum and present a range of options from which people can choose ones they are willing to use.

The EU Landfill Directive (CEC, 1999) requires member states (MS) to reduce the amount of biodegradable waste disposed to landfill in order to reduce methane emissions (CH_4). Methane has 25 times the climate change effect of carbon dioxide (CO_2)

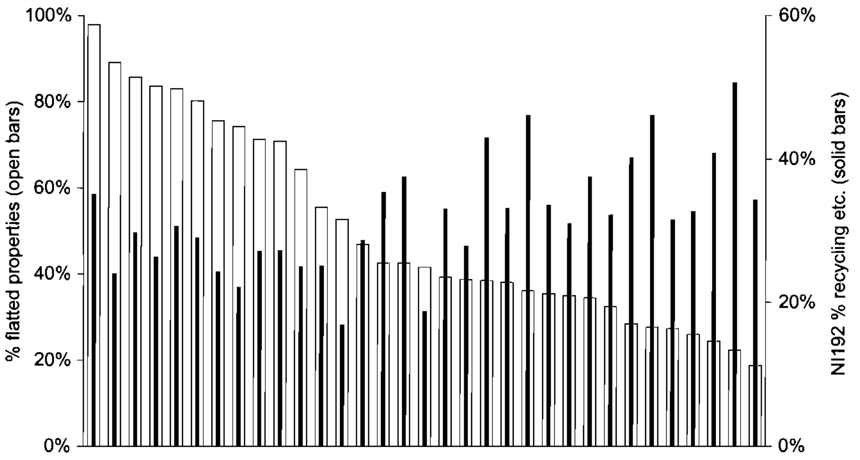

Figure 1. Negative correlation of percentage recycling with percentage flatted properties in London boroughs

over 100 years (IPCC, 2007). The EU also aspires to change from a disposal society to a recycling society.

'Kerbside' collection of source segregated wastes requires the solid waste from domestic and commercial premises to be stored in separate containers, collected separately and taken to treatment facilities. Dry recyclables (paper, glass, plastic and metal) can be segregated mechanically after collection but their value is reduced if they are contaminated with wet food waste (Yang *et al.*, 2010). The biodegradable fraction of solid waste is generally composted or anaerobically digested (AD). Methane from AD is used to produce renewable energy and the digestate can be used as soil improver. Separate collection often necessitates extra truck traffic, especially during summer when it is not acceptable to store biodegradable waste for long periods prior to collection because of odour.

The food waste disposer (FWD) was invented in 1927 by architect John W. Hammes of Racine, Wisconsin, USA to be a convenience for his wife. After 11 years of development his company started manufacturing and selling FWDs in 1938. Some cities in USA mandated FWD for all new build residential properties. FWDs fit the standard drain outlet hole of kitchen sinks and there are adaptors for other sizes. FWDs comprise a 'grind chamber' which has perforated walls; the floor is a disc with lugs driven by an electric motor that spins the food scraps against the wall by centrifugal force. There are no knives in a FWD so it cannot cut plastic or fingers. FWDs operate with a stream of cold water (which could be the vegetable washing water); this conveys the ground food waste through the drains. Particles cannot escape the grind chamber until they are small enough to pass the outlet screen. The grind effectiveness does not deteriorate with time. When FWDs wear out it is because the bearings have failed: life is typically 12 years. FWDs are 95% recyclable at end of life (InSinkErator, private communication, 2010).

Field trials have found user satisfaction with FWD is high, for example, Nilsson *et al.* (1990) found 96% satisfaction; Karlberg and Norin (1999) also reported 96% satisfaction in the trial before launching FWD as an option; NILIM (2005) found 80% of users would use FWD after their trial.

Today approximately 50% of households in the USA have a FWD; in some cities more than 90% have them. Atwater (1947) reported that initially sewerage engineers in the USA were apprehensive that the output of FWDs might affect their sewers and/or wastewater treatment adversely, but after reviewing the experiences of about 300 municipalities he concluded that their fears were unfounded. New Zealand and Australia also have high rates of installation at more that 30% and more than 20% respectively. Installation in EU member states (MS) is 6% or less. However the density of installation in commercial kitchens is very much greater. Generally domestic food waste in the EU is dealt with as part of the solid waste system; however, in some MS interest in FWD is growing for reasons discussed below. For example, Stockholm Water has evaluated the evidence; it now encourages FWD installation and use because it wants more biogas (Gustafsson, 2008).

2. Discussion

Because FWDs are 'novel' in the European waste management context, the current paper discusses their impacts in relation to the other options.

2.1 Effects on sewers

Several field studies have inspected sewers with and without FWD (e.g. Battistoni *et al.*, 2007; Karlberg and Norin, 1999; New York City DEP, 1999; Nilsson *et al.*, 1990) none reported any change in sediment accumulation or any other impedance to the flow. Nilsson *et al.* (1990) simulated 15 years of FWD use in a laboratory rig using a mixture of foods that included 8·5% w/w lard and 1·7% w/w margarine. They found no blocking of the pipes. Kegebein *et al.* (2001) measured the particle size distribution of FWD output using two mixtures of foods and also waste from the university's cafeteria. They found 40–50% of the output was < 0·5 mm, 98% was < 2 mm and 100% was < 5 mm by sieve analysis; between 15 and 36% of the output was in their 'dissolved' fraction. They observed sediment-free transport at 0·1 m/s, which is well within design standards for sewers (0·48–0·9 m/s, Ashley *et al.*, 2004).

Sewerage operators are rightly concerned about fat, oil and grease (FOG) which can block or severely impede sewers, but FOG is an entirely separate issue from FWD and requires proper attention (Ducoste, *et al.*, 2008). NILIM (2005) in Japan found no deposits in sewers where FWD had been installed and no difference in n-Hex (fat, oil and grease). Fat, oil or grease should never be poured down drains. Low-melting-point substances solidify on the cold walls but a different and more intractable substance forms by chemical reaction. Research suggests that this results from hydrolysis of FOG to form free fatty acids that saponify with calcium to form insoluble soaps. FOG samples analysed by Ducoste *et al.* (2008) were dominated by saturated fatty acids; they found no evidence of ground food waste fragments (Kevin Keener, Purdue University, private communication, 2010). They are found downstream of food service establishments particularly. Quite possibly, some passive grease traps are hydrolysis reactors releasing free fatty acids into the wastewater. Research into the subjects of FOG chemistry and of FOG separators is on-going and further results will assist development of better solutions. FOG has a large biogas yield so there is an opportunity for well-designed active-separators, installed appropriately, so that FOG can be collected and tankered away to anaerobic digestion and renewable energy generation (Larson, 2010).

2.2 Water use

FWDs use water to transport the ground food waste out of the grind chamber and through the drainage system. Field studies that have measured water use by households with and without FWD have shown water use is related to food preparation events, not to the number of people in a household.

Nilsson *et al.* (1990) metered 100 apartments and measured the duration of use per start and water use; duration was 38 s, daily water use decreased from 183 l/person during the 6 months without FWD to 170 l/person during the 11 months with FWD. Jones (1990) monitored 45 homes for 2 months with FWD and 2 months without FWD. He concluded that the influence on water use was not significant within the overall 'noise' in measured water use. Ketzenberger (1995) reported a detailed stratified survey that found that FWDs are used for about 15 s per start irrespective of the number of people in the household; subjectively this seems sensible and would account for the range of reported water-use when expressed as litres per capita. Karlberg and Norin (1999) reported 3 years' monitoring when 32 out of 39 apartments were fitted with FWD; water consumption reduced by 25% during the survey period, which the authors did not wish to attribute to FWD even though they had no other explanation for the result.

The largest field study into FWD was in New York City. It involved 514 apartments with FWDs compared with 535 apartments without FWDs. They were in four different localities to reflect some of the city's diversity. The survey comprised 2014 people in total; it concluded 'There is no statistically significant evidence that any change in water consumption has occurred as a result of the installation of FWDs at the three test sites. Each site faced serious challenges to observing a change in water consumption'. It went on to assume for the purpose of predicting impact on water resources that there would be an increase of 1 US gallon per person per day but this seems to have been arbitrary and unconnected with the actual measurements made in the field study (New York City DEP, 1999).

Evans *et al.* (2010) found the flow into a wastewater treatment works (WwTW) did not change significantly between the time when there were no FWDs and when 50% of the 3700 households used FWDs.

On the basis of field studies, 5 l/hhd.day (less than one flush of a modern toilet) would be a conservative (upper) estimate of additional water use (approximately 1·5%); this is of no consequence to sewer hydraulic capacity and negligible in terms of sewage pumping or water resources. The factor that stresses the hydraulic capacity of sewers is surface water; as far as possible, it should be controlled at source.

2.3 Energy and global warming potential

Domestic FWDs have a 350 to 750 W electric motor. Based on the field studies of usage discussed above under water use, the expected annual electricity consumption is 1·5 kWh_e/hhd.year, where kWh_e denotes kilowatt hour of electricity.

Kegebein *et al.* (2001) estimated that where the WwTW receiving the kitchen food waste treated its sludge by AD, the biogas from food waste would amount to approximately 300 MJ (mega Joule)/resident.year, which corresponds to a heating value of 8 litres of diesel fuel or 183 kWh (kilowatt hour) /hhd.year (2·2 people per household). At 40% electricity generation efficiency, this is 73 kWh_e/hhd.year electricity generation, which at the EU average for electricity generation is a global warming potential of −33 $kgCO_2e$/hhd.year ($kgCO_2e$ denotes kilograms carbon dioxide equivalent – 100-year global warming potential); that is, compared with the +1 kg CO_2e /hhd.year used to run the FWD. In 2005, 64% w/w of sewage sludge in England and Wales was treated by AD; by 2015 this will have increased to 85% (Keith Panter, Ebcor Ltd., private communication, 2010).

Lundie and Peters (2005) concluded 'FWD performed well in terms of energy usage, climate change and acidification potentials, although it makes a large contribution to eutrophication and toxicity potentials. ... centralised composting has a relatively poor environmental performance due to the energy-intense waste collection activities it requires. Implementing a separate collection and transportation system for organic waste results in relatively high environmental impacts due to the frequency of collections and the small quantities of green waste collected per household ... home composting is clearly the best option in terms of the categories examined in this LCA, there is an important caveat to this result. If operated without due care, home composting loses its allure due to the high greenhouse gas emissions consequent to anaerobic methanogenesis. Although home composting has the capacity to be the best food waste management option, it can also perform worst in relation to a subject in which Australia is already at the bottom of its class.' The question of methane from home composting has almost certainly been exaggerated. Smith and Jasim (2009) monitored home composting by 64 homeowners over 2 years and detected only traces of methane occasionally. They reasoned that, if formed in anaerobic microzones, methane would be oxidised by methanotrophic bacteria, which are ubiquitous.

Evans (2007) showed that the global warming potential (GWP) of delivering source segregated food waste to AD by way of FWDs and the sewers was equivalent to kerbside collection and transport to AD by road (≈ −170 $kgCO_2e$/t food waste). Both routes to AD were better than composting, incinerating or landfilling food waste (−14, +13 and +740 $kgCO_2e$/t food waste respectively). The incineration and landfilling scenarios both included energy recovery. The composting scenario was based on measurements performed on 16 in-vessel plants in the Netherlands reported by Smith *et al.* (2001); the plants' operating conditions pre-dated the Animal by-Products Regulation (CEC, 2002); operating under ABPR would have increased energy and carbon use somewhat so, if anything, Evans (2007) understated the GWP of centralise composting (−14 $kgCO_2e$/t food waste).

Based on the author's observations at waste treatment sites and discussions with operators, the inconvenient truths about separate collection of food waste are that people like to use bags or liners to keep their kitchen caddies clean and that cutlery and other items get into the waste by mistake. Riedel (2008) reported contamination (glass, metal, plastic) in household biowaste increased from 4% to 20% with time in Germany as householders became less diligent about sorting. Levis *et al.* (2010) reported at least 10–12% of compost feedstock in the US and Canada is glass, metal and plastic. Harrison (2010) reported that a food waste AD facility in Scotland is removing 20% w/w of the incoming material before digestion. Biodegradable bags degrade during composting but they are incompatible with wet AD. Fragments of plastic float and accumulate at the top of digesters; this raft of plastic would have to be removed periodically, which is expensive and hazardous because of the methane in the digester. Composting is reasonably tolerant of plastic, cutlery and other physical contaminants (although they might deteriorate compost quality), but they are incompatible with AD and resilient processes to remove them are essential; this is still an area for operational development. FWDs do not grind plastic, which therefore remains in the grind chamber and can be lifted out.

2.4 Odour, rats and disease

Unintended consequences of obliging people to store food waste might be nuisance (odour and vermin) and exposing them to health risks. The British Pest Control Association considered that since 98% of the ground food waste from FWDs is < 2 mm, it would not be detectable by rats (Adrian Meyer, private communication, 2005) but spilled and poorly contained food on the surface would attract rats, gulls and other scavengers. Wouters *et al.* (2000) reported that keeping separated food waste in kitchens increases bioaerosols and allergens compared with mixed waste that contains food waste; they concluded this is a respiratory risk to susceptible individuals.

2.5 Cost saving to waste collection and disposal agencies

Evans (2007) analysed the audited 2005/06 performance data for Herefordshire and Worcestershire (two counties in England that cooperate on waste management). The average household waste collected (weighted by population in each collection agency) was 894·8 kg/hhd.year. The range for the collection agencies was 1145 kg to 743 kg, reflecting that some offered kerbside collection of garden waste whereas others did not. The weighted average kerbside collection and disposal (including landfill tax) costs were respectively £43·89 and £61·97 /hhd.year. If the proportion of food waste was 17·6% (Hogg *et al.*, 2007), the combined collection and disposal cost for food waste was £18·63 /hhd.year. The escalation of landfill tax would have taken this to more than £30 /hhd.year in 2010.

2.6 Cost transfer to wastewater treatment

Surahammar in Sweden provided Evans *et al.* (2010) with an opportunity to assess the cost transfer from solid waste to wastewater, because in the space of 12 years FWD installation changed from 0% to 50% of households and throughout this period the WwTW that serves the municipality collected and analysed 4-weekly, 24-hour composite samples of the influent. The sewerage is largely separate surface and sanitary sewers with interconnection to relieve excess flow. During the 14 years of monitoring data, there was no major change in the domestic population or in trade effluent (non-domestic) discharge.

The FWD installation resulted from the municipality introducing tiered charges for food waste management. People who home-composted food waste paid nothing, those who leased a FWD from the municipality (8-year lease) paid £27 per year and those who chose kerbside collection paid £209 per year. The charge for the residual waste bin was also related to usage. There was a bring system for cardboard, glass, metal and plastic (i.e. drop-off locations to which residents take these materials). The policy was effective in that the tonnage of waste to landfill from the municipality decreased from 3600 t/year in 1996 to 1400 t/year in 2007.

FWD installation started in May 1997. Surprisingly the mean flow and mean loadings of BOD_7 (biochemical (or biological) oxygen demand (as mgO_2/l) for aerobic biological degradation of organic matter in water sample at certain temperature and time; '7' refers to 7 days, which is the standard time in Sweden), COD (chemical oxygen demand – measures organic matter degradable by a chemical oxidising agent, it is quicker than BOD. COD is typically 2 to 2·5 times BOD), nitrogen and ammoniacal-N were all less in December 2006 to April 2009 than they had been in January 1995 to April 1997, although the differences were not statistically significant (Table 1). Unfortunately, suspended solids were not one of the parameters in the analytical suite for the influent samples. The mean phosphate loading decreased 26% ($P = 0{\cdot}002$), which was probably because of a contemporaneous change to phosphate-free and low-phosphate detergent products. Sweden introduced a voluntary limit of 7·5%P in laundry detergents in 1970, which was so effective that the government was able to ban phosphate in laundry detergents from 1 September 2008 (as part of concerted action by Baltic countries) and to propose a ban of phosphate in domestic dishwasher detergents from 1 July 2011. Mean biogas production increased by 46% ($P = 0{\cdot}01$). The extra biogas at 40% electricity generating efficiency would equate to 76 kWh_e/hhd.year electricity generation, which agrees very well with the 73 kWh_e/hhd.year predicted by Kegebein *et al.* (2001) from experimental work.

The median influent flow for January 1995 to April 1997 (before FWD) was 4020 m^3/d, whereas the median for mid-December 2006 to April 2009 (when 50% of households had FWDs) was 3575 m^3/d. The scatter of results showed that despite maintenance work, a substantial amount of surface water and infiltration entered the sewers. Inevitably, some old domestic appliances will have been replaced by more water efficient ones during this 14 year monitoring period and this would result in some reduction in water use; overall there is no evidence that FWD affected the hydraulic loading on sewers.

The increase in biogas is evidence that the FWDs provide additional substrate for biogas production, presumably in the form of particulate material that settles in the primary tanks. The absence of change in BOD, COD or nitrogen is consistent with the observation of Karlberg and Norin (1999) that electricity use by the activated sludge plant had not changed as a result of FWD installation.

Sewers are linear bioreactors with some activity in the suspended biomass, which is flushed through continuously, and more in the biofilms attached to the sewer walls. DNA profiling has revealed that biofilm ecology differs from one location to another reflecting the sewage flowing past (Catherine Biggs, Sheffield University, private communication, 2009). Anammox bacteria, which convert nitrite and ammonia to nitrogen gas, are found in sewer slimes, estuary mud and anoxic or anaerobic ecological niches. The trends in the influent monitoring data (BOD, COD, N and NH_4^+) are consistent with a hypothesis that the biofilm ecology has acclimated to the change in sewage composition. The difference between the 120 week pre-installation data and the 533 week post-installation data are consistent with the hypothesis that sewer ecology acclimated to the additional dissolved and fine particulate load. It also indicates the duration of studies that is needed when interpreting field studies, because a short duration study would not have seen this important effect because there would not have been enough time for acclimation.

Thermal electricity generation uses about 80 litres water/kWh_e; the UK's average electricity generation emission factor is 0·541 $kgCO_2e/kWh_e$ (National Energy Foundation); it is greater than the EU average. The offset from the electricity from biogas is thus 6000 l water and 41 $kgCO_2e/kWh_e$, which is a net annual benefit (after deducting additional water and electricity to run the FWD) of about 4100 l water and 40 $kgCO_2e$/hhd. year per household.

	Flow m^3/d	kgBOD_7/d	kgCOD/d	kgN/d	kgNH_4/d	kgP/d	BOD_7:N	m^3 biogas/d
Mean pre FWD 120 weeks 11/01/95–30/04/97	4706	408	1084	113·6	74·0	18·0	3·50	331
Variance	3 034 123	46 620	394 192	979	405	49·9	1·695	1036
Mean post FWD 533 weeks 12/01/99–01/04/09	4538	381	1062	108	67	15·4	3·55	447
Variance	7 171 537	38 370	262 063	1084	490	26·6	1·902	3005
Difference ($post_{533}$-pre)	−3·7%	−7·1%	−2·0%	−5·3%	−9·5%	−14%	+1·63%	+35%
P (1-tail, *t*-test)	0·34	0·27	0·43	0·19	0·06	0·04	0·42	0·002
Mean early post FWD 120 weeks 12/01/99–02/05/01	5194	520	1420	113.8	62·4	17·5	4·60	410
Variance	13 156 275	69 225	425 475	1507	391	22·4	2·341	6·937
Difference (early $post_{120}$ −pre)	+10·3%	+27·4%	+31·0%	+0·16%	−15·7%	−2·6%	+31·5%	+23·9%
P (1-tail, *t*-test)	0·25	0·04	0·03	0·49	0·02	0·39	0·002	0·03
Mean late post FWD 120 weeks 13/12/06–01/04/09	4678	331	892	107	71	13·3	3·11	484
Variance	5 675 190	17 138	167 426	548	282	12·7	1·191	3147
Difference (late $post_{120}$ − pre)	−0·59%	−19·0%	−17·7%	−6·1%	−3·9%	−26·1%	−11·1%	+46%
P (1-tail, *t*-test)	0·50	0·06	0·09	0·18	0·28	0·002	0·11	0·01

Table 1. Student's t-test comparing influent and biogas pre and post FWD installation (from Evans *et al.*, 2010)

2.7 Sludge production

FWDs do add to biosolids production but the increase is small. Food waste is typically 70% moisture (30% dry solids) and 90% volatile solids (weight loss on ignition of the dry matter). It is very biodegradable; the volatile solids reduction during AD is about 90%. Thus, 1 t food waste (fresh weight) contributes about 50 kg dry solids to digestate production, which is recycled as part of the biosolids recycling programme with all of its proven safeguards (e.g., CEN, 2007; National Research Council, 2002; Smith, 1996, 2000). All of the nutrients in the food waste going into AD are retained in the digestate.

3. Conclusions

Practical experience and research into in-sink FWDs demonstrate that while apprehensiveness might be understandable, it is unfounded and FWDs constitute one of the viable tools for managing kitchen food waste. FWDs segregate food waste at source and have a high user satisfaction rate. Source segregation and storage of food waste for home composting or for kerbside collection is acceptable to many citizens but experience shows that a substantial proportion of the population is unwilling to participate in this means of recycling. FWD linked to the public sewer and delivering to WwTW is a valid means of diverting kitchen food waste from the general waste stream (and landfill). Treatment by AD creates non-fossil, baseload electricity. Use of biosolids from wastewater treatment on land is a well-demonstrated, safe means of completing nutrient cycles and conserving soil organic matter; integrating treated food waste is sensible.

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