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Heaven, S., Salter, A.M., and Banks, C.J. (2011) Integration of on-farm biodiesel production with anaerobic digestion to maximise energy yield and greenhouse gas savings from process and farm residues. *Bioresource Technology* 102(17), 7784–7793
doi.org/10.1016/j.biortech.2011.06.029

Integration of on-farm biodiesel production with anaerobic digestion to maximise energy yield and greenhouse gas savings from process and farm residues

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Abstract

Anaerobic co-digestion of residues from the cold pressing and trans-esterification of oilseed rape (OSR) with other farm wastes was considered as a means of enhancing the sustainability of on-farm biodiesel production. The study verified the process energy yields using biochemical methane potential (BMP) tests and semi-continuous digestion trials. The results indicated that high proportions of OSR cake in the feedstock led to a decrease in volatile solids destruction and instability of the digestion process. Co-digestion with cattle slurry or with vegetable waste led to acceptable specific and volumetric methane productions, and a digestate low in potentially toxic elements (PTE). The results were used to evaluate energy balances and greenhouse gas emissions of the integrated process compared with biodiesel production alone. Co-digestion was shown to provide energy self-sufficiency and security of supply to farms, with sufficient surplus for export as fuel and electricity.

Keywords: Anaerobic digestion, biodiesel production, oilseed rape, renewable energy, agro-wastes.

1 Introduction

Oilseed rape (*Brassica napus*) is now commonly grown across northern Europe as part of a crop rotation in cereal production. Grown in this way it provides a cropping system that has environmental benefits both for the soil and for wild bird populations (Henderson et al., 2009, Kleijn et al. 2009), as well as leading to reduced weed and pathogen problems in subsequent cereal crops. Biodiesel can be produced from oilseed rape (OSR) seed using relatively simple methods that can be applied at small scale on the farm (Balat and Balat, 2008, Murugesan et al., 2009). The seed is crushed to extract the oil which is then filtered and converted into biodiesel through a trans-esterification process involving the addition of an alcohol (usually methanol). Both of these stages require energy, mainly in the form of electricity, whereas the major energy input in the production of the oilseed and cereal crops is diesel fuel (Boatman et al., 1999).

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The sustainability of the biodiesel production process could be improved by substitution of imported energy with farm-produced sources of both fuel and power. The majority of farm machinery can run on farm-produced biodiesel, and electricity can be generated on site from a combined heat and power (CHP) unit operating on this product. Alternatively, biogas produced from anaerobic digestion (AD) could be used as a fuel source. Feedstock for the digestion process could include the secondary products from biodiesel production, which are oilseed rape cake (the remains of the seed after crushing to remove the oil) and crude glycerol (produced during esterification of the oil to biodiesel). In practice these would probably be co-digested with other agricultural residues and wastes produced on the farm or imported onto it.

Production and utilisation of energy on the farm improves its environmental footprint by reducing greenhouse gas (GHG) emissions, as both power and fuel are derived from carbon neutral sources. Further potential benefits from coupling biodiesel production to an AD plant are that the majority of nutrients are conserved, and the digestion process makes them more readily available for plant uptake (Lukehurst et al., 2010). The digestate therefore provides a valuable source of bio-fertiliser which can be used on the farm to replace mineral fertilisers, and also offsets the GHG emissions associated with their production. It is important that this type of integrated approach is adopted, as any process for the production of renewable energy can only be considered sustainable if the energy required to produce the fuel is less than the energy value of the final fuel product (Salter and Banks, 2009). This is particularly the case for biodiesel, as oilseed crop yields are relatively low: in the UK, for example, the average yield of OSR seed is 3.5 tonnes ha⁻¹ (Defra, 2009), giving a much lower net energy yield per unit area of land cultivated than alternative biofuel crops such as wheat grain for bio-ethanol or perennial ryegrass for bio-methane (Patterson et al., 2008).

The research evaluated the potential of this type of integrated approach, through a case study of a group of farmers in the north of England who were considering on-farm biodiesel production. The main activity of the consortium was cereal production but one member also undertook dairy farming and others had commercial interests in a vegetable processing plant. Energy balances and GHG savings were quantified assuming on-farm processing of the oil seed with and without anaerobic co-digestion of residues, for a number of scenarios typical of this type of farming. The financial viability of the scenarios was not evaluated as this is highly dependent on fluctuating commodity prices and changes in subsidy regime, including measures specifically introduced to promote renewable fuel production (Banks et al., 2009). The work included an extended laboratory study of the anaerobic digestion of the biodiesel by-products and farm residues to allow assessment of the specific methane potential of the mixed substrates, the digestate characteristics, and the stability of the digestion process.

2 Materials and Methods

The farming cooperative consisted of five farms and a vegetable processing plant. One of the farms had a dairy herd of 390 cows kept in housing all year and producing 12 000 tonnes year⁻¹ of slurry. This slurry is stored in an open tank and subsequently applied as fertiliser to 181 ha of grassland. All five farms grow OSR as part of their crop rotations, with an average yield of 3.7 tonnes seed ha⁻¹. The vegetable processing plant produces 10,400 tonnes year⁻¹ of waste with a seasonal variation of 20-60 tonnes day⁻¹; the waste consisted of peelings from swede (*Brassica napus napobrassica*) and the outer leaves and trimmings of sprouts (*Brassica oleracea gemmifera*).

The base case scenario was that the cooperative of farmers only installed a biodiesel production unit, with no internalisation of energy usage other than direct use of the biodiesel in crop production. The other four scenarios all included integration of an anaerobic digester with the biodiesel plant to maximise the internalisation of energy use. These additional scenarios were differentiated by the materials used as digester feedstock. The location of the proposed digester was determined by land availability, and also by proximity to a potato processing plant with a requirement for both electricity (3250 MWh year⁻¹) and heat (877 MWh year⁻¹). In the base case scenario the biodiesel processing unit is located on the dairy farm as this is the largest producer of OSR seed, and the pressed OSR cake can also be used to feed the cattle. Where an integrated process is modelled the AD plant and biodiesel production plant are co-located on one site so that maximum advantage can be taken of the CHP output of the AD plant. The sizes of the farms, their current OSR production and distances to the related infrastructure are shown in Table 1.

2.1 Feedstocks

Four substrates were considered as inputs for AD. These were oilseed rape cake (OSRC), crude glycerol from biodiesel production, cattle slurry from the dairy herd, and waste from the vegetable processing plant. Samples of these substrates were obtained from the farms, with the exception of crude glycerol which was provided by D1 Oils Ltd of Teeside, UK. Table 2 shows the annual production of OSRC, vegetable waste and cattle slurry, and the estimated tonnage of crude glycerol that would be produced from trans-esterification, based on data supplied by D1 Oils.

Three mixed feedstocks were made up proportionally on a wet weight (WW) basis to represent the tonnages produced, as shown in Table 2. The cattle slurry and the vegetable wastes were first homogenised by passing them through a macerating grinder (S52/010, IMC Ltd, Wrexham, UK). Each mix was then prepared as a single batch by combining the ingredients in a 70-litre container, using an electric mixer to ensure uniformity. Each mix was then portioned into 4-litre sealed containers, labelled and frozen. Feed was defrosted as required and once thawed was kept refrigerated for not more than one week before use.

A fourth feedstock (Mix 4) consisting of vegetable waste only was also used in the study. This consisted of swede peelings and sprout leaves in the same proportion as the previous batch of vegetable waste, but with a higher total and volatile solids concentration due to a reduced volume of washwater.

2.2 Laboratory-scale anaerobic digestion study

A semi-continuous anaerobic digestion study was carried out in duplicate on each mix, using digesters with a working volume of 4 litres which were continuously stirred at 40 rpm by a mechanical mixer inserted through a gas-seal draught tube. The digesters were maintained at 37 °C by circulation of hot water from a thermostatically-controlled pump through an external heating coil. Initially each digester was seeded with 4 litres of cattle slurry taken from the farm consortium; but due to very low biogas production this was supplemented after a few days with digestate from an AD plant treating municipal wastewater biosolids (Millbrook, Southampton, UK). The inoculum cattle slurry and the biosolids digestate were sieved through a 1 mm mesh size sieve to remove gross contaminants such as stones and hair before use. Feed was added directly to the digesters via a bung-hole in the top plate, and digestate removed via a wide-bore tube in the base. A volatile solids (VS) loading of 1 kg m⁻³ day⁻¹ was applied for the first few days, then gradually increased over an acclimatisation

period of 2-3 weeks to the working organic loading rate (OLR) of 3 kg VS m⁻³ day⁻¹. During this period the digesters were only monitored for biogas production and pH.

The digesters were operated according to the parameters in Table 2 for approximately three times their respective hydraulic retention times (HRT), to allow the establishment of stable operating conditions. During this time substrate was added to each digester daily and a sufficient quantity of digestate removed to maintain a constant working volume. This volume was checked twice a week, and any difference from the reference level compensated for by adjusting the amount of digestate removed. The digesters were monitored for biogas production and composition, pH, solids destruction, alkalinity, ammonia and volatile fatty acid (VFA) concentrations.

2.3 Chemical and biochemical analysis

Total solids (TS) and volatile solids (VS) were measured according to Standard Method 2540 G (APHA, 2005). Total Kjeldahl Nitrogen (TKN) and digestate ammonia were determined using a Kjeltech digestion block and steam distillation unit, according to the manufacturer's instructions (Foss Ltd, Warrington, UK). Potassium and phosphorus were extracted with concentrated HNO₃ in a CEM Microwave Accelerated Reaction System for Extraction (MAR SX, CEM Corporation, North Carolina, USA). Potassium was quantified using a Varian Spectra AA-200 atomic absorption spectrophotometer (Varian, Australia) according to the manufacturer's instructions. Phosphorus was measured spectrophotometrically by the ammonium molybdate method (ISO 6878: 2004). Digestate pH was measured using a combination glass electrode and meter calibrated in buffers at pH 4, 7 and 9. Alkalinity was measured by titration with 0.25 N H₂SO₄ to endpoints of pH 5.75 and 4.3, in order to allow calculation of total (TA), partial (PA) and intermediate alkalinity (IA) (Ripley et al., 1986). VFA were quantified in a Shimadzu GC-2010 gas chromatograph (GC) with a flame ionisation detector and a capillary column type SGE BP-21. The carrier gas was helium at a flow of 190.8 ml min⁻¹ and a split ratio of 100 to give a flow rate of 1.86 ml min⁻¹ in the column and a 3.0 ml min⁻¹ purge. The GC oven temperature was programmed to increase from 60 to 210 °C in 15 minutes with a final hold time of 3 minutes. The temperatures of injector and detector were 200 and 250 °C, respectively. Samples were prepared by acidification in 10% formic acid. A standard solution containing acetic, propionic, iso-butyric, n-butyric, iso-valeric, valeric, hexanoic and heptanoic acids, at three dilutions to give individual acid concentrations of 50, 250 and 500 mg l⁻¹ respectively, was used for calibration. Biogas composition was measured using a Varian CP 3800 GC with a gas sampling loop using argon as the carrier gas at a flow of 50 ml min⁻¹. The GC was fitted with a Hayesep C column and a molecular sieve 13 x (80-100 mesh) operated at 50 °C. Gas volumes in the semi-continuous digestion study were measured using a tipping-bucket gas flow meter (Walker et al., 2009). Gas volumes were corrected to standard temperature and pressure (STP) of 101.325 kPa and 0 °C as in Walker et al. (2009).

The biochemical methane potential (BMP) of the feedstocks was measured using 1.5-litre working volume digesters continuously stirred at 40 rpm and maintained in a thermostatic water bath at a temperature of 37±1 °C. The inoculum used was sieved digestate from the Millbrook AD plant, as above. Samples were run at an inoculum:substrate VS ratio of 4:1 in triplicate against triplicate blanks containing inoculum only. For the first 14 days, biogas was collected in calibrated glass cylinders by displacement of a 75% saturated sodium chloride solution acidified to pH 2. The height of the solution in the collection cylinder was recorded by a headspace pressure sensor and logged at 5-minute intervals, with manual readings to check calibration. After 14 days, the digesters were disconnected from the cylinders and gas

was collected in Tedlar bags (SKC, Blandford Forum, UK) with volumes measured using a weight-type gasometer (Walker et al., 2009). Gas compositions were measured each time a cylinder or bag was refilled and gas volumes were corrected to STP as above.

2.3.1 Solids destruction

TS and VS destruction was calculated on a weekly basis by mass balance. For this purpose it was assumed that the wet weight of digestate removed was equal to the wet weight of feedstock added, minus the weight of biogas removed. The weight of biogas removed was estimated from the weekly average volume and gas composition in terms of % CH₄ and CO₂ (ignoring water vapour and other gases).

2.4 Energy and GHG analysis

Energy requirements considered include those for crop production and transport, mineral fertiliser production, biodiesel production, digester operation and digestate transport and application. GHG emissions include those from direct and indirect use of fossil based fuels, but not from manure or digestate management or enteric emissions from cattle. Biodiesel and biogas are carbon neutral as they are part of the short-term carbon cycle, and their combustion products are therefore not considered to contribute to GHG emissions.

Diesel fuel requirements for OSR production were calculated using literature data and standard operations, as follows: ploughing (23.2 l ha⁻¹), 2 x seed bed preparation (5.7 l ha⁻¹ operation⁻¹), drilling (2.8 l ha⁻¹), rolling (1.1 l ha⁻¹), 5 x spraying (0.9 l ha⁻¹ operation⁻¹), 2 x mineral fertiliser application (0.7 l ha⁻¹ operation⁻¹) and harvesting (18 / ha⁻¹) (Audsley et al., 2006; KTBL, 2009; Mortimer et al., 2003; Richards, 2000). The energy value of diesel was taken as 35.7 MJ l⁻¹ (AEA, 2010). Biodiesel with an energy value of 32.8 MJ l⁻¹ (Mortimer et al., 2003) was assumed to replace fossil fuels for the transport of oilseed, waste and digestate, giving a GHG emissions saving of 0.0748 kg CO₂ equivalent MJ⁻¹ (AEA, 2010).

The oilseed rape in the study was autumn-sown and fertiliser application rates were taken as 190 kg N ha⁻¹, 80 kg P₂O₅ ha⁻¹ and 70 kg K₂O ha⁻¹ (Defra, 2010). Fossil fuel based energy use in mineral fertiliser production was taken as 40.3, 3.4 and 7.3 MJ kg⁻¹ for N, P₂O₅ and K₂O respectively, based on averages from European producers (Kongshaug, 1998); a further 2.6 MJ kg⁻¹ product was assumed for packaging and transport (Mortimer et al., 2003). GHG emissions for mineral fertiliser production were taken as 6.81, 1.74 and 1.81 kg CO₂ equivalent kg⁻¹ product for N, P₂O₅ and K₂O respectively (Mortimer et al., 2003).

Energy used in the digestion process was calculated for the chosen digester design and operating mode based on the values in Salter and Banks (2009). As the feedstocks were waste materials, no energy input was included for production, but the energy used in transport from the source to the digester was calculated based on mileage. It was assumed that the biogas produced is used in a CHP unit to provide heat and electrical energy which, in the first instance, is used to satisfy the parasitic energy demand of the digester. Any surplus electricity was assumed to be used firstly in biodiesel production, and secondly exported. The GHG emissions saving from replacement of grid-based electricity generated from fossil fuels was taken as 0.166 kg CO₂ equivalent MJ⁻¹ (DECC, 2010).

Where the feedstock included slurry it was assumed that an amount of digestate with a nitrogen content equivalent to that required to fertilise 181 ha of grassland at 250 kg N ha⁻¹ is returned to the dairy farm. The energy for transport of this material was taken into account, but the energy for spreading digestate was not, as this operation would also be necessary for the slurry it replaces. It was assumed that any additional digestate is applied to the OSR crop

at an application rate based on the digestate nitrogen concentration. The diesel requirement for spreading was taken as 3.6 l ha⁻¹ operation⁻¹ based on the use of a trailed hose applicator (KTBL, 2002). Any remaining nutrient requirement for the OSR is assumed to be applied in the form of mineral fertiliser. In the scenarios where the AD plant receives no slurry, all of the digestate was assumed to be available to provide fertiliser for the OSR fields. In the scenario where the feedstock consisted of vegetable waste, it was assumed that biodiesel production continues but the OSRC and glycerol are used for other purposes, e.g. as cattle feed or to other markets.

3 Results and Discussion

3.1 OSRC and crude glycerol characteristics.

Feedstock characteristics of the cattle slurry and vegetable waste are not reported in detail as literature values are widely available (e.g. Burton and Turner, 2003; Gunaseelan, 1997), but the characteristics of the biodiesel components OSRC and crude glycerol are shown in Table 3 as these differed slightly from typical values. The lipid content of OSR seed is typically around 45% on a TS basis (Norton and Harris, 1983) while that of cold pressed cake is 15-25% (DLG, 1997), indicating that the efficiency of the extraction process used was slightly below average.

The theoretical maximum methane potentials of the OSRC and crude glycerol calculated using the Buswell equation (Symons and Buswell, 1933) are 0.693 and 0.529 m³ CH₄ kg⁻¹ VS respectively. Based on its biochemical composition the theoretical methane yield of the OSRC is 0.532 m³ CH₄ kg⁻¹ VS taking into account proteins, lipids and carbohydrates (Angelidaki and Sanders, 2004); and 0.572 m³ CH₄ kg⁻¹ VS including hemi-cellulose and cellulose. Comparison of the elemental composition of the crude glycerol sample with a theoretical value based on the chemical formula for glycerol (C₃H₈O₃) confirms that the sample is unrefined, but no further analysis was carried out to determine the nature of the impurities.

3.2 Laboratory anaerobic digestion studies

3.2.1 Gas production

Specific methane production in the semi-continuous digestion study is shown in Figure 1a-c. As can be seen, Mix 1 approached a stable methane yield quite rapidly. Mix 2 also stabilised rapidly: there was some difference between the duplicates from day 75 onwards but values converged again by the end of the run. Mix 3 was less stable than the others, showing a rapid but unequal initial increase in methane production in the two digesters followed by a fall after day 40.

One possible cause for the failure of Mix 3 was considered to be the relatively high proportion of OSRC, with its residual content of fats and oils which are known to cause problems in digestion (Chen et al., 2008). This may have been compounded by a lack of trace elements in the feedstock: the other mixes all included cattle slurry which often contains a variety of trace elements from feed additives given to improve ruminant digestion (McDowell, 1996). The two digesters fed on Mix 3 were therefore supplemented at day 50 by adding 1 ml l⁻¹ of a trace elements solution (Gonzales-Gil et al., 2001), and then left without feeding for 9 days to recover. To establish whether either of the suggested factors contributed to the fall in methane production feeding was then resumed, initially at a lower loading rate, with R5 fed on Mix 3 as before and R6 on vegetable waste without OSRC (Mix 4). Both

digesters received a weekly supplement of the trace element solution at a dose equivalent to the amount removed in digestate. The OLR was gradually increased to its former level over periods of 20 and 30 days for Mix 3 and 4 respectively. The trace element solution allowed both digesters to respond well to their respective mixes and it is therefore likely that trace element deficiency was a factor in the previous failure. In the final three weeks of operation, however, specific methane production in R5 began to fall again (Figure 1c), losing around 10% of its previous value of $\sim 0.48 \text{ l CH}_4 \text{ g}^{-1} \text{ VS}_{\text{added}}$ by the end of the experimental period.

3.2.2 Digester stability

Digestate pH values are shown in Figure 1d-f. Mix 1 showed a gradual increase, stabilising between pH 7.7-7.9. For Mix 2, pH fell rapidly from 7.5 to 7.1 at day 26 then recovered to 7.7 over the next 5 days and stabilised at ~ 7.9 . For Mix 3 pH declined between day 30-50 from 7.5 to 6.8 in R5 and to 7.1 in R6, parallel to the fall in methane production. Once feeding was resumed the pH in both reactors stabilised, at around 7.9 and 7.7 for Mix 3 and Mix 4 respectively.

Table 4 shows values for digestate alkalinity, ammonia and VFA at the end of each run. Mix 1 maintained an IA/PA ratio of around 0.3 indicating good stability (Ripley et al., 1986). Mix 2 showed slightly higher TA, PA and IA than Mix 1 with a similar IA/PA ratio. The IA/PA ratio for Mix 3 reached 2 and 1.7 on day 50 in R3 and 4 respectively, when pH and gas production fell, but recovered to around 0.3 from day 79 onwards under the new feeding regimes. From day 122 alkalinity values for Mix 3 appeared stable at around 17.6, 13.7, 3.9 $\text{g CaCO}_3 \text{ l}^{-1}$ for TA, PA and IA respectively; but in the last 2 weeks of the run IA increased and the IA/PA ratio rose to 0.62. TA, PA and IA values for Mix 4 were still falling slightly at the end of the run, and had reached 10.0, 7.0 and 3.0 $\text{g CaCO}_3 \text{ l}^{-1}$ respectively by day 175. As with Mix 3 the IA/PA ratio appeared stable at ~ 0.3 until the end of the run when it showed a small increase to 0.43.

Ammonia concentrations stabilised at around 2.3 $\text{g NH}_3\text{-N l}^{-1}$ for Mix 1 and reached 3.8-4.0 $\text{g NH}_3\text{-N l}^{-1}$ for Mixes 2 and 3, reflecting the higher proportion of OSRC in these feedstocks. After the change of feedstock to Mix 4, the ammonia concentration in R6 fell to around 1.5 $\text{mg NH}_3\text{-N l}^{-1}$ by the end of the run.

Total VFA concentrations in the digesters fed on Mixes 1 and 2 remained below 200 mg l^{-1} throughout, indicating stable operation. The VFA concentration in the digester fed on Mix 3 remained low until day 110 after which acetic acid began to rise steadily, reaching 5790 mg l^{-1} by day 175. Other VFA species also began to rise from day 153 onwards with propionic, iso-butyric and iso-valeric acids reaching concentrations of 927, 193 and 368 mg l^{-1} respectively by the end of the run. Together with the fall in methane production and the rise in IA/PA ratio this indicated some instability, which only developed after a considerable run time. Possible reasons for this include the relatively high ammonia concentration which could be toxic to the methanogenic population (Chen et al., 2008); insufficient trace element supplementation; or the accumulation of non-degradable or toxic intermediates from the OSRC and glycerol, e.g. long chain fatty acids, soaps and methanol. Mix 4 also showed an increase in total VFA concentration to 1419 mg l^{-1} at the end of the run, consisting primarily of acetic acid at 1296 mg l^{-1} . It is unlikely that this was a result of toxicity, due to the low ammonia concentration and absence of OSRC and glycerol: the most likely explanation is thus the deficiency of one or more trace elements. A further study (not reported here) indicated that VFA accumulation in digesters fed on vegetable waste only could be remedied by increasing the amount of selenium in the trace element supplementation. Mixes 1 and 2

did not show the stability problems encountered with Mix 3 and 4, despite the fact that Mix 2 contained a higher proportion of OSRC than Mix 3, at 59.4% and 51.5% on a VS basis respectively. A possible explanation is the presence of cattle slurry in Mixes 1 and 2, which may have supplied any missing trace elements.

3.2.3 Solids destruction

Figure 2 shows TS and VS destruction in the digesters. Mix 1 showed consistent TS and VS destructions of around 63 and 70% respectively from day 50 onwards. The digesters fed on Mix 2 had slightly different solids destruction rates, at 44 and 50% TS and 53 and 57% VS for R3 and R4 respectively, reflecting slight differences in methane production (Figure 1b). Solids destruction for Mix 3 also mirrored methane production, and after modification of the feeding regime reached apparently steady rates of around 62 and 70% (TS) and 67 and 76% (VS) for Mixes 3 and 4 respectively. In the case of Mix 3 the tail-off in methane production towards the end of the run can also be seen in a slight decline in solids destruction (Figure 2). Solids destruction rates broadly reflected the proportion of OSRC in the feedstock, suggesting that a fraction of the pressed cake material is resistant to anaerobic degradation, perhaps due to its lignin content (Table 3).

3.2.4 Digestate properties

Plant nutrient and heavy metals concentrations in the digestates are shown in Table 4: values for Mix 1 and 2 are averages for the duplicate digesters, which showed good agreement. Values for Mix 3 and 4 were determined before the digesters had completed 3 HRT of operation and may therefore not represent steady state values. Despite relatively low of heavy metal concentrations in the feedstocks (not shown) and in the wet digestates, when expressed on a TS basis these are in some cases close to the limit values in the UK's PAS 110 digestate specification (BSI, 2010) (e.g. for cadmium, chromium and nickel). These values reflect the degree of solids destruction achieved in the digestion process: since heavy metals are conserved in the digestion process, the better the performance in terms of solids destruction, the more difficult it is to meet a standard based on g kg^{-1} TS rather than on wet weight of digestate applied to land.

3.2.5 BMP results and residual biogas production

Results from the first 14 days of the BMP tests are shown in Figure 3. There was good agreement between triplicates, with the exception of one replicate of Mix 3 with slightly lower gas production. The gas production curves in each case are typical of substrates containing a high proportion of readily degradable material, with 75-80% of methane produced in the first 5 days. The methane yields after 72 days for Mixes 1 and 2 were 0.474 and $0.436 \text{ m}^3 \text{ CH}_4 \text{ kg}^{-1} \text{ VS}_{\text{added}}$, and after 77 days for Mixes 3 and 4 were 0.543 and $0.414 \text{ m}^3 \text{ CH}_4 \text{ kg}^{-1} \text{ VS}_{\text{added}}$ respectively. These high values, especially for Mix 3, reflect the contribution from the OSRC and crude glycerol. They are also based on measured VS, but in the method used crude glycerol is likely to evaporate during the initial TS analysis, giving an artificially low VS content and thus a high BMP.

To determine residual methane potential, at the end of each semi-continuous digestion run 3 litres of digestate were left in the digesters which were stirred and maintained at 37°C without further feeding, with gas production recorded until day 287. The residual methane values obtained in this way were 7.28 , 5.68 , 9.78 and $5.02 \text{ l CH}_4 \text{ l}^{-1} \text{ digestate}$ for Mixes 1, 2, 3 and 4 respectively. When combined with the average methane yields from Mix 1, 2, 3 and 4 in the semi-continuous trials the totals correspond to 103%, 91%, 97% and 97% of the respective BMP results, showing close agreement between the methane production potentials

as determined by these two methods. These values may not represent typical residual methane production from digestates stored at ambient temperature without stirring; but they provide some indication of the potential for GHG emissions from the digested material, or for further energy recovery from covered storage.

3.2.6 Summary of results

Values obtained from the laboratory studies and required for full-scale digester design and energy balance assessment are summarised in Table 5. The volumetric methane production is dependent on the OLR applied, but a value in excess of 1 is regarded as acceptable for most commercial purposes.

The results of the laboratory study confirm that semi-continuous testing is essential for estimation of digester design parameters and energy yields in full-scale operation, as use of BMP values alone leads to over-estimation of the energy production potential; and more importantly, may not indicate any potential inhibition. Mix 1 and 2 were suitable substrates for stable digestion, and showed that the vegetable waste component is not essential for successful operation in cases where this type of activity does not occur on participating farms. Mix 3 and 4 showed the potential for instability after extended runs but might respond to appropriate trace element supplementation; alternatively, a slight improvement in oil extraction efficiency may improve stability with Mix 3.

3.3 Estimation of on-farm energy production, usage and indirect savings

3.3.1 Energy requirement for biodiesel production

The energy requirement can be considered in three parts: crop growth and transport (crop production); converting seed into oil (substrate conversion); and esterification into biodiesel (fuel conversion).

The diesel fuel energy for crop production was calculated as 2178 MJ ha⁻¹ excluding fertiliser application. For the base case without AD, the energy requirement for mineral based fertiliser is 9324 MJ ha⁻¹ plus 50 MJ ha⁻¹ for application (two operations) giving a total of 11.55 GJ ha⁻¹.

With the current oil extraction efficiency, estimated yields from biodiesel production are around 273 kg (310 litres) of biodiesel and 727 kg OSR cake per tonne of seed. Energy is required in the form of electricity for the crusher (Strähle SK 190/1, 80kWh tonne⁻¹ seed) and for esterification (66 kWh tonne⁻¹ oil) (Elsayed et al., 2003); this is equivalent to 1.31 GJ ha⁻¹ or 1.1 MJ l⁻¹ of biodiesel produced. The energy for production and conversion is thus 12.86 GJ ha⁻¹ and the fuel value of the biodiesel is 37.65 GJ ha⁻¹ giving a net energy yield of 24.79 GJ ha⁻¹.

The data in Table 5 were used to model energy balances for full-scale digesters. The required digester capacities, assuming an OLR of 3 kg VS m⁻³ day⁻¹ as in the laboratory trials and including 10% capacity for biogas storage, are shown in Table 6. The digestate nitrogen contents in Table 4 were used to calculate the volume of digestate that could be returned to the dairy farm or applied to fertilise the oilseed rape, with any balance made up using mineral fertiliser.

3.3.2 Overall energy balances and GHG emissions savings

Energy balances are shown in Table 6. In the current study, the surplus heat available in all four scenarios is greater than required for the nearby potato processing plant. None of the

scenarios produce sufficient surplus electricity for the potato plant; but Mixes 1 and 3 could supply 70% or more of this.

In general it is clear that on-farm biodiesel production combined with AD of residues has the potential to offer energy self-sufficiency and security of supply for farms, as well as providing a surplus of fuel and electricity for export. The decision on whether to use OSRC as a digester feedstock in a given year will depend on the value of the material on commodity markets as an animal feedstuff, compared with that of the energy which could be obtained from it by AD. The energy balance for co-digestion of the biodiesel by-products, however, is independent of these market-driven factors and remains favourable. An increase in the efficiency of oil extraction above that achieved in the current study would alter the partitioning of energy between fuel types, but will not greatly affect the overall energy balance: more efficient extraction will increase biodiesel production but reduce the methane yield, leading to lower heat and electricity outputs, and a small increase in emissions savings. Economic uses for surplus heat are not always easy to find, although in the UK OSR seed is usually dried for storage (Armitage et al., 2005), creating further possible opportunities for energy savings which were not taken into account here. Where there is no local power demand electricity can be exported to the grid, although local consumption is preferable as energy losses through transmission are lower: this saving and the associated reduction in GHG emissions have not been quantified.

GHG emissions savings are shown in Table 6. Emissions savings for electricity do not take into account the parasitic electricity consumption of the AD plant, as this energy would not otherwise have been used. In the case of biodiesel the emissions savings are based on the total fuel production, as this replaces fossil fuel usage: emissions associated with waste and digestate transport are taken into account as these would not have occurred without the AD plant. Emissions associated with growing and harvesting the OSR are not included, as the crop would have been grown as part of the crop rotation even if not processed on the farm. On-farm use of the residues and wastes has broader environmental advantages associated with the retention of nutrients from biomass on the farm and the return of these to land with the digestate. Although this use of digestate reduces the mineral fertiliser requirement for the oilseed rape crop, some imported fertiliser is still required (Table 6). The specific values shown are derived for UK conditions but the same approach can be generalised to other locations where OSR is grown.

4 Conclusions

Digestion of OSRC, cattle slurry and glycerol from the five farms could potentially generate 1733 MWh year⁻¹ of electricity and reduce GHG emissions by 2662 tonnes year⁻¹; adding vegetable waste increased this to 3020 MWh year⁻¹. A high proportion of OSRC in the feedstock caused process instability, but trace element supplementation overcame this, at least temporarily. Longer-term instability was probably due to build-up of non-degradable components of OSRC, indicated by reduced VS destruction. The digestate had a low PTE content, and a residual biogas potential which when added to the process gas production equalled the feedstock BMP.

Acknowledgements

This research was supported by the Rural Economy and Land Use (RELU) programme (RES-229-25-0022) and the EU FP6 CROGEN project (SES6-CT-2004-502824). The authors

would like to thank Denise Daly-Walton, Angus Bell and the members of the East Berwickshire Bioenergy group for their help in providing materials and data for this research.

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Figure captions

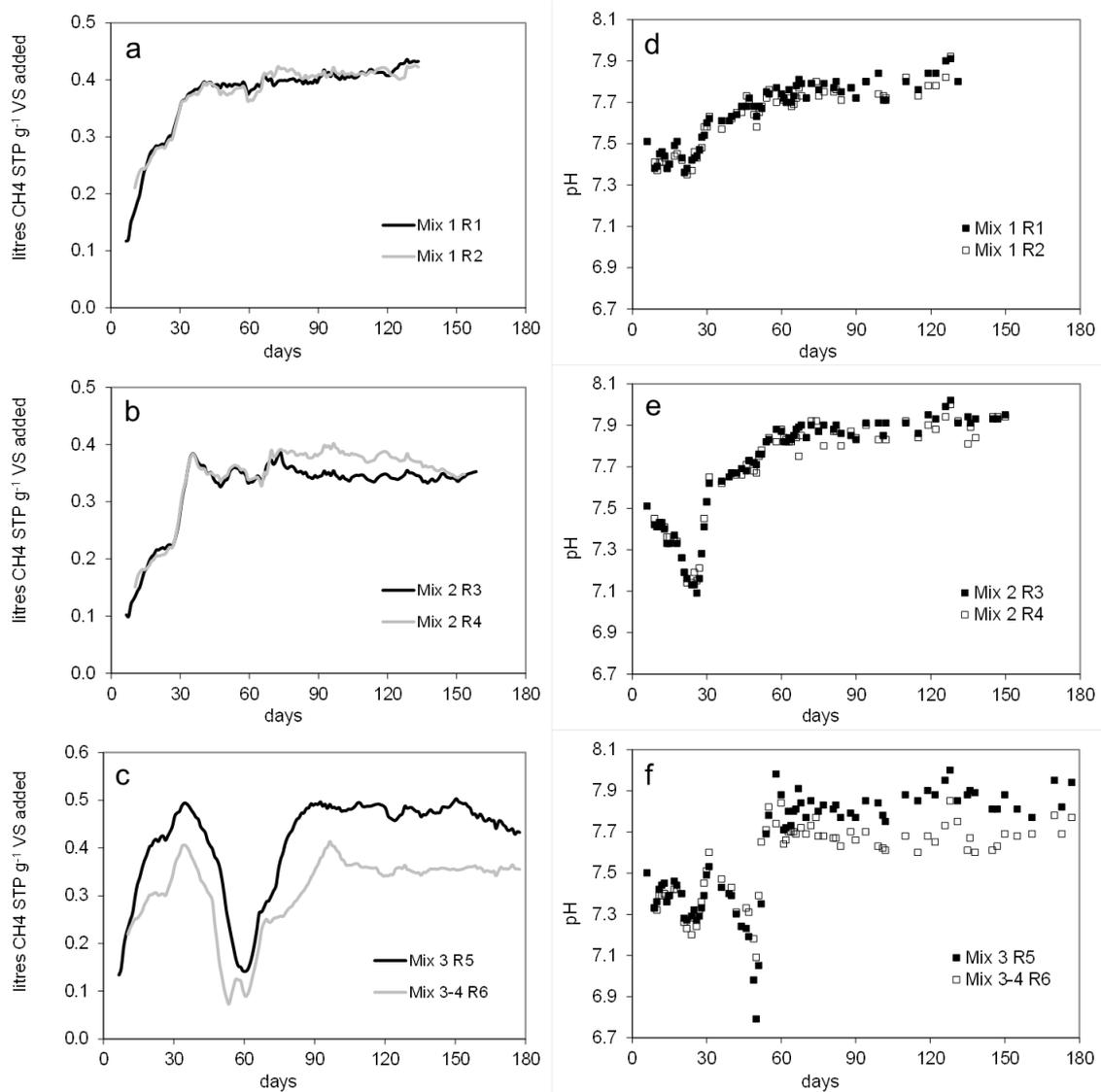


Fig. 1. Specific methane production and pH in semi-continuous digesters fed on the different feedstock mixes (Mix 1 = OSRC, crude glycerol, slurry, veg waste; Mix 2 = OSRC, crude glycerol, slurry; Mix 3 = OSRC, crude glycerol, veg waste; Mix 4 = veg waste only).

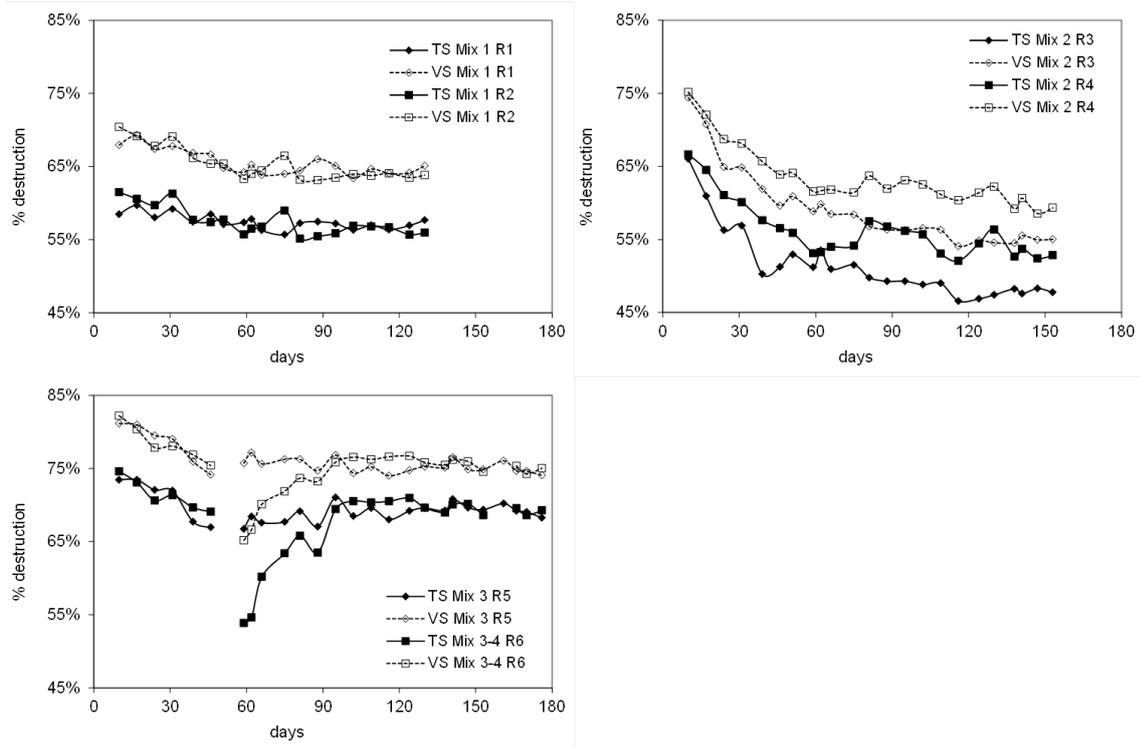


Fig. 2. Percentage solids destruction against time in semi-continuous digesters fed with Mixes 1, 2, 3 and 4 (Mix 1 = OSRC, crude glycerol, slurry, veg waste; Mix 2 = OSRC, crude glycerol, slurry; Mix 3 = OSRC, crude glycerol, veg waste; Mix 4 = veg waste only).

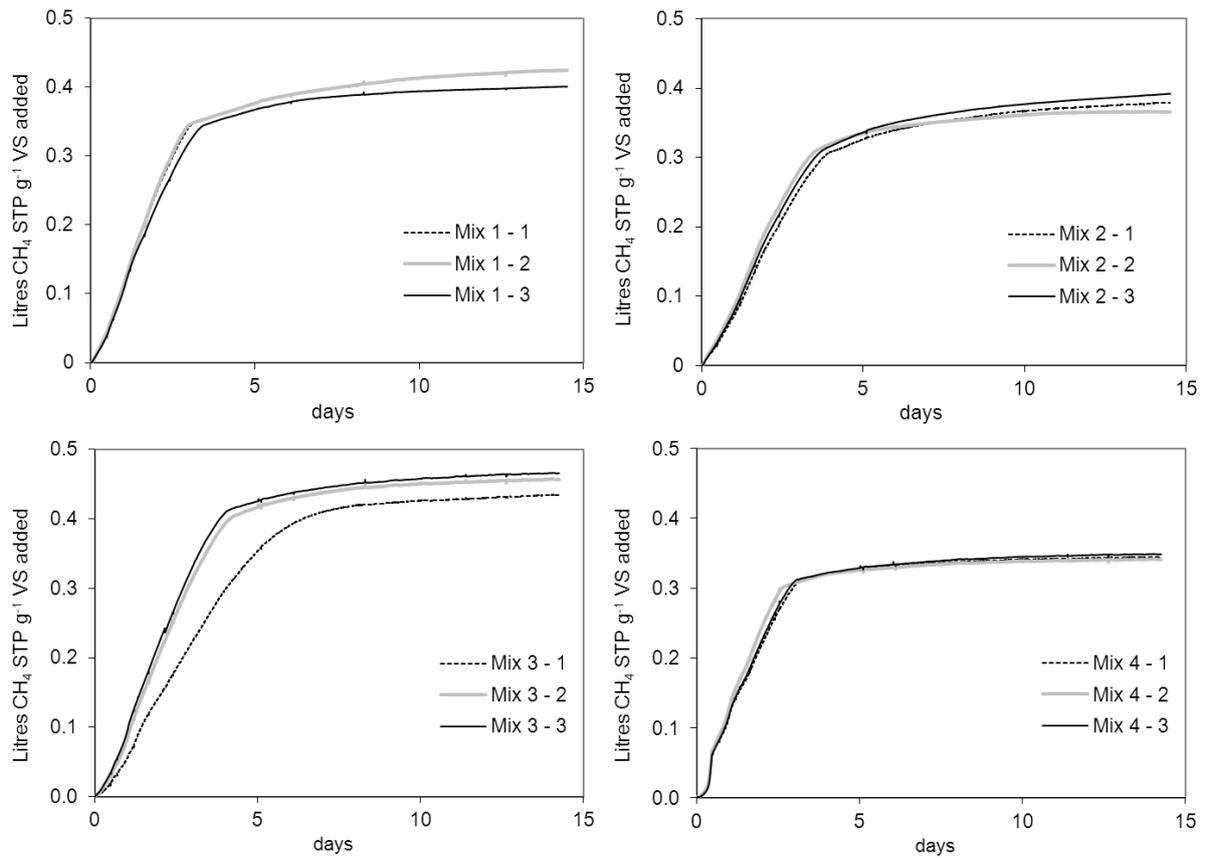


Fig. 3. Cumulative specific methane production during the first 14 days of BMP tests for Mix 1, 2, 3 and 4 (Mix 1 = OSRC, crude glycerol, slurry, veg waste; Mix 2 = OSRC, crude glycerol, slurry; Mix 3 = OSRC, crude glycerol, veg waste; Mix 4 = veg waste only).

Table 1. Farm distances and areas of oilseed rape

	Distance to biodiesel unit in base case (km)	Distance to AD plant (km)	Area for OSR production (ha)	OSR seed for biodiesel (tonnes year ⁻¹)
Farm 1	6.5	5.5	122	450
Farm 2	5	4	29	105
Farm 3 (dairy farm)	0	1	163	600
Farm 4	12	11	46	170
Farm 5	8.5	7.5	114	420
Vegetable processing plant	-	18	-	-

Table 2. Annual tonnages of feedstock materials with total and volatile solids content, and semi-continuous trial conditions

	Total			Mix 1	Mix 2	Mix 3	Mix 4
	tonnes WW year ⁻¹	g TS kg ⁻¹ WW	g VS kg ⁻¹ WW	tonnes WW year ⁻¹	tonnes WW year ⁻¹	tonnes WW year ⁻¹	tonnes WW year ⁻¹
OSRC	1200	903	855	1200	1200	1200	0
Crude glycerol	107	992	963	107	107	107	0
Slurry	12000	63	50	12000	12000	0	0
Veg. waste	10400	92	83	10400	0	10400	10400
Total	23707	-	-	23707	13307	11707	10400
<i>Trial conditions</i>				R1 & 2	R3 & 4	R5	R6 ^b
OLR	kg VS m ³ d ⁻¹			3	3	3	3
Feedstock VS	g VS kg ⁻¹ WW			99.2	124.6	153.8	113.7
Feedstock added	kg WW m ³ d ⁻¹			30.2	24.1	19.5	26.4
HRT	days			33.1	41.5	51.3	37.9
Run length ^a	days			132	152	177	177

^a including acclimation period^b R6 was fed on Mix 3 until day 50 then on Mix 4 from day 59 onwards.

Table 3. Physico-chemical characteristics of crude glycerol and OSRC components

	Units	Crude glycerol	OSRC
pH	-	12.19	-
Total organic carbon (TOC)	% TS	32.1	55.7
Total solids (TS)	g kg ⁻¹ WW	992.0 ^a	902.9
Volatile solids (VS)	g kg ⁻¹ WW	963.0	855.2
Total nitrogen (TN)	g kg ⁻¹ WW	BDL	4.23
Total Kjeldahl nitrogen (TKN)	% TS	< 0.05	4.30
Calorific value (CV)	kJ g ⁻¹ TS	18.86	24.95
Carbohydrates	g kg ⁻¹ VS	ND	171
Lipids	g kg ⁻¹ VS	ND	284
Crude proteins	g kg ⁻¹ VS	< 5	286
Hemicellulose	g kg ⁻¹ VS	ND	40
Cellulose	g kg ⁻¹ VS	ND	54.9
Lignin	g kg ⁻¹ VS	ND	116
Elemental N	% TS	< 0.05	4.23
Elemental C	% TS	32.3	55.9
Elemental H	% TS	7.69	8.46
Elemental O	% TS	34.5	24.2
Elemental S	% TS	< 0.05	0.63
Elemental N	% VS	< 0.05	4.23
Elemental C	% VS	33.0	59.0
Elemental O	% VS	34.9	25.3
TN	g kg ⁻¹ TS	BDL	42.3
TP	g kg ⁻¹ TS	BDL	6.86
TK	g kg ⁻¹ TS	BDL	9.02
Cadmium (Cd)	mg kg ⁻¹ TS	BDL	BDL
Chromium (Cr)	mg kg ⁻¹ TS	BDL	BDL
Copper (Cu)	mg kg ⁻¹ TS	BDL	7.3
Nickel (Ni)	mg kg ⁻¹ TS	BDL	BDL
Lead (Pb)	mg kg ⁻¹ TS	BDL	BDL
Zinc (Zn)	mg kg ⁻¹ TS	BDL	49.0

^a Solids determination by Karl Fischer titration

BDL = below detection limit, ND = not determined

Table 4. Digestate properties

	Unit	Mix 1	Mix 2	Mix 3	Mix 4	PAS110
<i>Operating parameters</i>						
pH						-
TA	g CaCO ₃ l ⁻¹	7.85	7.92	7.87	7.80	-
PA	g CaCO ₃ l ⁻¹	13.63	18.68	17.12	10.08	-
IA	g CaCO ₃ l ⁻¹	10.55	14.32	10.55	7.03	-
IA/PA		3.10	4.36	6.57	3.05	-
Ammonia N	g N l ⁻¹	0.30	0.32	0.62	0.43	-
Total VFA	g l ⁻¹	2.32	3.78	4.01	1.59	-
Average digestate TS	g kg ⁻¹ WW	0.30	0.25	7.39	1.42	-
<i>Plant nutrients</i> ^c						
TKN (N)	g kg ⁻¹ WW	53.3	75.6	59.0	41.6	-
Phosphorus (P)	g kg ⁻¹ WW	4.35	5.71	5.38	5.55	-
Potassium (K)	g kg ⁻¹ WW	0.85	1.09	1.13	0.55	-
<i>PTE</i> ^c						
Cadmium (Cd)	g kg ⁻¹ TS	2.27	2.39	2.88	3.4	-
Chromium (Cr)	g kg ⁻¹ TS	1.5	1.6	1.9	0.8	1.5
Copper (Cu)	g kg ⁻¹ TS	74.5	48.3	83.8	82.5	100
Nickel (Ni)	g kg ⁻¹ TS	137.9	163.9	47.8	50.2	200
Lead (Pb)	g kg ⁻¹ TS	43.8	28.5	46.5	46.6	50
Zinc (Zn)	g kg ⁻¹ TS	1.4	1.9	ND	1.5	200
TS of sample analysed	g kg ⁻¹ WW	157.7	185.0	123.6	66.7	400
		51.3	67.1	57.1	40.6	-

^a Average for last 4 weeks of run - stable period.

^b Final values - not stabilised.

^c Final sample

Table 5. Results of laboratory trials for use in energy modelling

	Unit	Mix 1	Mix 2	Mix 3	Mix 4
Feedstock total solids	g TS kg ⁻¹ WW	112.6	142.3	164.4	124.4
Feedstock volatile solids	g VS kg ⁻¹ WW	99.2	124.6	153.8	113.7
Specific methane production	m ³ CH ₄ kg ⁻¹ VS _{added}	0.416	0.350	0.464	0.356
% of final BMP value		87.7%	80.3%	84.2%	85.2%
Average methane concentration		61.0%	63.4%	60.6%	51.9%
Volumetric methane production	STP m ³ m ⁻³ day ⁻¹	1.25	1.05	1.39	1.07
VS reduction		64.1%	57.6%	74.9%	75.0%

Table 6. Energy and GHG emissions balances per year

		Base case	Mix 1	Mix 2	Mix 3	Mix 4
OSR biodiesel produced	l year ⁻¹			543678		
OSR biodiesel produced	GJ year ⁻¹			17833		
OSR crop production fuel (excluding fertiliser application)	GJ year ⁻¹			1032		
OSR transport	GJ year ⁻¹	17.8			16.7	
Veg waste transport	GJ year ⁻¹		357.6	0.0	357.6	357.6
Digester input	tonnes year ⁻¹		23707	13307	11707	10400
Digester capacity	m ³		2360	1666	1809	1188
Digestate applied to OSR	tonnes year ⁻¹		11287	4330	9997	9310
Digestate applied to grass (farm 3)	tonnes year ⁻¹		10402	7925	0	0
Digestate transport	GJ year ⁻¹		125.4	56.4	93.1	84.0
Digestate application to OSR	GJ year ⁻¹		60.9	60.9	60.9	60.9
OSR mineral fertiliser energy	GJ year ⁻¹	4420	1877	3171	1628	1876
OSR mineral fertiliser application	GJ year ⁻¹	23.7	11.8	11.8	11.8	11.8
CHP electricity generated	GJ year ⁻¹		12251	7275	10474	5278
AD parasitic electricity	GJ year ⁻¹		782	439	386.3	343.2
Biodiesel parasitic electricity	GJ year ⁻¹	598	598	598	598	598
Surplus electricity	GJ year ⁻¹		10871	6238	9490	4337
Surplus electricity	MWh year⁻¹		3020	1733	2636	1205
Surplus heat	MWh year⁻¹		3225	1902	2976	1351
Surplus biodiesel	GJ year ⁻¹	16759	16228	16655	16260	16269
Surplus biodiesel	l year⁻¹	510942	494756	507763	495742	496020
<i>Emissions saved</i>	tonnes CO ₂ eq year ⁻¹					
- from electricity generation		-99	1904	1135	1675	819
- from biodiesel		1321	1268	1317	1288	1289
- from mineral fertiliser replacement			428	210	472	421
Total emissions saved	tonnes CO₂ eq year⁻¹	1222	3618	2662	3434	2529