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Willow for landfill leachate remediation and bioenergy, is it an effective solution?

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ABSTRACT

Landfill leachate is a major problem and conventional treatments can be problematic and expensive. Short rotation coppice willow is a fast growing, high yielding energy crop well suited to temperate climates, has a favourable energy balance and performs well from an environmental perspective. It has previously been shown to be effective for bioremediation but there is limited information regarding the energy and carbon impacts of a large-scale system in which landfill leachate is remediated by a willow plantation. The aim of this paper was to investigate the impact on carbon and energy of such a system. An energy ratio of 5.3 was found for the system. Greenhouse gas savings of 60% could be achieved compared to conventional treatment methods. Replacing an oil heating system with heat from the willow chips could see a reduction in greenhouse gas emissions of 579 tCO_2eq over the plantation lifetime for a biomass boiler with 85% conversion efficiency. There are clear environmental benefits, but further improvements could be made with alternative harvest methods (full stem harvest) and the use of renewable electricity to meet the parasitic demands.

KEYWORDS

willow, life cycle assessment (LCA), landfills, wastewater treatment, energy balance, greenhouse gases (GHGs).

INTRODUCTION

Landfill management presents a significant challenge. While in recent years there has been increased focus on recycling and efficient resource management, in 2016, 25% of municipal waste in the European Union (EU) was still being sent to landfill [1]. Landfill leachate is a major problem and conventional treatments can be problematic and expensive [2]. Landfill leachate is generated when pollutants in waste are transferred, through a combination of chemical, physical and microbial processes, into rainwater percolating through the landfill site [3]. The contamination of groundwater and surface water by untreated landfill leachate has negative impacts on the local environment and subsequently the human population [4]. A landfill site produces leachate throughout its working life but will also continue to produce leachate for several hundred years after closure [4]. Therefore, even with the anticipated

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reduction in landfilling of waste, in line with the EU Waste Framework Directive, the treatment of leachate will still present a significant issue for many years to come.

In Europe, the conventional method of treating landfill leachate is to add the leachate to the wastewater influent at a wastewater treatment works (WwTW) [4]. Over the past number of years, the EU has issued stricter requirements for WwTWs, making this method of treatment unsustainable [2]. With this growing concern, different methods of remediating landfill leachate are being researched. One solution that has been suggested is the use of short rotation coppice (SRC) willow, grown on decommissioned landfill sites and irrigated with the landfill leachate [2].

SRC willow is a fast growing, high yielding energy crop [5], which can be utilised as a biomass fuel for combustion in replacement of conventional fossil fuels, thereby providing associated carbon benefits. SRC willow is well suited to the temperate climates of northern Europe and, as an energy source, typically has a favourable energy balance and performs well from a carbon footprint perspective [5]. A new plantation is typically cut back one year after establishment to encourage the growth of multiple shoots. They are then allowed to grow for a further 2, 3 or 4 years before harvest. Harvest is typically completed using a direct chip harvester after which the chips must be dried artificially, or a full stem harvester after which the stems can be dried naturally before being chipped prior to conversion. The harvest cycle can be repeated 7 or 8 times before the crop must be removed completely and the plantation re-established.

SRC willow has previously been successfully used as a method of managing wastewater [2]. A number of investigations have found significant increases in biomass yields of trees when irrigated with leachate compared with water or rain irrigated controls. Landfill leachate has been shown to be a good fertiliser for SRC willow, particularly from older landfills [6]. *Salix aquatica* irrigated with landfill leachate on a restored landfill yielded 12.5 t dry matter (DM) ha^{-1} yr^{-1} compared with unirrigated controls yielding 7.3 t DM ha^{-1} yr^{-1} [7].

Willows also have high transpiration rates and biofiltration properties. Their presence on a landfill site can have the overall effect of increasing the evapotranspiration of the leachate and therefore reducing the quantity of leachate [8]. Good removal efficiencies for problematic landfill leachate components have been achieved in Sweden using willow stands. Over a 10-year period the nitrogen component of leachate was reduced by 93% from 1600 kg N ha^{-1} yr^{-1} to approximately 100 kg N ha^{-1} yr^{-1} [9]. The willow stands also successfully reduced ammonia levels, with 96.8 to 99.9% removal efficiency [9]. According to Dimitriou and Aronsson [10], irrigation of SRC willow and poplar with landfill leachate is an increasingly interesting treatment option for their research lysimeters established at Uppsala, Sweden.

However, upon a review of the literature there is a paucity of research regarding the use of established, large-scale SRC willow sites to remediate landfill leachate. To date there have been no studies investigating the greenhouse gas savings that could be achieved using SRC willow remediation of landfill leachate compared to conventional treatments. Alongside this there is a gap in the knowledge regarding the energy balance of such a system.

Therefore, the aim of this work was to investigate the effectiveness of SRC willow to remediate landfill leachate on a large-scale site. To do this, life cycle analysis (LCA) was undertaken to investigate a pilot site which has been established in Churchtown, Co Donegal, Ireland. The LCA focused on the energy balance and CO_2eq emissions impact categories, comparing the results with conventional treatment methods.

MATERIALS AND METHODS

The greenhouse gas emissions and energy requirements were calculated using LCA methodology. LCA is a commonly used technique that addresses the environmental aspects and potential impacts associated with a product, process or service, following a standard methodological framework: goal and scope definition, inventory analysis, impact assessment and interpretation of results [11]. The goal and scope outline the purpose for carrying out the assessment and the extent to which the results will apply. As part of this step a flow diagram was produced and system boundaries were defined.

For the inventory analysis, the resource and energy inputs and outputs were determined including both direct and indirect energy requirements and greenhouse gas (GHG) emissions. Direct energy usage and GHG emissions arise from onsite activities, such as the combustion of diesel during farm operations. Indirect energy usage and GHG emissions arise from the production of substances which are used within the system boundaries, e.g. the production of the diesel used on site. Where available, impacts were quantified using site specific data, supplemented by information from the literature. Fuel consumption for the establishment phase, except cuttings transport, and direct chip harvesting was taken from Goglio & Owende [12]. The density and energy content of diesel was taken as 1.2 $l\ kg^{-1}$ and 36.09 $MJ\ l^{-1}$ respectively [13]. The GHG emissions factor for diesel was taken as 2.5725 $kgCO_2eq\ l^{-1}$ for an average diesel biofuel blend, accounting for CO_2, CH_4 and N_2O [14].

Willow cuttings were transported 192 km from the nursery in the midlands of Ireland to the site; diesel consumption of 0.33 $l\ km^{-1}$ was assumed [15]. The energy requirement and GHG emissions related to the production of one willow cutting was taken from Wolsey et al. [16]. Quantities of pesticides are site specific with their embodied energy values taken from Fearon et al [17] and emission factors from Clair et al. [18]. Pumping energy requirements for the irrigation of the willow plantation are site specific and are met by Irish mix grid electricity. The GHG emission factor used for electricity was 0.4366 $kgCO_2eq\ kWh^{-1}$ [13]. Embodied energy values for diesel and electricity were taken from Wolsey et al. [16] and indirect emission factors for diesel and electricity production were taken from Defra [14].

As the site has not yet been harvested a yield of 55.56 $t\ ha^{-1}$ per three year rotation at 55% moisture content (MC) biomass was taken from Wolsey et al. [16], as the willow was grown under similar climatic conditions and management practices. The fresh willow chip was assumed to be transported 73.6 km to the drying facility where it was dried to 20% moisture before being transported back to Churchtown for use within the local biomass fuel market. Heat for drying was provided by biomass and electricity for the fans was provided by Irish mix grid electricity. The energy requirements to dry 1 tonne of willow chips from 55% moisture to 20% moisture and diesel consumption per tkm for tractor and trailer transport were taken from Wolsey et al. [16]. Direct emissions for the combustion of wood chips were set to zero as is standard for the combustion of biomass.

Following the completion of the inventory analysis the functional unit was defined, and impacts were quantified. The functional unit is used to define exactly what is being studied and is the unit through which the system is analysed. In the impact assessment stage the inputs and outputs from the inventory analysis were assessed according to the impact categories chosen. Following this the results of the impact assessment were interpreted highlighting environmental hotspots, and a sensitivity analysis was carried out to determine future improvements to the system. The results were then compared to that of a conventional WwTW used to treat an equivalent nutrient load. The results were also compared with fossil fuel energy production to determine potential carbon savings compared to the fuel displaced.

RESULTS

Goal and scope

The goal of this project was to determine if the utilisation of SRC willow for landfill leachate remediation is an effective solution compared to a conventional WwTW. A cradle-to-plant LCA was performed and the scope and boundaries can be seen in Fig. 1. The system was split into four categories to enable the identification of hotspots. The impact categories investigated were the energy balance and CO_2eq emissions. For continuity with previous work by the authors [16,17] the functional unit was taken as MJ ha^{-1} yr^{-1}. A second functional unit of $kgCO_2eq$ ha^{-1} yr^{-1} was chosen for the assessment of CO_2eq emissions.

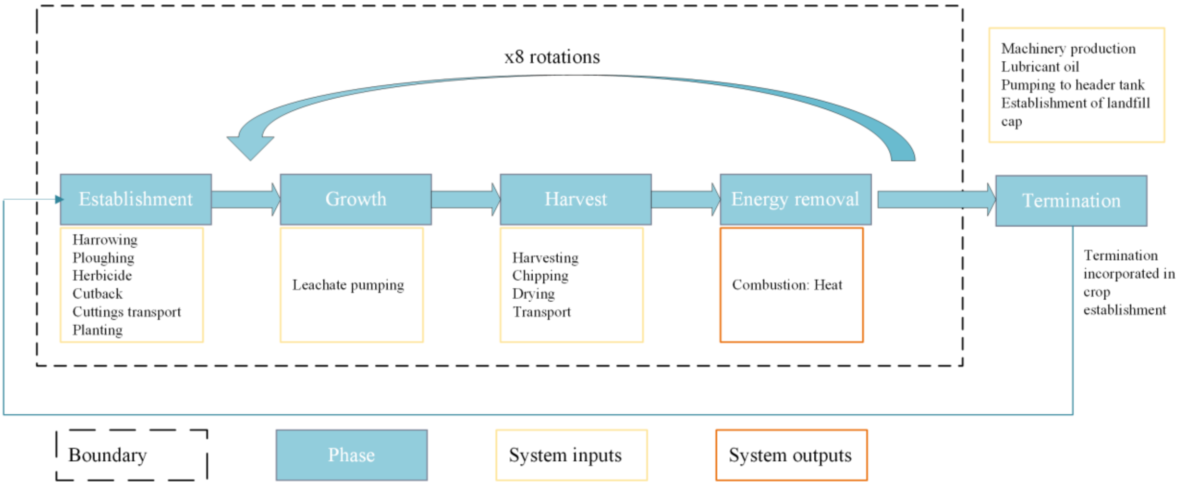

Figure 1. System boundary for LCA

The Churchtown site is situated beside the River Finn. The River Finn drains the Bluestack mountains and has an approximate catchment area of 500 km^2 with an overall channel length of approximately 100 km [19]. The Churchtown site incorporates a 7.5-hectare clay cap with a depth of 0.5 m sealing the landfill and a further layer of topsoil, approx. 0.5m deep. The Churchtown site was originally designed on a dilute and disperse basis with an underlying clay layer preventing downward migration of leachate. The Irish Environmental Protection Agency (EPA) required the landfill site to be restored after its closure in 2000. A 2.5-hectare plantation of willow was planted on the landfill cap in 2014 alongside Integrated Constructed Wetlands (ICW) on either side. The leachate generated is collected and pumped to a header tank to be stored before being applied to the willow and the ICWs. The ICW system was considered to be beyond the scope of this work and so was excluded from the system boundaries. A three-year harvest rotation cycle has been implemented and there are anticipated to be 8 cycles over the plantation lifetime. Along with a one-year establishment phase, this equates to a 25-year life cycle for the crop. For the analysis, the yields, energy inputs, energy outputs and GHG emissions were averaged over the 25-year plantation lifetime.

Manufacture of machinery and construction activities were excluded from the system boundary; this is in line with the requirements of the revised Renewable Energy Directive when assessing the GHG impact of bioenergy production [20]. Plantation termination processes were also excluded, as these would be allocated to the establishment for the next life cycle [17]. As the amount of lubrication oil required for machinery was expected to be negligible in comparison with diesel consumption, this was not included in the system boundary [12]. The pumping of leachate to irrigate the willow plantation was included in the system boundaries while the pumping of leachate to the header tank as well as the establishment of the landfill cap were excluded to allow comparison with previous research [16,17].

Energy inventory and impacts

For the direct energy inputs (Table 1), 74% of the total energy consumption was associated with the harvesting phase. This was largely due to the transport of willow chips to and from an external contractor for drying 73.6 km away, which accounted for 68% of the energy use in this phase. Drying of the willow chips was responsible for a further 30% of the energy use in this phase. The establishment phase made only a minor contribution (2%) to overall lifetime energy requirement, while the growth phase, with its high use of grid electricity for leachate pumping, was responsible for 24%. Overall, the use of diesel (farm operations and transport) was the largest direct energy component (Fig. 2).

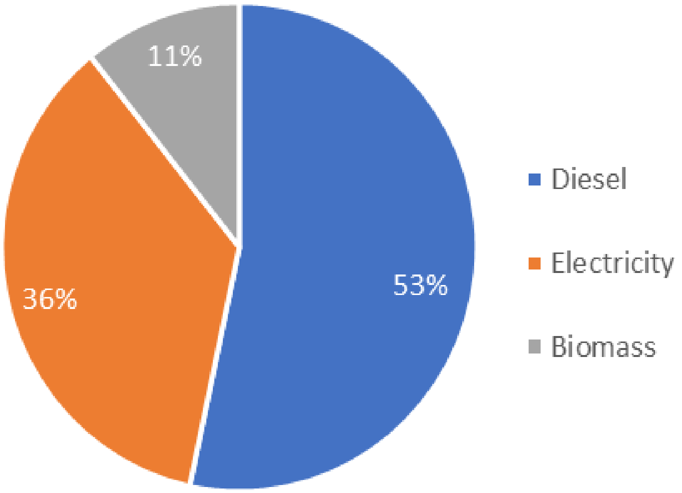

Figure 2. Breakdown for direct energy impacts over plantation lifetime

Table 1. Direct energy and emissions inventory and impacts per hectare

Operation	**Method**	**Fuel consumption (lifetime)**		**Lifetime energy MJ**	**Lifetime GHG emissions kgCO$_2$eq**
Establishment					
Ploughing	Tractor	52	l	1869	134
Harrowing	Tractor	12	l	422	30
Herbicide application	Tractor	28	l	1012	72
Insecticide application	Tractor	14	l	505	36
Cuttings transport	Articulated lorry	26	l	923	66
Planting	Tractor + step planter	55	l	1991	142
Cutback	Tractor	8	l	278	20
Establishment total				6999	500
Growth phase					
Leachate pumping	Electric motor	25,088	kWh	90,317	10,953
Growth phase total				90,317	10,953
Harvest phase					
Combined harvest and chipping	Direct chip harvester	114	l	4103	293
Transport to drying	Tractor + trailer	3137	l	113,214	8093
Drying	Heating (wood chip)	11,206	kWh	40,342	0
Drying	Fans	12,229	kWh	44,024	5339
Transport from drying	Tractor + trailer	2091	l	75,464	5395
Harvesting total				277,148	19,121
Direct impacts during crop lifetime				374,463 MJ	30,574 kg CO$_2$eq
Direct impacts per year of crop lifetime				14979 MJ	1223 kg CO$_2$eq

Within the indirect energy analysis (Table 2), the growth phase accounted for the largest contribution with 54 % of the total indirect energy requirements due to the electricity requirements for pumping the leachate. The harvest phase accounted for 39% of the indirect energy requirements, largely due to the use of electricity to power the fans for the drying process, with a smaller portion associated with the establishment phase (7%). Overall, the use of grid electricity accounted for 80% of the indirect energy requirements (Fig. 3).

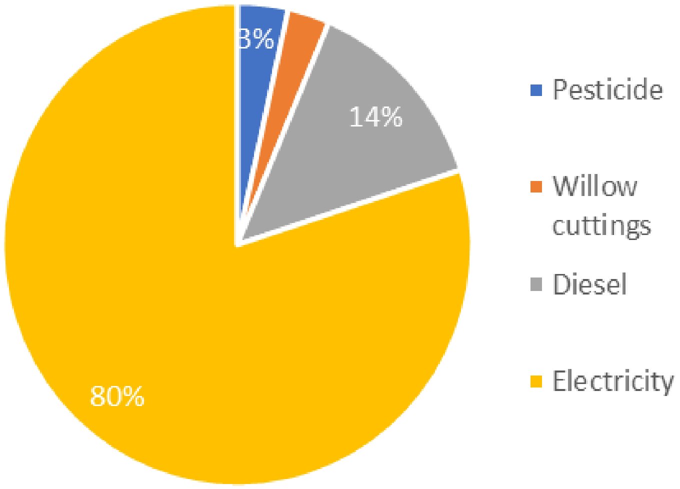

Figure 3. Breakdown for indirect energy impacts over plantation lifetime

Table 2. Indirect energy and emissions inventory and impacts per hectare

Input	**Lifetime demand**	**Embodied energy**	**Lifetime energy MJ**	**Emissions Factor**	**Lifetime GHG kgCO$_2$eq**
Establishment					
Herbicide (Roundup)	6.5 l	772 MJ l^{-1}	5017	4.55 kgCO$_2$eq l^{-1}	30
Herbicide (Pendimethalin)	29.7 l	176 MJ l^{-1}	5212	4.55 kgCO$_2$eq l^{-1}	135
Insecticide	6 l	350 MJ l^{-1}	2100	2.3 kgCO$_2$eq l^{-1}	14
Willow cuttings	15,000 cuttings	0.68 MJ cutting^{-1}	10,200	0.03 kgCO$_2$eq cutting^{-1}	450
Diesel	7360 MJ	0.24 MJ MJ^{-1}	1766	0.02 kgCO$_2$eq MJ^{-1}	118
Establishment total			24,209		741
Growth					
Electricity	90,317 MJ	2.1 MJ MJ^{-1}	189,665	0.02 kgCO$_2$eq MJ^{-1}	1742
Growth total			189,665		1742
Harvest					
Diesel	192,782 MJ	0.24 MJ MJ^{-1}	46,268	0.02 kgCO$_2$eq MJ^{-1}	3098
Electricity	44,024 MJ	2.1 MJ MJ^{-1}	92,451	0.02 kgCO$_2$eq MJ^{-1}	880
Harvest total			138,719		3979
Indirect impacts during crop lifetime			352,593 MJ		6462 kgCO$_2$eq
Indirect impacts per year of crop lifetime			14,104 MJ		258 kgCO$_2$eq

Gross energy production was calculated using a net calorific value of 13.2 GJ t^{-1} [21] for 36.11 t ha^{-1} of wood chip produced per rotation (20% MC). A total energy input of 29 GJ ha^{-1} yr^{-1} (Table 3) of direct and indirect energy was calculated for the system which results in an energy ratio of 5.3. This value is in the same range as results from as other studies in the literature with a similar boundary and scope [12,16,17].

Table 3. Energy balance results

Energy	Direct MJ ha^{-1} yr^{-1}	Indirect MJ ha^{-1} yr^{-1}	Total MJ ha^{-1} yr^{-1}
Gross	152,529	N/A	152,529
Establishment	280	968	1248
Growth	3613	7587	11,199
Harvesting	11,086	5549	16,635
Total	14,979	14,104	29,082
Net	137,550	N/A	123,446

GHG emissions results

Total emissions were 1.5 tCO_2eq ha^{-1} yr^{-1} (Table 4). Direct emissions were the main contributor and were responsible for 83% of the total emissions. As with direct energy requirements, the harvesting phase accounted for the majority of the direct emissions (63%). Again, this was largely due to the transport of the willow chips to and from the drying facility, accounting for 71% of the emissions in this phase. The use of electricity to power the fans for chip drying accounted for a further 28% of the emissions in this phase. The growth phase was responsible for 36% of the direct emissions. The establishment phase only made up 2% of direct emissions and 11% of indirect emissions. The harvesting phase was responsible for the most indirect emissions (62%), again due to the use of diesel for transport of the willow chips to and from the drying facilities.

Diesel use accounted for 47% of direct emissions while the use of grid electricity made up the remaining 53%. Diesel production was the largest contributor to indirect emissions with 50% of the total indirect emissions (Fig. 4). The production of grid electricity (41%) was another large contributor of indirect emissions. It should be noted that this analysis did not take into consideration emissions from leaf litter or those given off by the leachate, both of which could be significant [16].

Table 4 GHG emissions results

Phase	Direct tCO_2eq ha^{-1} yr^{-1}	Indirect tCO_2eq ha^{-1} yr^{-1}	Total tCO_2eq ha^{-1} yr^{-1}
Establishment	0.02	0.03	0.05
Growth	0.438	0.07	0.508
Harvesting	0.765	0.159	0.924
Total	1.223	0.258	1.481

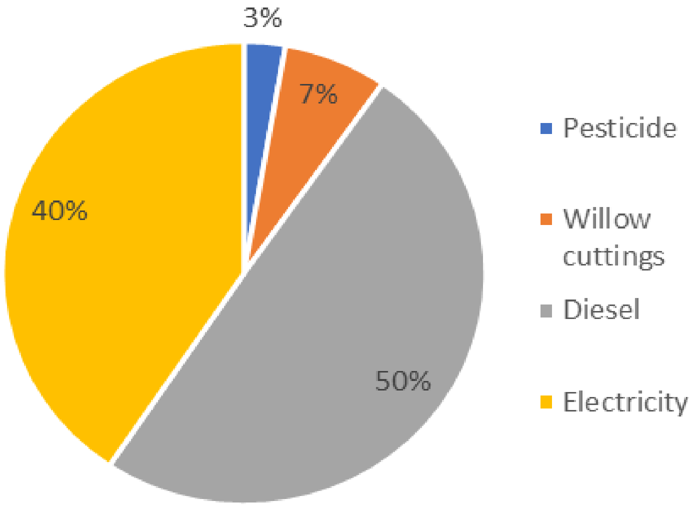

Figure 4. Breakdown of indirect emissions over plantation lifetime

DISCUSSION

Comparison with conventional leachate management

The conventional method of remediating the leachate is to transport the leachate by tanker to a local WwTW. The closest WwTW to the site at Churchtown is located in Letterkenny, Co Donegal, at a distance of 24 km. For the comparison between the two methods, the energy and emissions related to the transport and processing of an equal volume of leachate as was treated by the willow were included. The energy and emissions relating to the transport of the leachate by tankers was adapted utilising data from the Department of Transport [22] and DEFRA [15]. The energy demand and CO_2 emissions for a conventional WwTW in Ireland were not readily available. Due to the close proximity of the site to Northern Ireland and its WwTW processes being consistent with Ireland, figures from NI Water were utilised instead [23].

2,352 m^3 ha^{-1} of leachate were pumped on average per year into the willow plantation, excluding the establishment year, giving a total of 56,448 m^3 ha^{-1} over the 25-year plantation lifetime. With an energy demand of 29 GJ ha^{-1} yr^{-1} this results in an energy demand of 12.88 MJ m^{-3} (Table 5). Replacing the conventional method with the SRC willow plantation could see a 74% reduction in energy demand alongside a 60% reduction in emissions. It must be noted that this does not account for the reduction in emissions that would be associated with the displacement of fossil fuels by the willow chip, which would result in even greater emissions and energy savings.

Table 5. Comparison with a convention leachate treatment system

Treatment system	**Energy demand MJ m^{-3}**	**Emissions kgCO_2eq m^{-3}**
Willow system	12.88	0.66
Conventional	49.71	1.63
Savings %	74	60

Identifying hotspots and system improvements

The main hotspot in the system is the drying of willow chips, with a major issue being the distance required to transport the willow chips to the drying facilities. Sourcing a closer drying facility or selling the willow chips on a market closer to the drying facilities would improve this figure. Alternatively, the willow chip could be harvested using a whole stem harvester or biobaler as when willow is harvested in this manner it would not require artificial drying and so could be stored locally and allowed to dry naturally before being chipped prior to combustion. Using the fuel consumption values for harvesting, chipping and transport from field to storage area from Goglio & Owende [12], this method could see a reduction in total energy requirements of 54% and total emissions of 58%. This would result in an increased energy ratio of 11.3. A further improvement could be made by using a renewable, carbon neutral source of electricity to power the pumps used for leachate dispersion. This would reduce emissions by a further 81% to just 0.12 $tCO_2eq\ ha^{-1}\ yr^{-1}$.

Replacement of fossil fuels

A woodchip boiler is a common energy conversion technology used for SRC willow systems, with the heat produced used for district heating to replace an oil powered system [21]. Assuming a conversion efficiency of 85% for a woodchip boiler [24] the site at Churchtown could provide 129.7GJ ha^{-1} of heat per year. Taking the base case scenario of 1.5 $tCO_2eq\ ha^{-1}\ yr^{-1}$ this equates to 11.6 $kgCO_2eq\ GJ_{heat}^{-1}$. Heating oil has an emissions factor of 83 $kgCO_2eq\ GJ_{heat}^{-1}$ including direct and indirect emissions [14]. Therefore, replacing oil heating with the willow chip produced by the entire site at Churchtown (2.5 ha) could lead to a reduction of GHG emissions of 579 tCO_2eq over its lifetime (25 years). This assumes that the oil and wood chip boilers have equal efficiency values, however, modern wood chip boilers could have efficiencies of over 85% compared to as low as 55% for older oil boilers so the carbon savings could be even higher [25]. If the improvements suggested in the previous section (full stem harvest and renewable electricity) were implemented the total reduction in emissions could be 665 tCO_2eq over its lifetime.

CONCLUSION

The aim of this work was to investigate the effectiveness of SRC willow as a possible treatment method for landfill leachate, with a focus on the life cycle impacts of the system on GHG emissions and the energy balance. The system results in a favourable energy balance, with an energy ratio of 5.3, considering both direct and indirect energy requirements. System hotspots include wood chip transport to and from drying facilities and the drying process itself. Alternative harvest methods and the use of renewable electricity were identified as key recommendations for improving the system. Carbon emissions of 1.5 t $CO_2eq\ ha^{-1}\ yr^{-1}$ were found for the system. The harvesting phase accounted for 63% of direct emissions and 62% of indirect emissions, largely due to the transportation distance to and from the drying facilities.

Compared to conventional a WwTW the SRC willow system results in a decrease in carbon emissions of 60% with a 74% reduction in energy demand in the base case. Using the willow chips to replace an oil heating system could see a further reduction in GHG emissions of 579 tCO_2eq over its lifetime. There are clear environmental benefits to the use of SRC willow to treat landfill leachate. Future work should expand on the boundaries of this study to investigate the impact on emissions and energy balance of including the landfill capping process.

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NOMENCLATURE

Abbreviations

DM: Dry matter
EPA: Environmental Protection Agency
EU: European Union
GHG: Greenhouse gas
LCA: Life cycle assessment
MC: Moisture content
SRC: Short rotation coppice
WwTW: Wastewater treatment works

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