CANADA'S SUBBOR, ENHANCED ANAEROBIC DIGESTION TECHNOLOGY: UTILIZATION OF WASTE BIOMASS AVOIDS GHG EMISSIONS AND PROVIDES ALTERNATE ENERGY

BY

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Abstract

Waste biomass disposition is a growing problem facing municipalities. Municipal Solid Waste (MSW), to name one example, comprises 300,000,000 tonnes of organic-rich refuse per year in North America. MSW contributes approximately 4% of all greenhouse gas (GHG) emissions through the release of methane from decomposing landfilled waste.

SUBBOR is a patented anaerobic digestion biotechnology that replaces landfills by processing wastes in a controlled industrial facility. The technology employs unique treatment steps that increase digestibility of wastes and therefore the biogas energy yield when processing biomass. Most biomass materials have suffered from limited digestibility and thus, poor utility, due to the physical/chemical nature of the lignin-rich fiber, prevalent in these materials.

SUBBOR's technological advances have overcome this problem. The integrated process provides enhanced biogas/energy yields, produces a stable peat-like by-product, destroys all pathogenic microorganisms and permits treatment of a wide range of biomass types.

Current life-cycle assessment models indicate that, relative to the baseline practice of landfill disposal, SUBBOR can provide a combined GHG off-set credit of up to 3 tonnes CO_2 per ton of MSW processed. This large GHG reduction potential is separate from other GHG mitigation approaches and therefore can greatly assist municipalities in achieving sustainable development while cushioning the economic impact of GHG reductions in the traditional energy-consuming sectors.

Introduction

Waste biomass includes forestry wastes, agricultural residues, sewage sludge, industrial organic residues and municipal solid waste (MSW). Such wastes present a growing threat to the health of the environment and represent a substantial source of Greenhouse Gas (GHG) emissions.

Canada and the USA will generate a combined total of 300,000,000 tonnes per year of MSW, alone, by 2010. Table 1 provides US summary data for MSW amounts and disposition.

Table 1 also shows that, while recycling efforts (blue box collection and recycling programs) have provided some diversion of waste, there is a practical limit (~30%) to the amount of waste components that are amenable to recovery by conventional techniques. The marginal contribution of composting and the projected decline in waste incineration shown in Table1 contribute to a very large residual MSW fraction (>50%) being sent to landfill.

Table 1

Generation and Disposition of MSW in the USA*

	1994	2000	2010
Generation (x 1,000 tons)	209,080	222,870	262,630
MSW (lbs/person/day)	4.4	4.42	4.78
Recovery/Recycling (% of total MSW)	20	25.5	29.7
Recovery/Composting (% of total MSW)	3.6	4.5	5.3
Total Recovery Recycling/Composting (% of total MSW)	23.6	30	35
Total Discard After Recovery (% of total MSW)	76.4	70	65
Combustion (% of total MSW)	15.5	15.3	14.5
Landfill (% of total MSW)	60.9	54.7	50.5

*U.S. EPA data

Consequently, without new approaches to MSW recycling, North America will be forced to landfill upwards of 200 million tonnes of MSW each year early in the new millennium.

More significantly, the environmental impacts of this waste placed in landfill have also increased. Recycling efforts tend to recover proportionately more mass of inorganic materials (steel, aluminum, etc.) resulting in enrichment of the organic content of the non-diverted waste, as shown in Table 2. It is the organic portion of MSW in a landfill that causes the various environmental impacts.

Table 2

Composition of MSW Discards by Organic and Inorganic Fractions
1960 to 1996
(In percent of total discards)*

Year	Organics	Inorganics
1960	77.3%	22.7%
1970	75.5%	24.5%
1980	77.5%	22.5%
1990	85.1%	14.9%
1996	85.5%	14.5%

*U.S. EPA data

The portion of MSW placed into landfill has been enriched in organic content from ~75% in 1970 to ~86%, presently. Therefore, MSW discarded to landfill, alone, represents disposal to the environment of more than 100 million tonnes per year of waste biomass in the U.S.A. Consideration of other biomass waste sources and extension of this problem to a worldwide basis, all illustrate the large problem and need for improved management practices in relation to waste biomass.

Man-made landfills receiving biomass waste result in an "uncontrolled" and Aopen≅ anaerobic digestion system that liberates methane and other gaseous (volatile organic compounds) and water-borne (metal and organic) emissions to the environment. Approximately 6% of the total anthropogenic greenhouse gas (GHG) emissions in North America are accountable from methane escaping from landfills and agricultural manures, together (Environment Canada, 1999 and U.S. EPA, 2001).

Previous life-cycle analyses of GHG emissions for various MSW management technologies concluded that controlled (contained) industrial anaerobic digestion of MSW with recovery of the resulting biogas energy had the highest potential for reducing this significant source of GHG emissions in comparison to landfill disposal, incineration, composting and other alternative approaches (Environment Canada, 1995).

Anaerobic digestion of biomass wastes is now an established and commercially proven approach for treatment and recycling (DeBaere 1999 and Mata-Alvarez, 2000). DeBaere (1999) has reviewed the industrial status of anaerobic digestion, reporting on 53 European facilities treating an aggregate of over 1,000,000 tonnes per year of biomass wastes.

However, MSW, in common with most other biomass wastes (forestry and agricultural residues) contains a high content of ligno-cellulosic containing fiber that is not readily digestible (Owens and Chynoweth, 1993, Speece, 1983, Rivard, 1996 and Liu et al, 2001). Consequently, anaerobic digestion procedures for these materials have been incomplete and typically rely on a short-term anaerobic digestion for the readily digestible materials followed by an aerobic composting "curing" step to stabilize the incompletely digested residues (DeBaere, 1999).

Various pretreatment and conditioning procedures (reviewed by Mata-Alavarez, 2000), employing chemical and enzymatic hydrolysis or particle size reduction of ligno-cellulosic materials have provided some modest improvements to digestion yields but these techniques have not proven commercially useful, due to the increased capital and operating costs associated with their use. Nevertheless, an effective means for improving digestion and biogas yields from biomass feedstocks would provide a more useful digestion of fiber-rich materials and mixtures of biomass sources (Hamzawi et al, 1998a, 1998b) and permit digestion of more difficult high lignin-containing materials such as bagasse, wood waste and agricultural residues (e.g. straw). The latter materials are not typically processed by anaerobic digestion facilities at present due to their limited digestibility.

The waste management industry requires technology that can accept mixed or poorly separated waste feed materials, rich in biomass and achieve a more complete digestion as well as cost effective processing. The environmental benefit of this would be elimination of a major source of GHG emissions and provision of sustainable energy.
The SUBBOR waste treatment technology has been developed to meet these technical objectives and realize these environmental benefits.

The SUBBOR Process

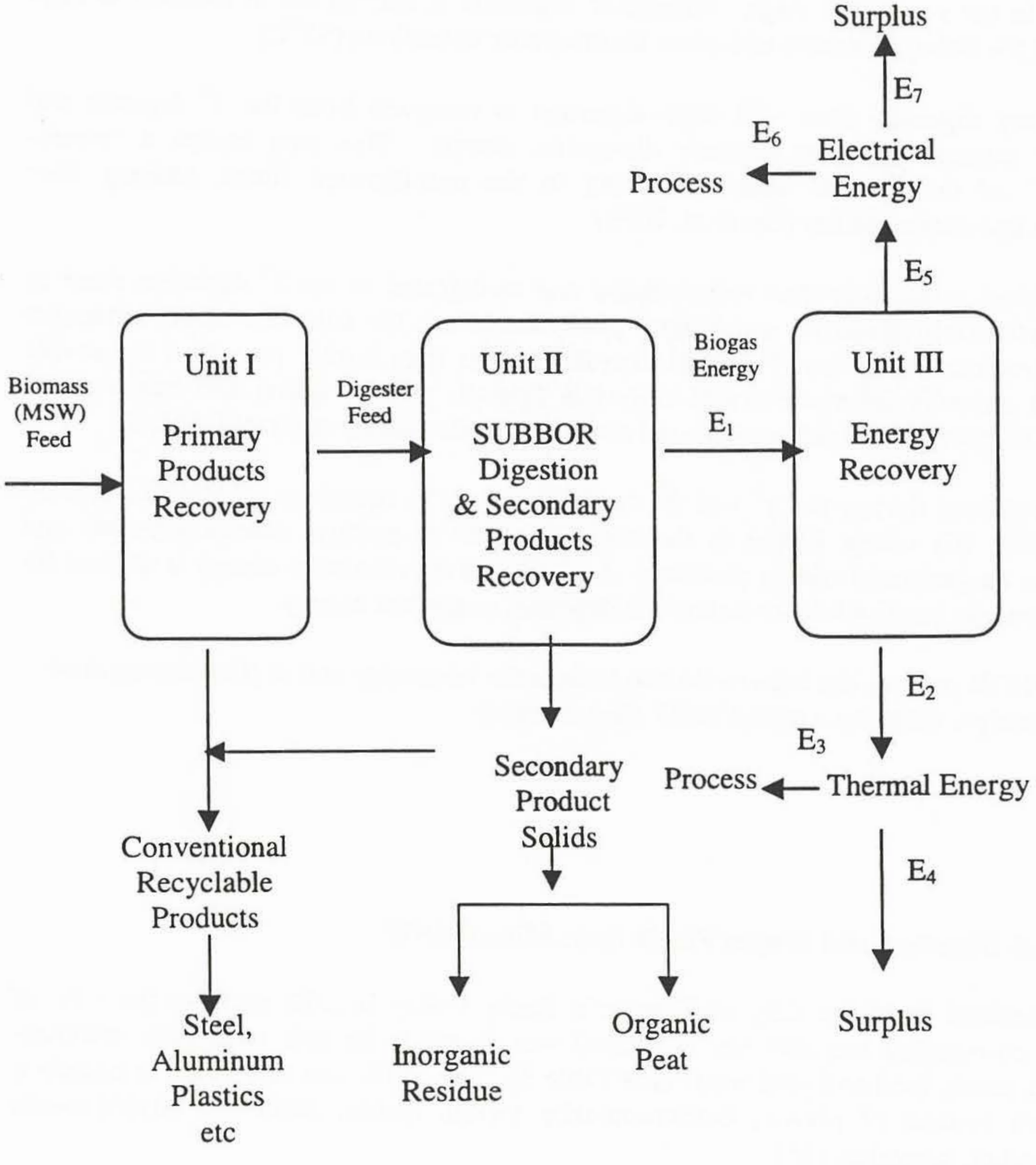
The SUBBOR technology followed from a scientific breakthrough when we demonstrated that steam-promoted pressure disruption of the digestate from (conventional) anaerobic digestion of MSW provided a disrupted material that could then be re-digested to provide large (40%) improvements in biogas production with similar improvements in overall mass (volatile solids) utilization (Liu et al, 2001 and Vogt *et al,* 1998). The increased overall digestion resulted in an organic peat by-product that was susceptible to removal of residual fugitive contamination including heavy metals.

The potential benefits from the approach of two-stage sequential digestion, namely, completion of digestion and enhanced biogas yields, led to the development of a new approach (SUBBOR Technology) for the treatment of unsorted mixed MSW.

The new process has been termed Super Blue Box Recycling (SUBBOR), so named as it can both complement or replace existing conventional ("Blue Box Recycling") waste recycling procedures.

The process flow diagram of the SUBBOR process is shown in Figure 1.

FIGURE 1: SUBBOR ENHANCED BIOMASS ANAEROBIC DIGESTION PROCES



A series of pre-digestion, conditioning/primary product recovery steps is employed (Unit I) to provide partial recovery of non-digestible components. MSW contains a high organic content but it also contains a significant amount of inorganic components as well as non-digestible "organic" (e.g. plastic) components. Unit I steps for mixed MSW provide useful recovery of a portion of the non-digestible components of the MSW prior to digestion. Unit I also provided mixing and milling to prepare the biomass components for digestion.

The heart of the SUBBOR process is the sequential multi-stage anaerobic digestion (Unit II, Figure 1) that employs steam pressure disruption of the primary digestate prior to its re-digestion in the secondary stage. Anaerobic digestion is carried out at medium to high solids (> 15% (w/w)) contents and under thermophilic conditions (55^0C).

The primary digestate after ~25 days digestion is removed from the 1^0 digester and processed through a steam pressure disruption circuit. This step causes a "steam-explosion" of the internal water remaining in the non-digested fibers, causing fiber disruption and comminution (Liu *et al*, 2001).

The disrupted material is then re-inoculated and re-digested in the 2^0 digestion stage to provide additional digestion and biogas production from the substrate made accessible through pressure disruption. The final digestate (2^0) is then further processed to provide additional recovery of non-digested materials (metals, plastic, glass) and heavy metal removal. These steps provide a recovered cleaned organic peat by-product fraction.

Biogas produced during the 1^0 and 2^0 digestion stages is routed to an energy recovery circuit (Unit III) where biogas is the energy source to produce electrical power and steam/heat co-generated energy products. A portion of the recovered energy is utilized for internal process needs while the balance is exported as product energy.

The SUBBOR process has been evaluated both in the laboratory and at pilot/demonstration scale at Guelph, utilizing a mixed MSW feed material.

Enhanced Digestion and Biogas Yields from Mixed MSW

MSW obtained from the City of Toronto's Keele Valley landfill or from the City of Guelph (co-mingled wet and dry materials) was found to be rich in organic materials including paper, food and yard waste (see Table 3). The MSW was also found to contain a significant content of plastic, macroscopically visible metals, glass and miscellaneous items (leather, ceramics, etc.).

Table 3
Characteristics of Raw MSW and Digester Feed Materials

Waste Component	Raw MSW % (w/w)	Digester Feed (Post Unit I) % (w/w)
Paper	29.6	40.7
Food/other organics	41.2	56.4
Plastic	20.3	< 1.0
Metal	2.1	~ 0.0
Glass	2.0	~ 0.0
Miscellaneous	4.8	1.9
Total	100	100

The Unit 1-sorted waste for digestion had an organic content of 86% (VS, volatile solids) and other characteristics as shown in Table 3.

A primary course of digestion of this material provided biogas production after an initial lag-phase (1-2 days) at a relatively constant maximal rate of 15–20 m^3/t VS/day of initial feedstock. This biogas production rate then fell after 25 days of digestion to $\leq 5m^3$/t VS/day indicating exhaustion of readily digestible materials for biogas production.

The 35-day primary digestion biogas yield is summarized in Table 4. The 60% CH_4 content of the biogas and overall CH_4 yield of 0.25 m^3/Kg VS provided for digestion were similar to yields for conventional anaerobic digestion technologies as reported by others (Owens and Chynoweth, 1993, Oleszkiewicz and Poggi-Varaldo, 1997, Mata-Alvarez et al, 1993).

The secondary digestion of the primary digestate following steam disruption treatment exhibited biogas production that rose sharply during re-digestion to ~ 60 m^3/t VS/day (yield normalized to VS initially provided to primary digester). This represented a gas production rate 3-4 fold higher than the maximum that had been obtained in the primary digestion. A similar marked increased biogas production in the secondary digestion stage was observed with both City of Toronto and City of Guelph MSW sources.

Table 4

Methane Yields and Mass Reductions from Enhanced Two-stage Digestion of MSW

		Biogas		Mass Reduction %	
Digestion Stage	Time of Digestion Days	CH_4 content %	Yield $m^3CH_4/kgVS$	TS	VS
Primary	35	60	0.25	40	48
Secondary	15	65	0.11	16	19
Total	50	60-65	0.36	56	67

The overall course of secondary digestion was shorter and biogas production fell to low rates (< $5m^3/t$ VS) after 10 days of digestion. However, the biogas yield in the secondary digestion was a substantial component of the overall CH_4 production as summarized in Table 4. A cumulative CH_4 yield of 0.36 $m^3/KgVS$ was obtained. Thus, secondary digestion improved biogas yields by 40% over those obtainable by primary (conventional) digestion alone.

Typically, digestion in commercial anaerobic facilities is terminated after only 15-20 days and processing is then completed by aerobic composting (DeBaere, 1999), as biogas production beyond 20 days of digestion is not justified economically. The diminished biogas production rate after about 20 days of 1^0 digestion, as confirmed by our results, indicates that maintaining 1^O digestion beyond 20 days would not be cost effective. Increased residence times require higher capital and operating costs and therefore a higher energy return to justify these costs. These criteria are not met by a prolonged inefficient digestion.

We have found that enhanced 2^0 digestion yields are achievable by actually shortening the course of 1^0 digestion, followed by steam pressure disruption of the digestate and secondary digestion. Thus, a correspondingly larger portion of the overall biogas yield can be obtained in the secondary digestion stage through an earlier termination of the primary stage followed by steam pressure disruption and re-digestion. This aspect is being further investigated as it holds potential for achieving similar overall yields with further reduced overall digestion times. The substantial boost to biogas production kinetics provided by the 2^o digestion stage following disruption, therefore provides process flexibility for adjusting the length of the overall digestion time needed for optimum gas yields.

Recovery of Cleaned Peat By-Product

The fine texture and small particle size of the residual non-digested organic fraction from the two-stage SUBBOR anaerobic digestion process facilitate the recovery of a peat by-product which has been processed so as to remove coarse non-digested contaminants such as remaining plastic, metals, glass and other inorganic residues.

The removal of the non-digested materials from the peat product achieves a significant lowering of heavy metal contamination.
Table 5 summarizes heavy metal contents of unprocessed secondary digestate solids and the two product fractions from the peat recovery steps, i.e. organic peat and inorganic residue.

Table 5
Distribution of Key Heavy Metals Among Recovered Fractions
Following Processing of Secondary Digestate

Fraction	% Mass [a]	Metal (mg/kg)		
		Cu	Pb	Zn
Secondary Digestate	100	120	72	252
Organic Peat	65	73	48	162
Inorganic Residue	28	202	112	646
> 5 mm Oversize debris	7	ND[b]	ND	ND

a, % of secondary digestate solids
b, not determined

While the heavy metal loads for the unprocessed secondary digestate are not large, the content of copper in this untreated digested material, alone, would cause it to fail scheduled criteria for Class A material (unrestricted usage) in Canada (CCME, 1996).
Recovery of a cleaned peat fraction through recovery of metals to the inorganic residue fraction provided a cleaned peat fraction representing ~ 65% of the secondary digestate solids and with reduced and acceptable heavy metal contents as shown in Table 5.
The cleaned peat fraction was more fully characterized and found to be acceptably low in all the scheduled criteria for its meeting Class A unrestricted designation as shown in Table 6.

Table 6

Characteristics of Cleaned Peat Product

Characteristic	Value	CCME Guideline Category A Limit[a]
Physical:		
Water content	35-40%	na[b]
Particle size	>95% < 2 mm	na
Sharp bodies	Nil	<3 mm
Largest particles	5 mm	<25 mm
Color	Light brown	na
Appearance	Peat-like	na
Total porosity	80-90%	na
Chemical:		
Organic matter	85%	na
Total nitrogen	0.9%	na
Total phosphorous	0.7%	na
Total potassium	0.3%	na
pH	7.9	na
Alkalinity	6.3%	na
Biological:		
Fecal Coliforms	Non detectable	<1000 MPN/g
Salmonella	Non detectable	<3 MPN/g
Trace Metals:	mg/kg	mg/kg
As	4.3	13
Cd	1.4	3
Co	3.5	34
Cr	36.6	210
Cu	73	100
Mo	<0.3	5
Ni	31.1	62
Pb	47.6	150
Se	<1.0	2
Zn	162	500
Hg	0.11	0.8

a, CCME (1996)
b, not applicable

The cleaned recovered peat was 95% < 2 mm and was free from sharp materials (> 3 mm) such as glass fragments. From a chemical composition perspective the peat was 85% organic material and had total N, P and K contents similar to other peat materials. The digested peat product material was more similar to naturally produced peat (i.e. from a Sphagnum bog) than to compost material produced from MSW, although it was of higher pH and alkalinity than sphagnum peat (MacLachlin et al, in preparation).

The steam pressure disruption step achieves a short-term processing at temperatures well above those required for sterilization and this ensures total elimination of any fugitive plant, animal or human pathogenic microorganisms. Fecal coliforms and *Salmonella* sp. were non-detectable in the recovered peat product (Table 6).

Table 6 also summarizes the residual contents of a range of heavy metal contaminants in the recovered peat. All metals in the recovered peat product were below the permissible maximum concentrations and therefore allow designation of this peat as Class A non-restricted product.

Analysis of the SUBBOR process peat fraction has also shown that it is enriched in lignin and depleted in cellulose and hemi-cellulose as compared to digestates obtained from a primary digestion alone (Liu *et al*, 2001).

The inorganic residue fraction was low in organic content and enriched in heavy metals. This material is not subject to the organic product guidelines but rather is subject to waste materials regulations pertaining to the re-use of the material either as a soil material (fill/cover) or an aggregate source. Preliminary results indicate acceptably low concentrations and a low leachability of the heavy metals from the inorganic residue fraction (Liu *et al*, unpublished) indicating that the inorganic residue product shown in Table 5 would not be a regulated waste and thus have reuse potential as an aggregate/fill material.

Overall Mass and Energy Balance for SUBBOR Process

The detailed SUBBOR process shown in Figure 1 was evaluated for both mass and energy flow and balance as shown in Table 7.

Mass balance data shown are in relation to processing mixed unsorted MSW with recoveries of each of the products as determined at pilot scale testing.

Energy flow/balance is projected for the process receiving 100,000 tonnes unsorted MSW per year and is based on biogas yield data from pilot testing and preliminary energy consumption estimates for the overall process.

Table 7
Summary of Mass and Energy Balance for SUBBOR Process
(100,000 tonnes/year Mixed MSW processed)

Mass Balance

Mass Flow (as per Figure 1)	% (of initial wet weight)
MSW Feed (mixed)	100.0
Steel	1.3
Aluminum	0.7
Plastics	19.3
Organic Peat	24.4
Inorganic Inerts	15.5
Biogas	26.2
Water/Vapor	12.9

Energy Flow and Balance

Energy Flow (as per Figure 1)	Flow rate MJ/hr	Balance % of Total	
E_1 (biogas recovered)	52,750	100	
E_2 (electrical energy recovered)	17,950 (5,000 kW)	34.0	
E_3 (process electrical)	6,500 (1,800 kW)		12.3
E_4 (electrical surplus)	11,450 (3,200 kW)		21.7
			(34.0)
E_5 (thermal energy recovered)	25,940	49.2	
E_6 (process thermal)	17,830		33.8
E_7 (thermal surplus)	8,120		15.4
			(49.2)
Energy Loss	8,850	16.8	

Electrical energy and steam energy co-generation can provide an overall recovery efficiency of 83.2% if an internal combustion engine/generator and exhaust heat recovery boiler are utilized. Of this energy recovered, 34% of this in the form of electrical energy (5 MW/hr) and 49.2% of this is in the form of heat energy (25,940 MJ/hr).

Internal process needs for electrical energy are only 1.8 MW/hr, therefore providing a surplus electrical energy process output of 3.2 MW/hr that can be sold onto the electrical power grid.

Similarly, process needs for thermal energy, even with utilization of steam disruption as a process step, are only 17,830 MJ/hr, providing an available surplus thermal energy of 8,120 MJ/hr.

Thus, of the total biogas energy produced and after meeting internal process energy needs 21.7% of the total energy recovered is electrical power product (3.2 MW/hr continuous) and 15.4% of the total energy recovered is thermal energy product.
The use of combined cycle electrical power production with gas and steam turbine electrical generation has the potential to further increase the portion of overall energy yield recoverable as electrical power but this has not been further analyzed at present.

GHG Reduction Benefit of SUBBOR Process

The current GHG assessment model (Environment Canada, 1995) can be utilized to compare GHG impacts for three waste management options (see Table 8). The data in the Table 8 and details as to their calculations can be found elsewhere (World Resource Review, submitted for publication).

Landfill disposal after conventional recycling represents the current baseline practice for MSW as this applies to the bulk of all waste handled in North America between 1991 and present (see Table 1). This management practice even with significant recycling credit results in a large net GHG emission (1.6 tonnes CO_2 /tonne of MSW), as the bulk of all waste currently placed into landfill is to landfills without gas (LFG) collection systems.
This worst-case baseline scenario provides a needed reference point to compare improved MSW management practices.

GHG emissions from landfills can be significantly decreased by the inclusion of LFG/energy recovery systems. Here, a substantial portion of the methane produced in the landfill (50% over the life of the landfill) is harvested and utilized as fuel for electrical power production. Note, while higher recoveries of LFG are achievable during the active portion of the landfill's life, gas losses in the inefficient early phases and late phases of the landfill, lower overall recovery on a life-cycle measurement basis.

Table 8

GHG Reduction Benefit from SUBBOR Processing of MSW[a]

MSW Management Option, Recycling Plus:	kg CO_2/tonne raw MSW			GHG Emission Reduction Credit Relative to Baseline Tonnes CO_2/tonne MSW
	Recycling Credit (-)	Residual fraction Emission (+) or Credit (-)	Net Emission (+) or Credit (-)	
Landfilling (Baseline)	-544	2180	+1636	Baseline
Landfilling with LFG collection/energy	-544	923	+379	-1.26
SUBBOR	-544	-599	-1143	-2.78

a: based on current (Environment Canada, 1995) GHG assessment models, updated to exclude biogenic carbon dioxide emissions and for a methane $GWP_{100} = 21$

The combined GHG reduction credits from SUBBOR are shown in Table 8. Gone are all landfill-associated GHG emissions and, in addition, a further GHG reduction credit is obtained for the energy produced. SUBBOR provides an overall potential reduction credit of 2.8 tonnes CO_2 reduction for each tonne of raw MSW managed. On this basis, the management of all of Canada's 30 million tonnes/year MSW represents a potential GHG reduction of ~90 million tonnes CO2/year.

This indicates that the SUBBOR Technology can play a large role in GHG reduction through the treatment of MSW, a component of GHG reduction that is completely complementary to any other reductions achieved in the usually identified petrochemical, manufacturing and transportation GHG-emitting sectors.
The SUBBOR role in GHG reduction can also be augmented through its application to other biomass wastes.

Thus, anaerobic digestion processing of MSW and other biomass wastes can provide a very large contribution to GHG emissions reduction.

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