



Pomace waste management scenarios in Québec—Impact on greenhouse gas emissions

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ABSTRACT

Fruit processing industries generate tremendous amount of solid wastes which is almost 35–40% dry weight of the total produce used for the manufacturing of juices. These solid wastes, referred to as, “pomace” contain high moisture content (70–75%) and biodegradable organic load (high BOD and COD values) so that their management is an important issue. During the management of these pomace wastes by different strategies comprising incineration, landfill, composting, solid-state fermentation to produce high-value enzymes and animal feed, there is production of greenhouse gases (GHG) which must be taken into account. In this perspective, this study is unique that discusses the GHG emission analysis of agro-industrial waste management strategies, especially apple pomace waste management and repercussions of value-addition of these wastes in terms of their sustainability using life cycle assessment (LCA) model. The results of the analysis indicated that, among all the apple pomace management sub-models for a functional unit, solid-state fermentation to produce enzymes was the most effective method for reducing GHG emissions (906.81 tons CO₂ eq. per year), while apple pomace landfill resulted in higher GHG emissions (1841.00 tons CO₂ eq. per year). The assessment and inventory of GHG emissions during solid-state fermentation gave positive indications of environmental sustainability for the use of this strategy to manage apple pomace and other agricultural wastes, particularly in Quebec and also extended to other countries. The analysis and use of parameters in this study were drawn from various analytical approaches and data sources. There was absence of some data in the literature which led to consideration of some assumptions in order to calculate GHG emissions. Hence, supplementary experimental studies will be very important to calculate the GHG emissions coefficients during agro-industrial waste management.

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1. Introduction

Agro-food industries generate large quantities of liquid and solid wastes which must be suitably managed before being directly discharged to the environment. In Canada, the majority of fruit processing industries are concentrated in Quebec (about 35% contribution), Southern Ontario, and British Columbia [1]. One third of the total apple production in Canada (449,190 tons/year, 20% contributed by Quebec) is processed to produce juices, flavors and concentrates [2]. The end result of an apple processing industry is a solid residue containing high moisture content (70–75%) and biodegradable organic load (high BOD and COD values) [3]. These wastes have low nutritional value and their high biodegradability causes environmental problems. A typical apple processing

industry generates 30–40% apple pomace and 5–11% sludge (liquid waste obtained after clarification). There are large quantities of solid wastes (apple pomace) produced round the world, including 16,209 tons in 2007 in Québec [1]. Apple pomace waste produced in Quebec was selected as the case study. These solid wastes being highly biodegradable, their disposal represents a serious environmental problem and presents many challenges [4,5]. In Quebec, this waste is mainly used as a source of crude animal feed by the farmers. Often only 20% is retrieved as animal feed and the rest 80% goes to landfill or composting sites which results in release of enormous quantity of greenhouse gases. Composting Council of Canada reported about 38% of Canada's methane emissions coming from organics decomposition in landfills [6]. Other modes of management of apple pomace comprise landfilling, composting, incineration and the innovative option of utilization of the apple pomace as a sole raw material for production of high value-added products, such as enzymes, organic acids, ethanol, among other products. In fact, the option of high value-added

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products formation by solid-state fermentation has been tested as a resourceful option in our laboratory as it is able to generate new bio-products and at the same time result in value-addition and management of the wastes [7]. Apple pomace studied in this work has been procured from a reputed juice transformation industry in Quebec. The distance between this industry and management sites was considered to be 25, 200, 100 and 200 km in the case of landfill, incineration, composting, and enzyme production, respectively. Meanwhile, in the case of animal feed, 20% of farmers were situated at 80 km distance from the apple juice industry and 80% of farmers were situated at 50 km from the juice industry.

The management of wastes is a significant source of GHGs [8]. The contribution of the waste management and disposal sector amounts to 4% of the various anthropogenic GHG emissions [9]. Various stages of the management of solid wastes including, collection, transportation, and disposal is generally followed by the release of GHG gases, such as carbon dioxide, methane, and N₂O. These gaseous components by virtue of their physical properties contribute to the GHG effect. Meanwhile, the increase in the concentration of these gases contributes to the global warming phenomenon.

In fact, there are various means to manage domestic or industrial wastes, where by the GHG emissions vary according to the consumption of energy, transportation, and technologies used for the process management [10]. To quantify the GHG emissions during waste management by different strategies, the best way is to conduct a comparative analysis through streamlined application of life-cycle assessment (LCA) model [11]. LCA is an analytical framework for understanding the material inputs, energy inputs, and environmental releases associated with manufacturing, usage, and disposal of a given material [11].

Many studies on environmental performance, especially with regard to GHG emissions, of various waste management strategies have been implemented for most developed countries and some developing countries [12–14]. To the best of our knowledge, there is no study reported till date which discusses the GHG emission analysis of agro-industrial waste management strategies, especially apple pomace waste management. The assessment and inventory of GHG emissions during solid-state fermentation was carried out for the first time in this study to evaluate the repercussions of value-addition of these wastes in terms of environmental sustainability. In the present study, LCA of apple pomace management by different strategies was conducted with an impact assessment limited to GHG emissions. Five apple pomace waste management strategies were used in the present study, namely, apple pomace incineration, landfill, composting, solid-state fermentation to produce high-value enzymes and animal feed.

The main objectives of this study were to develop the inventory of apple pomace management scenarios (incineration, landfilling, composting, animal feed and enzyme production) with details in methods section to assess and compare the environmental impacts of related management scenarios and determine environmentally most respectful scenarios of the environment.

2. Methodology

2.1. Life cycle assessment

Environmental assessment of a product (apple pomace waste) over its entire lifecycle can indicate the extent of the manufacturer's environmental responsibilities beyond the boundaries of its own facilities, and it can help to identify appropriate management

options. Life cycle assessment (LCA) is a technique for assessing the environmental aspects and potential impacts associated with a system (product system or service system) by:

- (i) compiling an inventory of relevant inputs and outputs of the system;
- (ii) evaluating the potential environmental impacts associated with those inputs and outputs; and
- (iii) interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study [15].

This methodology has been already used in many studies to evaluate the environmental impact during the management of different wastes such as municipal waste, agricultural waste paper, glass, metal, and plastic materials [12,16,17].

2.2. The goal and scope

The goal of this study is to evaluate GHG emissions of the existing apple pomace management systems based on life cycle perspective. Specifically, GHG emissions are considered in this study as climate change is a priority area in Quebec particularly for policy making..

2.3. Systems boundaries and function unit

The system boundaries include collection and transportation of apple pomace from its source (apple juice industry) to be treated by various management methods in each scenario. It should be noted that equal amount of the apple pomace waste (16,209 tons/year) of the same composition are treated in all scenarios. Besides, direct processes relating to waste management systems, other relevant processes interacting with the waste management systems are also included. Production of energy, i.e., electricity and diesel are also included as such energy is directly used in waste management systems and background systems. In animal feed scenario, the management of manure was not taken in account. The system was considered until enteric fermentation related to animal feed. The energy recycling was taken into account only in the case of incineration as this practice is more popular in Quebec for this scenario. Enzyme production system was considered only until fermentation. Similarly, the composting system was considered until composting process and the compost landfilling was not taken into consideration.

The functional unit (FU) providing a reference to which the inputs and outputs are related is defined as "the total production of apple pomace in Québec at 2007 of 16,209 tons"

2.4. Emission categories

The GHGs from apple waste management using different scenarios are of distinct origin which has been considered for the present study as follows:

- (a) Transportation and collection of waste
- (b) Landfilling of waste
- (c) Composting of waste
- (d) Incineration
- (e) Animal feed
- (f) Solid-state fermentation to produce enzymes

For the above waste treatment practices, the principal basis was for each 16,209 tons of apple waste produced (equivalent to total apple pomace production in Quebec in 2007). For the selection of GHG types, the gases CO₂, CH₄ and N₂O which directly influenced the greenhouse effect were selected for assessment. As each GHG

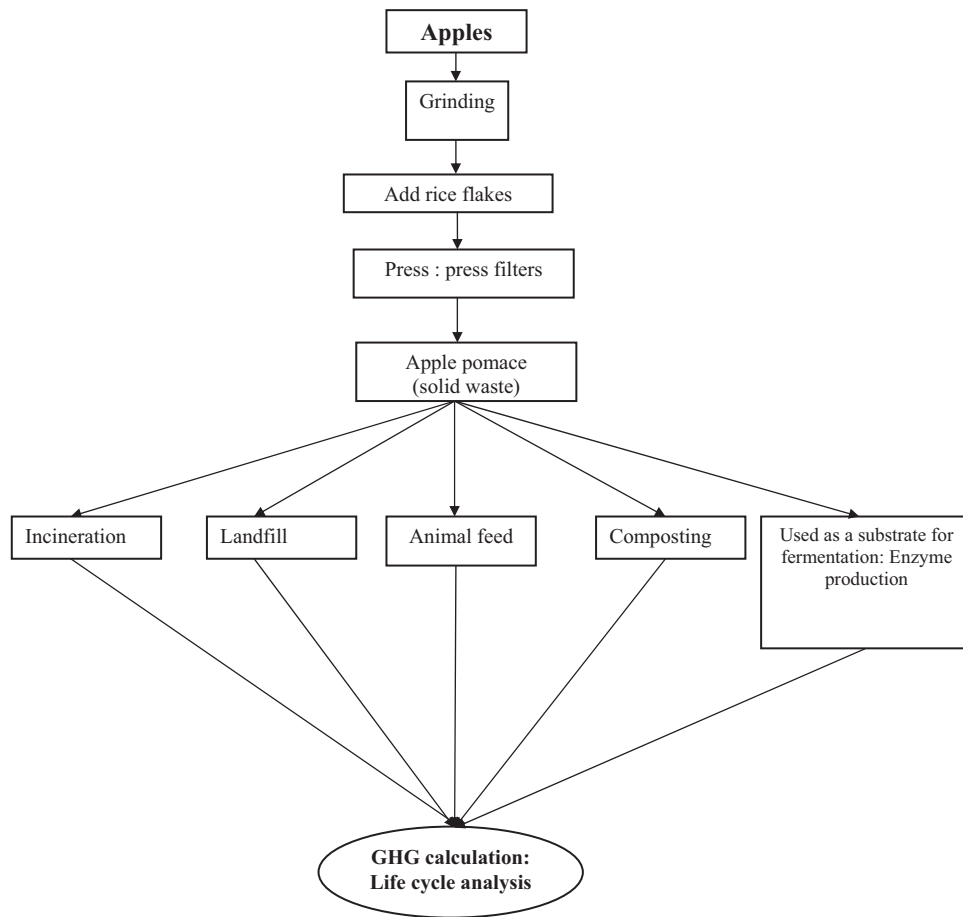


Fig. 1. Scenarios of apple pomace management.

differed in the strength of their heat-trapping potential, the heat-trapping potential of CO₂ was used as the basis to show the level of relative contribution to global warming of each gas. The heat trapping potential of CH₄ and N₂O are about 21 and 310 times more powerful than carbon dioxide on a per molecule basis, respectively. The different scenarios of management of apple pomace waste are presented in details in Fig. 1.

2.4.1. GHG emissions from the waste collection and transportation

GHG emissions from the waste collection and transportation mainly came from CO₂ generated by the transport vehicles during usage of fuel. The actual emissions varied with the vehicles' engine model, fuel type (petrol and diesel), size and load [18]. The total emissions could also be derived from the total mileage or fuel usage. In the case of animal feed, 20% of farmers were situated at 80 km distance from the apple juice industry and 80% of farmers were situated at 50 km from apple juice industry. To transport apple pomace from the industry to farmer, the vehicles used were 3 axle semi-trailer. This type of vehicle was used to transport apple pomace waste in all management scenarios. These semi-trailers generally transport 14.1 tons of merchandise in Canada [19]. The different emission coefficients of GHGs relative to various vehicles in Canada are presented in Table 1. Further, the distance between management sites and apple juice industry was considered to be 25, 200, 100 and 200 km in the case of landfill, incineration, composting, and enzyme production, respectively. For GHG calculation, the number of vehicles transporting 16,209 tons of apple pomace was calculated. The vehicles used for transportation of apple pomace consumed 35 L of diesel/100 km [20].

All calculations were carried out in Excel spreadsheet programme. The collection and transportation component of GHG emissions during solid waste management was therefore calculated using Eq. (1):

$$E_t = \frac{N \times D \times C}{100} \times \frac{(C_{CO_2} + C_{N_2O} \times 310 + C_{CH_4} \times 21)}{1000} \quad (1)$$

E_t is the GHG carbon equivalence from collection and transportation of waste (kg CO₂ equivalent/year); N is the number of vehicles; D is the distance between the industry and management site; C is the fuel consumption/100 km = 35 L/100 km; C_{CO_2} is the CO₂ emission coefficient (g of CO₂/L of fuel); C_{CH_4} is the CH₄ emission coefficient (g of CH₄/L of fuel); C_{N_2O} is the CH₄ emission coefficient (g of N₂O/L of fuel); 310 = heat trapping potential of N₂O/heat trapping potential of CO₂; 21 = heat trapping potential of N₂O/heat trapping potential of CO₂.

2.4.2. Production of enzymes

When assessing GHG emissions during the use of apple pomace waste as substrate to produce value-added products (enzymes) by *Phanerocheate chrysosporium* using solid state fermentation method [24], three emission sources must be considered: (1) GHGs emissions are primarily produced during the transportation of apple pomace from the industry to the fermentation installation, these emissions were calculated as indicated in Section 2.4.1, the distance between juice industry and the fermentation installation was 200 km; (2) CO₂ produced during fermentation, O₂ was converted to CO₂ in the case of aerobic fermentation; (3) GHG emissions related to consumption of electricity to maintain the conditions of fermentation such as, temperature and agitation.

Table 1
GHG emission coefficients related to the combustion of fuels by semi-trailers.

		Coefficients of emissions by heavy commercial vehicles: Government of Canada		
Use		Coefficients of emission		
		CO ₂ (g/L gasoline)	CH ₄ (g/L gasoline)	N ₂ O (g/L gasoline)
Gasoline vehicles	- 3-way catalytic converter	2360	0.17	1
	- Non-catalytic system	2360	0.29	0.046
	- No cleansing system	2360	0.49	0.08
Diesel vehicles	- Sophisticated cleansing system	2730	0.12	0.08
	- Cleansing system of average efficiency	2730	0.13	0.08
	- No cleansing system	2730	0.15	0.08

In order to calculate the GHG production during fermentation, which is primarily carbon dioxide, the experimental set-up comprised of solid state fermentation under aerobic conditions as illustrated in Fig. 2. During the fermentation, there was continuous production of CO₂. To quantify CO₂ production, CO₂ was captured in 220 ml NaOH (5 M). CO₂ reacted with NaOH throughout fermentation to form Na₂CO₃. Consequently, at the end of fermentation, unreacted residual NaOH solution was titrated against HCl (1 M) solution to quantify CO₂ formed during fermentation. Quantified CO₂ corresponded to 40 g of pomace. Thus, we were able to determine the emissions of CO₂ corresponding to 16,209 tons pomace disposed per annum. This GHG emission corresponded to 684.83 tons of CO₂/year.

The electrical energy consumed in in-vessel composting varies between 9 and 65 kWh tons⁻¹ waste [29–32]. The electrical energy consumed during fermentation of apple pomace was about 37 kWh tons⁻¹ of waste. The quantity of pomace produced per year is 16,209 tons. Hence, the electrical energy consumed during fermentation of pomace translates to 599733 kWh. The indirect emission factor due to consumption of electricity is 0.0014 kg CO₂ equivalent/kWh [33]. Thus, indirect GHG emissions related to the consumption of electrical energy during fermentation of apple pomace were calculated. All these calculations were performed in Excel spreadsheet programme.

2.4.3. Animal feed

The use of apple pomace for animal feed is one of the waste recycling categories. Apple pomace, rich in sugar when fed as cattle feed becomes significant source of CH₄ and N₂O. When assessing GHG emissions by using apple pomace waste as cattle feed, two emission

sources must be considered: (1) enteric fermentation in cattle; (2) transportation from the industry to farmers, these emissions were calculated as indicated in Section 2.4.1, the distance between juice industry and 80% of farmers was 50 km, while 20% of these farmers were situated 80 km from Lassonde, Inc. (Juice industry) [28]. In this study, manure management was not taken into consideration. GHG emissions produced during transportation were calculated as explained in part 2.2.1. Each cattle could digest approximately 1 kg apple pomace waste each day. If 16,209 tons of apple pomace were produced each year, the apple pomace waste could feed around 44,408 cattle a year. Apple pomace was considered to be supplemented with other kind of diet each day to the cattle (Table 2).

Thus, apple pomace also resulted in the production of methane during enteric fermentation of cattle. The contribution of pomace was calculated by taking into account percentage of carbon present in pomace and percentage of carbon contained in the feed ration of fattening cattle. For this calculation, the quantity of corn and soya was calculated which was necessary to replace them by one kilogram of pomace in a standard ration given to the fattening cattle comprising maize, soybean oil cake, mineral and urea. The replacement was based on percentage of carbon and nitrogen in the feed. Table 2 represents the contributions of carbon and nitrogen in various feeds present in the standard diet of fattening cattle. The standard ration corresponded to ration A and the ration containing pomace referred to as ration B are presented in Table 2. Different emission coefficients of GHGs during enteric fermentation of fattening cattle are presented in Table 3. These coefficients were multiplied by the number of cattle fed per annum and the incorporation of pomace, to determine GHG emissions during enteric fermentation. The number of cattle was calculated by taking the ratio of quantity of pomace disposed per annum (16,209 tons) over 365 days.

2.4.4. Incineration

In Quebec, the majority of solid wastes are incinerated. As per the general incineration process trends in Quebec, the collection trucks dump apple pomace waste in the waste pit which is further crane lifted to be placed in the mouth of the four furnaces (boilers).

Calculation of GHG emissions during the incineration of apple pomace was carried out using the method of Tchobanoglous et al. [21] prescribed in the Canadian inventory of green house gases (1990–2002) [22]. GHGs produced during incineration were mainly CO₂ and N₂O [23]. The calculations for the incineration GHG factors included: (1) emissions of GHGs during transportation from the industry to incinerators, these emissions were calculated as indicated in Section 2.4.1, the distance between juice industry (Lassonde, Inc.) and the nearest incinerator was 200 km; (2) emissions of N₂O; (3) CO₂ produced while generating power instead of utilities; and (4) reduction in emissions caused by energy consumption due to the recovery of non-combustible metals for use in manufacturing. The efficiency of energy recovery during incineration was considered to be 90%.

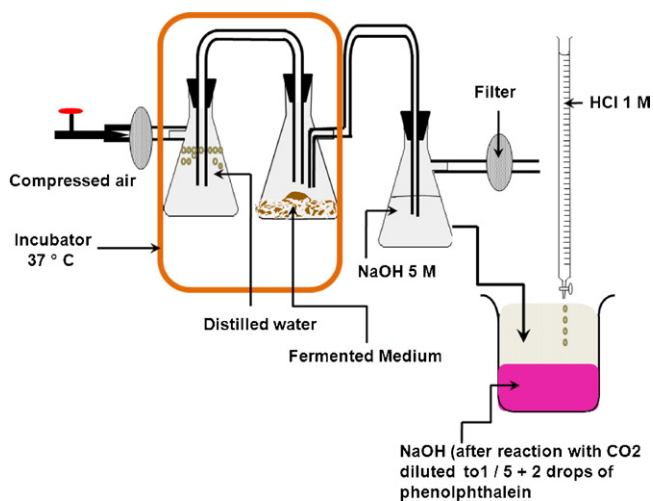


Fig. 2. Schematic for aerobic fermentation of apple pomace to produce enzymes: collection of CO₂ as a GHG.

Table 2
Feed rations of cattle and carbon and nitrogen contributions of different nutrients.

Nutrition	Carbon %	Nitrogen%	Ration A	Ration B
Corn ensilage	43.8	1.0	14 kg	14 kg
Hay	40	2.5	1 kg	1 kg
Maize	44	1.4	5 kg	4.862 kg
Soya	42	6	0.3 kg	0.107 kg
Minerals			0.100 kg	0.100 kg
Urea	20	46	0.050 g	0.050 kg
Pomace	14.3	1.1	0 kg	1 kg

2.4.4.1. *Emissions of CO₂*. CO₂ emissions during incineration were calculated by using Eqs. (2)–(5) as given below:

$$C_{\text{available}}(y) = (\text{Waste type}) \times (1 - \% \text{Humidity}) \times \% C_{\text{Waste type}} \quad (2)$$

where $C_{\text{available}}(y)$ is the available carbon by type of waste for a province y , in time t (year); waste type is the quantity of the type of incinerated waste, in time t (year); % humidity is the percentage of moisture content by type of waste; $\% C_{\text{Waste type}}$ is the percentage of carbon contained in fossil fuels for each type of incinerated waste.

%C in pomace: 14.3% [24].

Quantity of pomace: 16,209 tons:

$$C_{\text{available}} = \frac{16,209 \times 14.3}{100} = 2317.888 \text{ tons} \quad (3)$$

$$\begin{aligned} CE_{\text{CO}_2-2007(y)} &= \frac{C_{\text{available}}(y)}{M_{\text{inc}}(y)} \times \frac{PM_{\text{CO}_2}}{PM_{\text{C}}} = \frac{2317.888}{16,209} \times \frac{44}{12} \\ &= 0.52433 \text{ tons of CO}_2/\text{tons of incinerated pomace} \end{aligned} \quad (4)$$

where $CE_{\text{CO}_2-2007(y)}$ is the coefficient of CO₂ emission in 2007 for the incineration of waste for a province y , in time for CO₂/tons of incinerated waste; $C_{\text{available}}(y)$ is the available carbon by type of waste for a province y , in time t (year); $M_{\text{inc}}(y)$ is the total mass of incinerated waste in 2007 for a province y , in time t (year); PM_{CO_2} is the molecular weight of CO₂, 44 t/t-mol tons/tons of moles; PM_{C} is the molecular weight of carbon, 12 t/t-moles.

$$\begin{aligned} \text{CO}_{2(x)} &= CE_{\text{CO}_2-2007} \times (M_{\text{inc}(x)}/\text{province}) = 0.52433 \times 16,209 \\ &= 8498.91 \text{ tons of CO}_2 \end{aligned} \quad (5)$$

2.4.4.2. *Emissions of N₂O*. Nitrous oxide emissions were calculated using Eq. (6) used in the method of Tchobanoglous et al. [21]:

$$\text{N}_2\text{O emissions} = \text{IWi} \times \text{EFi} \quad (6)$$

where N₂O emissions is the emissions of N₂O in the year of inventory, tons/year; IWi is the volume of waste type i incinerated/burnt in free oxygen, tons/year; EFi is the emission factor of N₂O (kg N₂O/Gg of waste) for waste of the type i .

The emission factor for the solid waste of pomace was equated to paper waste and it was taken as 10 g of N₂O per ton of waste [25]. This factor was taken into account as nitrogen content of the paper waste was similar to that of apple pomace.

2.4.5. Composting

GHG emissions during composting are of two types, CH₄ and N₂O. CO₂ is produced during windrow composting while turning the rows and also during transportation of the waste to the

composting site. GHG emissions during transportation were calculated as indicated in Section 2.4.1, the distance between juice industry and the fermentation installation was 100 km. Moreover, we did not take into consideration the production of CH₄ during composting, as waste is generally maintained in aerobic medium, with a small amount of oxygen leading to aerobic decomposition of materials. For this reason, the release of methane gas was neglected. Production of N₂O was also taken into account. The emissions of N₂O originating from composting were calculated using the method suggested by GIEC [34]. Apple pomace was transported to a composting site with a capacity of 38,534 m³/year. The emissions produced by the retournor of windrow composting were calculated using the consumption of diesel. The composting unit uses an automated turner for piles requiring a power of 75 kW consuming 12 L of diesel per hour. The composting site is in operation for 261 days/year for a working period of 8 h/day, considering an operation efficiency of 90%. The consumption of diesel is thus equivalent to 0.6 L of diesel per cubic meter of composted solids. The quantity of pomace to be composted is 16,209 tons per year. This solid waste has a density of 444 kg m⁻³. Thus, the volume of apple pomace to be composted per year is equal to 36,506.75 m³. The quantity of diesel consumed to turn over the apple pomace during composting is thus equal to 21,904.05 L per year. Coefficients of emissions of GHG related to the combustion of diesel by tractors [2] are 2730 CO₂ g/L, 0.12 g/L of CH₄ and 0.1 g/L of N₂O. Eventually, the total emissions are calculated.

2.4.6. Landfill

Landfilling is a mode of waste management where the wastes are stored under soil which is almost deprived of oxygen. The anaerobic storage of waste is accompanied by the decomposition of organic residues thus producing methane gas, which is 21 times superior to CO₂ in terms of greenhouse gas effects. The transportation of wastes from the industry to the landfill site requires the use of fuel which inevitably produces GHGs, in particular, CO₂. The calculations for the landfilling GHG factors included: (1) emissions of GHGs during transportation from the industry to landfill site, these emissions were calculated as indicated in Section 2.4.1, the distance between juice industry and landfilling site was 25 km; (2) emissions during the process of landfilling resulting from decomposition of organic residues.

To calculate the GHGs produced during landfilling of pomace, a first-order-decay (FOD) model was used [26]. The first-order-decay (FOD) model is generally recognized as being the most widely used approach, as it is recommended by the Intergovernmental Panel on Climate Change [18]. Landfill gas (LFG) formation from a certain amount of waste is assumed to decay exponentially in

Table 3
Coefficients of emissions of CH₄ for enteric fermentation—for bovine cattle from 1990 to 2006 (adopted from Boadi et al., 2004).

Coefficients of emission, or CE _{(CE)_T} , in kg CH ₄ per animal, per year								
Year	Milking cows	Dairy cattle	Bulls	Cows	Heifers	Heifers for slaughter	Cattle	Calves
2006	135.2	73	92.9	84.8	75.3	67.0	60.4	48.3

time. The FOD model has been applied to other developed models, such as Palos Verdes Model, Sheldon- Arleta Model, Scholl Canyo Model and First-Order Model TNO (The Netherlands Organization of Applied Scientific Research) used in this study. The first order model Netherlands (TNO), can be described mathematically by Eq. (7). The TNO model is derived assuming the amounts of degradable organic carbon. For the best results, preferably the same waste composition should be used when using this model to predict LFG production on other sites. It makes the model less dependent on errors during estimates of waste composition. To calculate methane production, the LFG production obtained with the TNO model is multiplied with the methane concentration of 50% and volumetric mass of $714 \text{ g CH}_4 \text{ m}^{-3}$. This model enables calculation of GHG emissions in m^3/year . The landfill gases make up to 50% of CH_4 and 50% of CO_2 [27]. In order to calculate the quantity of each gas in kg, it is necessary to multiply half of the gas volume by CO_2 density and second half by methane density. The total emissions are thus calculated in kg equivalent of CO_2 :

$$\text{GHG}(t) = f \times 1.87 \times A \times C_0 \times k_1 \times e^{-K_1 \times T} \quad (7)$$

where GHG is the production of landfill gas, at a given time, t (m^3 GHG/year), f is the factor of dissimilation (0.58), $1.87 =$ conversion factor (m^3 of landfill gas/kg C degraded), A is the quantity of wastes loaded into the incinerator (1000 kg), C_0 is the quantity of organic carbon in the waste ($\text{kg C}/1000 \text{ kg of wastes}$) = $498 \text{ kg}/1000 \text{ kg}$ of pomace, k_1 is the constant of degradation, 0.094 (per annum) t is the time elapsed since the waste deposit (year).

Composition of landfill gases was taken as 50% of CH_4 and 50% of CO_2 [27] with the density of each of the gases being:

$$\begin{aligned} \text{Density of CH}_4 &= 714 \text{ g m}^{-3}. \\ \text{Density of CO}_2 &= 1870 \text{ g m}^{-3}. \end{aligned}$$

2.5. Major limitations

The analysis and use of parameters in this study was drawn from various analytical approaches and data sources. These approaches have their research limitations. Additionally, the analyses and assessment in this model framework is based on some major assumptions. The major limitations in the study and various assumptions are listed below:

- The net GHG pollutants produced by the incineration of waste can be reduced through improvement in the efficiency of the incineration system.
- The pollutant emissions from composting depended on the type/quantity of supporting material as well as the temperature, water content and supply of oxygen during the composting process. This led to a wide range of emission volumes. Hence, for the analysis of emissions, it was considered that there was no production of CH_4 during composting as the compost was properly returned and aerated.
- The landfill analysis was based on GHG inventory of Quebec (1990–2002) [35], the coefficients used were that of municipal waste considering the fact that characterization data were same. There was no data available for apple pomace waste or fruit waste or even any other agro-industrial or agricultural wastes. Lack of relevant data on CH_4 emissions from the landfill surface and carbon storage meant there were a large number of uncertainties involved.
- During the use of apple pomace as animal feed for cattle, the emissions of N_2O during manure management were not taken into consideration as there was no data on N_2O emission by cattle in Quebec, unlike swine.
- The analysis of CO_2 emissions during fermentation was carried out in lab scale fermentation system. The results could be changed

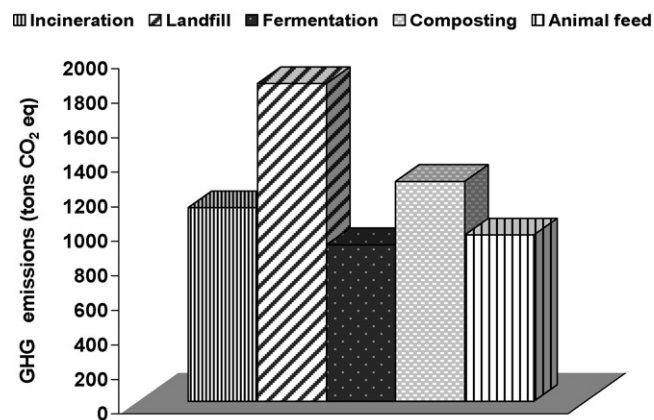


Fig. 3. Net GHG emissions from various apple pomace waste management methods.

during scale-up of the process by carrying out fermentation using large scale fermentor where carbon dioxide analysis can be performed automatically by using gas analyzer. In fact, it is assumed that at large scale, the fermenters will produce less CO_2 due to optimal environmental conditions.

3. Results and discussion

GHGs produced during different modes of waste management of apple pomace can be quantified by taking the sum of the results obtained during transportation and during the actual management process. The net GHG emissions from various apple pomace waste management options are presented in details in Fig. 3 and GHG emissions during different steps of each management scenario are presented in details in Table 4. The total GHG emissions (Fig. 3) were 1122.1; 1841.00; 906.81; 1273.78; and 963.38 tons of CO_2 eq. per annum during incineration, landfilling, fermentation, composting and animal feed, respectively.

As seen in Table 4, all scenarios considered during the course of evaluation of different waste management options generate GHG emissions. The production of enzymes and animal feed were the least polluting scenarios of the environment in terms of release of GHGs, followed by incineration, composting and landfilling.

3.1. Production of enzymes

As per the results of life cycle analysis, the fermentation method to produce ligninolytic enzymes is the most environmentally sustainable process (906.81 tons of CO_2 eq.) (Fig. 3). This is due to the aerobic mode of fermentation. During aerobic fermentation, the microorganisms use oxygen and transform the solid biomass into CO_2 contrary to the anaerobic digestion where there is production of CH_4 . The global warming potential of CO_2 is 21 times less than CH_4 . This very well proves the lower emissions of GHG during fermentation. In addition to the environmental sustainability, fermentation seems to be the most economic process for waste management as there is a possibility of production of high-value products which encompass huge commercial value. On the other hand, all other methods of waste management encumber high process costs. For example, landfill needs the presence of landfill sites that are very costly in contrary to solid state fermentation that can be performed in a simple tray without sophisticated equipment.

3.2. Animal feed

Lower GHG emissions were observed during apple pomace waste transformation usage as animal feed (963.38 tons of CO_2 eq.) (Fig. 3). This fact may be related to the point that manage-

Table 4
GHG emissions during different scenarios of apple pomace management.

Scenario (tons of CO ₂ eq. per year)	Animal feed	Landfill	Incineration	Enzyme production	Composting
GHG emissions during transportation	62.15	27.75	221.98	221.98	110.99
CO ₂ emissions	Not considered	201.13	8498.91	684.83	57.79
CH ₄ emissions	901.23	1612.69	Not considered	Not considered	Not considered
N ₂ O emissions	Not considered	Not considered	50.24	Not considered	1105
Energy recovery	Not considered	Not considered	7649.01	Not considered	not Considered

ment methods for manure produced by the cattle during the use of pomace in animal feeds (N₂O and CH₄ gases produced) were not taken into account. The management of manure was not taken into account as there was no literature data for the coefficients of emissions of N₂O and CH₄ related to the management of manure produced by cattle as compared to the management of manure by swine (Quebec Inventory on GHGs [35]). The consideration of GHG emissions during management of manure will increase the total assessment of GHG emissions as global warming potential of N₂O is 310 higher than CO₂. In other words, if the management manure during this strategy was taken into account, the animal feed scenario will become the most polluting with higher release of GHGs.

3.3. Incineration

The total GHG emissions during incineration were 1122.10 tons of CO₂ eq. per year (Fig. 3). In spite of the recycling of CO₂ produced during the process, incineration was the third most polluting management strategy. If the recycling of CO₂ was not taken into account, it will become the most polluting with higher release of GHGs. This can be explained by the fact that incineration mode of management completely destroys the waste which is transformed into ash and gases. On the other hand, other modes of waste management transform the waste into other products which is a simple transformation and not complete destruction. Meanwhile, in the literature [36,37], it has been demonstrated that incineration is the most environmentally sustainable mode of waste management. This can be explained by the fact that there will be value-addition of burned wastes, in particular within the framework of the urban heating, similar to the assumption fixed in this study. Chen and Lin [36] estimated that the total GHG emissions produced were much higher in the case of animal feed as compared to incineration which is contrary to the results produced in our study. This is explained by the fact that the GHGs produced during management of manure produced by the cattle was not taken into account as its management would lead to production of GHGs, such as CH₄ and N₂O.

3.4. Composting

GHG emissions during composting of apple pomace waste were 1273.00 tons of CO₂ eq. per annum (Fig. 3). These emissions were much lower than those produced during landfilling. This may be due to the fact that only small quantity of N₂O was produced during composting, which was related to lower nitrogen content present in pomace waste. In addition, CH₄ emissions during composting have been neglected as the process has been considered under strict aerobic conditions.

3.5. Landfill

According the results of life cycle analysis shown in Fig. 3, landfilling as a mode of apple pomace waste management resulted in higher GHG releases. Other studies, which were carried out to take into account the greenhouse gas balance for the management of

municipal solid wastes [36,37] also demonstrated that landfilling was the most polluting strategy leading to release of GHGs at elevated rate and hence global warming. Higher GHG emissions during landfilling were necessarily due to landfill gases produced during anaerobic digestion of apple pomace. During the landfill process, wastes are disposed in a site by burial. In the landfill site, organic wastes are decomposed by microorganisms in the absence of oxygen, this decomposition causes the production of a gas which is composed primarily of methane, a greenhouse gas contributing to climate change. The global warming potential of CH₄ is 21 times higher than that of CO₂. This gives explanation for elevated GHG emissions as equivalent of CO₂ during landfilling of apple pomace waste. There is another aspect of GHG production during landfilling that GHGs produced during landfilling could be reduced if CH₄ is trapped and further used for heating and production of electricity. According to Spokas [38] and Bahor et al. [39], the efficiency of trapping of landfill GHG gases can be between 35% and 85%. For this reason, if the value-addition of landfill gases is taken into account, the total GHG assessment during landfilling will drop considerably. The value-addition of the process was not considered during this study as this mode will considerably increase the cost of management. At some landfills, it is cost-effective to install gas recovery wells throughout the landfill and recover the gas for its energy value. In addition to the wells that may be constructed along the landfill perimeter for migration control, wells are placed in a grid pattern to recover gas that might otherwise escape through the landfill cover. Thus, the cost of the process will increase if the landfill gas will be trapped. A comprehensive techno-economic analysis will be necessary to identify the most economic method of management of apple pomace waste in this case.

The LCA of apple pomace management by different strategies: incineration, landfill, composting, solid-state fermentation to produce high-value enzymes and animal feed clearly showed that solid state fermentation is the most efficient strategy in terms of greenhouse gas emission reduction. The results of the assessment during animal feed showed lower values of GHG emissions unlike the results found in literature as management methods for manure produced by the cattle during the use of pomace in animal feeds (N₂O and CH₄ gases produced) were not taken into account. Thus, value-addition of apple pomace by fermentation gave higher environmental performance in terms of lower GHG emissions than animal feed.

The contribution to GHG emissions made by apple pomace waste management policy can be clearly quantified through life-cycle assessment. The assessment and inventory model used in this case can not only provide a reference for the central and local government of Quebec in their waste management policy but also can be used by apple juice industry to select the policy producing less greenhouse gases. Waste management strategy in Quebec has mostly favored incineration due to local considerations (difficulty of land acquisition) and a policy of promoting energy recovery through maximizing extraction of calorific value from waste. The results from the assessment indicated that the fermentation of apple pomace waste to produce high value-products constituted a new and efficient management method to reduce GHG emissions.

4. Conclusions

The greenhouse gases emissions produced during apple pomace waste management were evaluated by taking into account five different scenarios. The different scenarios evaluated were: (a) incineration; (b) landfill; (c) animal feed; (d) enzyme production by fermentation; and (e) composting. To determine the balance of GHG emissions, life cycle analysis method (LCA) was adopted. The results obtained in this study showed that enzyme production (906.81 tons of CO₂ equivalent per year) and animal feed (963.38 tons of CO₂ equivalent per year) were the least polluting options of the environment in terms of GHG emissions followed by incineration (1122.10 tons of CO₂ equivalent per year), composting (1273.00 tons of CO₂ equivalent per year) and landfill (1841.00 tons of CO₂ equivalent per year).

The assessment and inventory model used in this study can provide not only a reference for apple pomace waste in their management policy but also can be used to select the best management policy to manage other kind of organic wastes, in particular agro-industrial wastes.

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