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GINA CODY SCHOOL OF ENGINEERING AND COMPUTER SCIENCE

Department of Building, Civil and Environmental Engineering

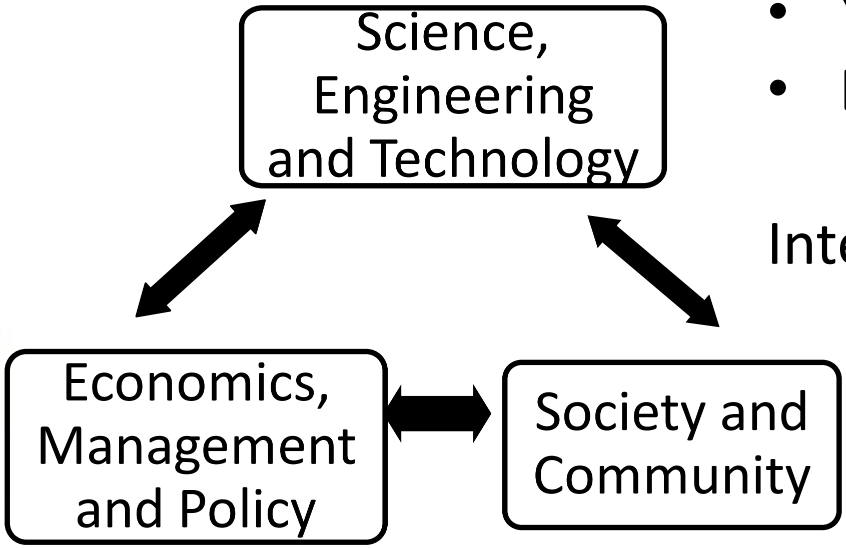
Concordia Institute of Water, Energy and Sustainable Systems

Catherine Mulligan, Director
www.concordia.ca/ciwess

Concordia Institute for Water, Energy and Sustainable Systems (CIWESS)

Multi-faculty approach:

- Engineering & Computer Science
- Arts & Science
- John Molson School of Business



Inter-university initiative:

- Concordia University
- McGill University
- Ecole de Technologie Supérieure
- UQAT
- York
- Dalhousie

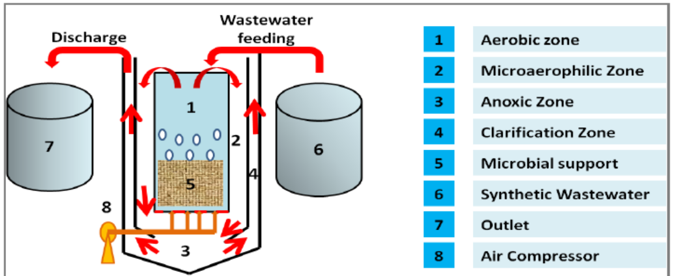
International collaborators

Mission and objectives

- CIWESS is an interdisciplinary team employing an integrated research and training program on water-energy systems such as for remote communities and activities in mining, resource management
- **Mission**
- To enable optimal management of the water-energy nexus in regards to SDG and climate change
- **Objectives**
  - To catalyze collaborations
  - To train HQP
  - To attract external funding

Examples of ongoing CIWESS projects

- Followup of CFI application currently in operation in Magog for lake/wetland system (A. Nazemi, City of Magog)
- Project for on site lake restoration of eutrophic lakes with Titan Environmental Containment.
- DFO funded project with numerous collaborations (C. An, Z. Chen, C. Mulligan etc.) for oil treatment and management
- Integrated biorefinery to valorize the waste streams into bioproducts and biopower (S. Brar and A. Kermanshahipour)
- Initiation of water/energy systems with Indigenous communities (C. Mulligan, C. An, Z. Chen, J. M. St. Jacques)



Zone	Height (cm)	Diameter (cm)	Volume (L)
Aerobic	-	16.7	17
Microaerophilic	91	35.7	61
Anoxic	100	-	22
Clarification	-	49.5	65

Figure 1: Schematic diagram of the BioCAST reactor

Development of ammonia nitrogen removal (annamox) by BIOCAST bioreactor (C. Mulligan/L. Yerushalmi with D. Walsh)

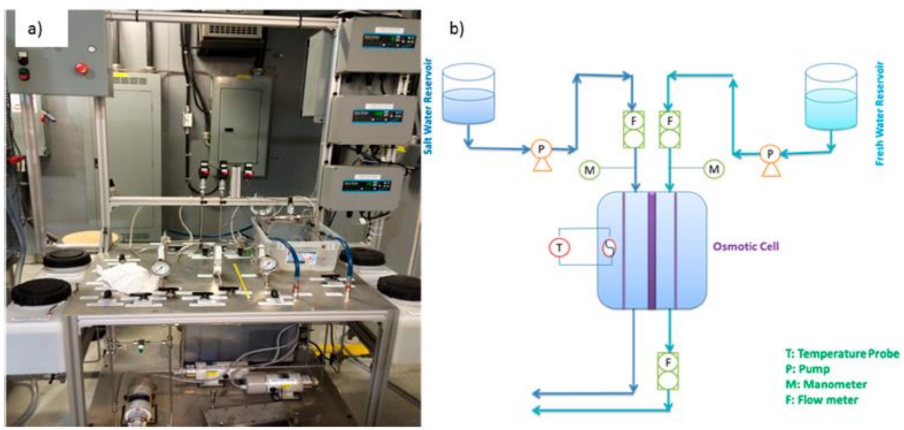


Figure 3. (a) PRO membrane setup at Hydro-Quebec Research Institute, (b) schematic of PRO membrane setup [6,12,25]

Development of PRO of C. Mulligan/ F. Nasiri for mining applications with UQAT (C M. Neculita/L. Coudert) and Agnico Eagle funded By FRQNT IMPULSION

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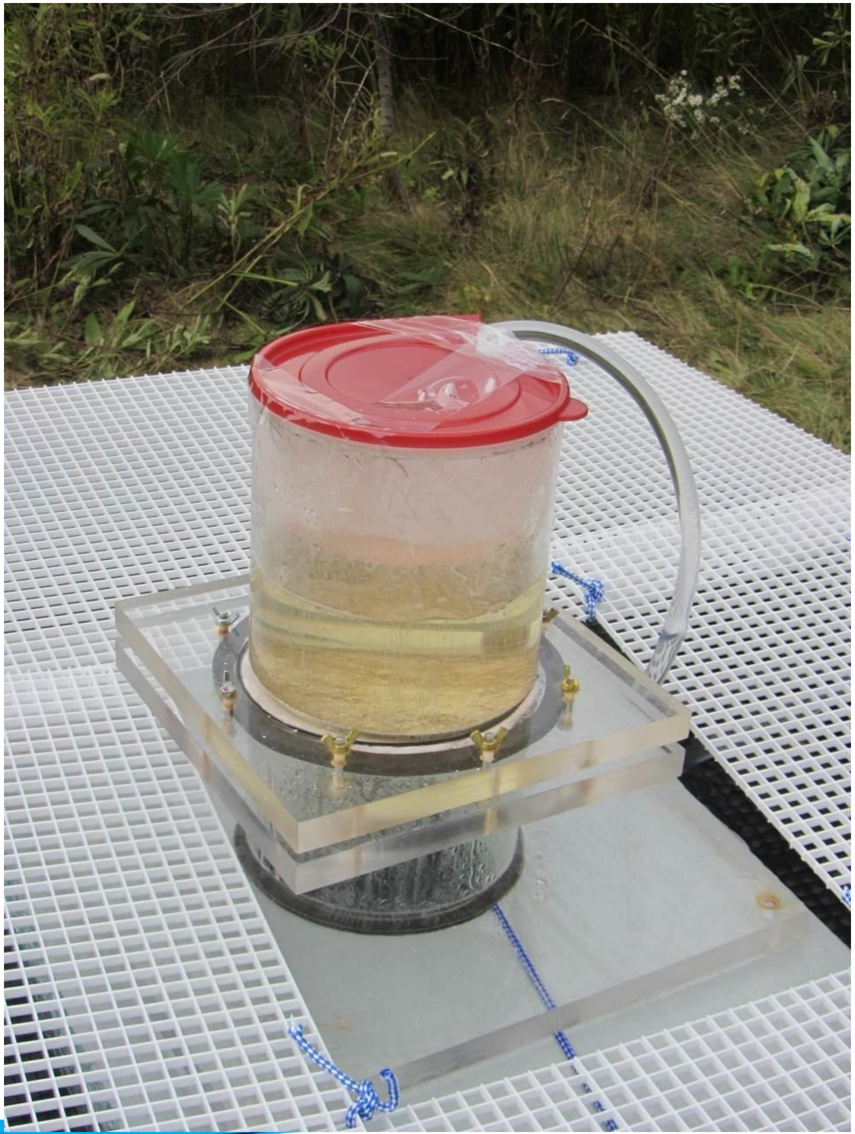


Rhamnolipid Biosurfactant

- *Pseudomonas aeruginosa* species has the ability to produce four different rhamnolipids (R1 – R4) which are biodegradable surfactants and environmentally friendly
- Anionic and capable of lowering the water surface tension from 72 to 29 mN/m
- Rhamnolipid important environmental applications are:
  - Enhanced biodegradation of petroleum hydrocarbons in water, soils, water, sediments
  - Removal of heavy metals and organics from soils, waste materials
  - Dispersing oil in contaminated water and enhanced sedimentation of oils sands tailings

Introduction

- Approximately 33.3% of food produced globally for human consumption is lost through the food supply chain.
- It costs around of $750 billion every year (Ma and Liu, 2019; Slorach et al., 2019)
- Developed countries tend to have major losses (70% to 80%) associated with the retail and consumer stages.
- Food wastage is higher at the immediate post-harvest stages in developing countries (Gokarn and Kuthambalayan, 2017). (Papargyropoulou et al. (2014)

Impacts of food waste

- Global food loss and waste generate annually 6.7% of total anthropogenic GHG emissions (Slorach et al, 2019)
- Disturbance of the biogenic phases of phosphorus and nitrogen, applied as fertilizers in agriculture (Papargyropoulou et al., 2014)
- Globally 45 tons of water is used each year to produce food that never reaches to our stomach.

Canadian context

- According to Gooch et al. Canadians waste around 40% of their food every year.
- This is equivalent to $27 billion dollars, 2% of Canadian GDP, 70% of Canadian Agri food export and 1.1 times of Canada's Agri food imports in 2009.
- This $27 billion does not include the opportunity cost nor include with environmental cost.

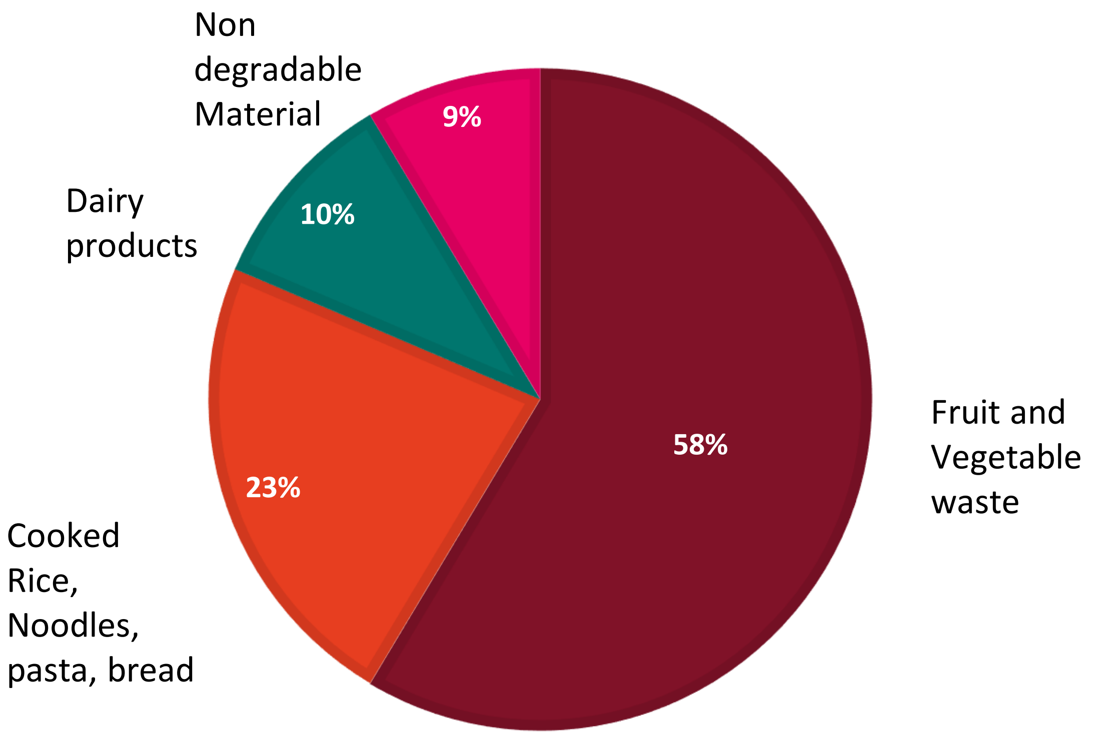
Food waste or food loss?

Food waste was broadly defined as edible material originally meant for human consumption but lost its value along the food chain.

Food loss refers to the decrease in mass or nutrition for human consumption.

We consider both food waste and food loss as potential feed for digestion

Composition Analysis of Food waste



Food waste composition from a typical collection facility

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Physio-chemical and Bio-chemical Properties of Food Waste

Source	USA	UK	China
pH	----------	5.02±0.01	4.2±0.2
TS(% fresh matter)	30.90±0.07	25.89±0.01	23.1±0.3
VS(% fresh matter)	26.35±0.14	24.00±0.03	21.0±0.3
VS(% TS)	85.30±0.65	92.70±0.12	90.9
TOC	----------	48.76±0.87	56.3±1.1
TKN(%TS)	----------	2.91±0.05	2.3±0.3

Source	USA	UK	China
Carbohydrate	----------	458±14	420
Lipid	----------	149±1	364
Crude Protein	----------	197±4	186
Hemi Cellulose	----------	88.6±1.2	
Cellulose	----------	66.1±0.1	109
Lignin	----------	21.7±0.1	

Source	USA	UK	China
N	3.16±0.22	2.91±0.05	----------
C	46.78±1.15	48.8±0.9	----------
H	----------	6.37±0.19	----------
S	0.81±0.03	----------	----------
O	----------	34.7±0.9	----------
P	5.2±0.8	2.82±0.13	----------
K	9.0±1.1	8.59±0.27	23.0±0.4

From VALORGAS (2011); [b]From Zhang et al. (2007); [c]From Zhang et al. (2013) and Shen et al. (2013); [d]From Zhang et al. (2011).

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Physio-chemical and Bio-chemical Properties of Food Waste

Source	USA	UK	China
Cobalt(Co)	----------	0.15±0.03	----------
Iron(Fe)	2480±1300	111±1	433±100
Manganese(Mn)	190±100	86.5±2.5	476±411
Molybdenum(Mo)	----------	2.8±0.6	----------

Source	USA	UK	China
Cadmium(Cd)	<3	<0.05	----------
Chromium(Cr)	10±3	4.21±0.62	----------
Copper(Cu)	100±3	4.69±0.84	----------
Mercury(Hg)	----------	----------	----------
Lead(Pb)	13±10	<0.6	----------
Nickel(Ni)	6±3	2.8±0.1	----------
Zinc(Zn)	250±70	22.4±0.8	693±130

From VALORGAS (2011); [b]From Zhang et al. (2007); [c]From Zhang et al. (2013) and Shen et al. (2013); [d]From Zhang et al. (2011).

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What is Anaerobic Treatment?

- Anaerobic treatment is a biological process which involves a group of consortium bacteria helps to break down organic components in the absence of oxygen.
- During the series of chemical reactions, a gas is mainly produced composed of CH_4 and CO_2, also referred to as biogas *(Mulligan 2002).*

Types of Anaerobic Treatment Process

Dry and Wet Digestion:

- Total Solid percentage < 15% (Dry Digestion)
- Total Solid Percentage>15% (Wet Digestion)

Mesophilic or Thermophilic Treatment:

- Mesophilic treatment temperature ranges from 22-40 degree Celsius.
- Thermophilic treatment varies between 40-55 degree Celsius

Batch or Continuous System:

- A reactor that is fed at one time with fresh FW and inoculum.
- Fresh FW is continuously loaded in the reactor.

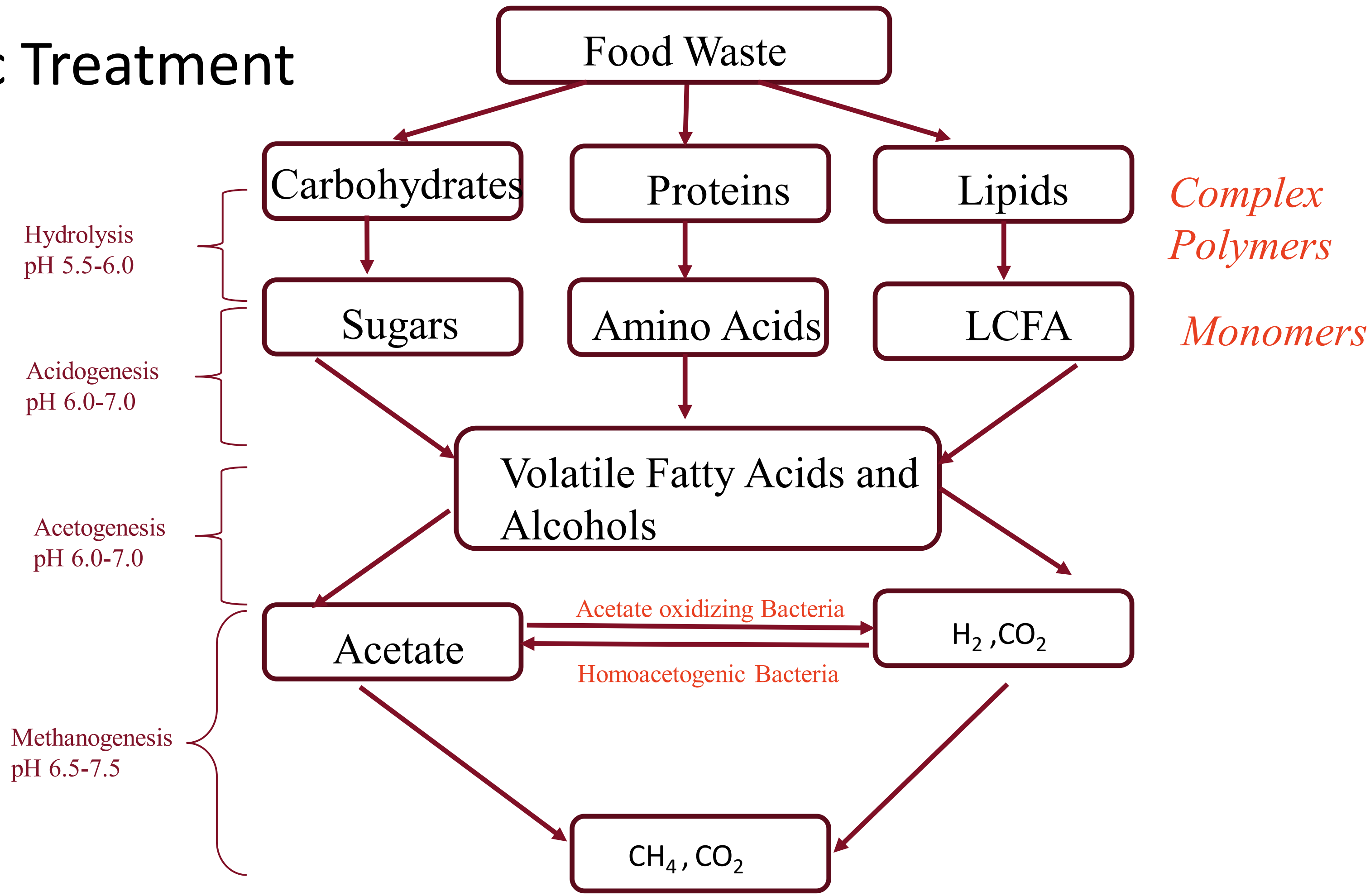
Single stage and Multistage process:

- Anaerobic digestion occurs in a single/one reactor.
- Multistage process consists of two or more reactors for digestion.

Factors Affecting Anaerobic Treatment

- pH
- Temperature
- Feed rate
- Alkalinity
- Total solid percentage
- Volatile fatty acids
- Composition of feedstock
- Carbon to nitrogen ratio

Anaerobic Treatment Flowchart



BMP and SMP of Food Waste

Bio Methane Potential:

The maximum theoretical bio methane potential (TMP) of organic substrates can be estimated by the Buswell formula (Symons and Buswell, 1933) based on elemental composition.

$$C_nH_aO_bN_c + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{3c}{4}\right)H_2O \longrightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3c}{8}\right)CO_2 + cNH_3$$

$$\text{TMP} \left(\frac{mL\ CH4}{g\ VS}\right) = \frac{22.4 \times 1000 \times \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right)}{12n + a + 16b + 14c}$$

Specific Methane Production:

Specific methane production of an organic substrate can be measured from the cumulative volume of methane produced per mass of VS added.

Energy Potential of Food Waste Digestion

Typical methane yields from biochemical components of food waste

Substrate	Typical composition	Methane yield [L CH_4 g^{-1} VS]	CH_4 [% Vol]
Simple sugars – e.g. glucose	$C_6H_{12}O_6$	0.373	50
Carbohydrate – complex	$C_6H_{10}O_5$	0.415	50
Protein	$C_5H_7NO_2$	0.495	50
Lipid	$C_{57}H_{104}O_6$	1.013	70
Cellulose	$C_6H_{10}O_5$	0.415 b	50
Hemicellulose	Variable	0.424 c	50

(adapted from Angelidaki and Sanders 2004)

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Chemical Reactions Associated with Anaerobic Treatment

$n\,(C_6H_{10}O_5) + nH_2O \rightarrow n(C_6H_{12}O_6)$

Polymers are transformed into soluble monomers

$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$

$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$

$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O$

$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO$

Soluble monomers convert into sugars, amino acids and fatty acids

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

$CH_3COOH \rightarrow CH_4 + CO_2$

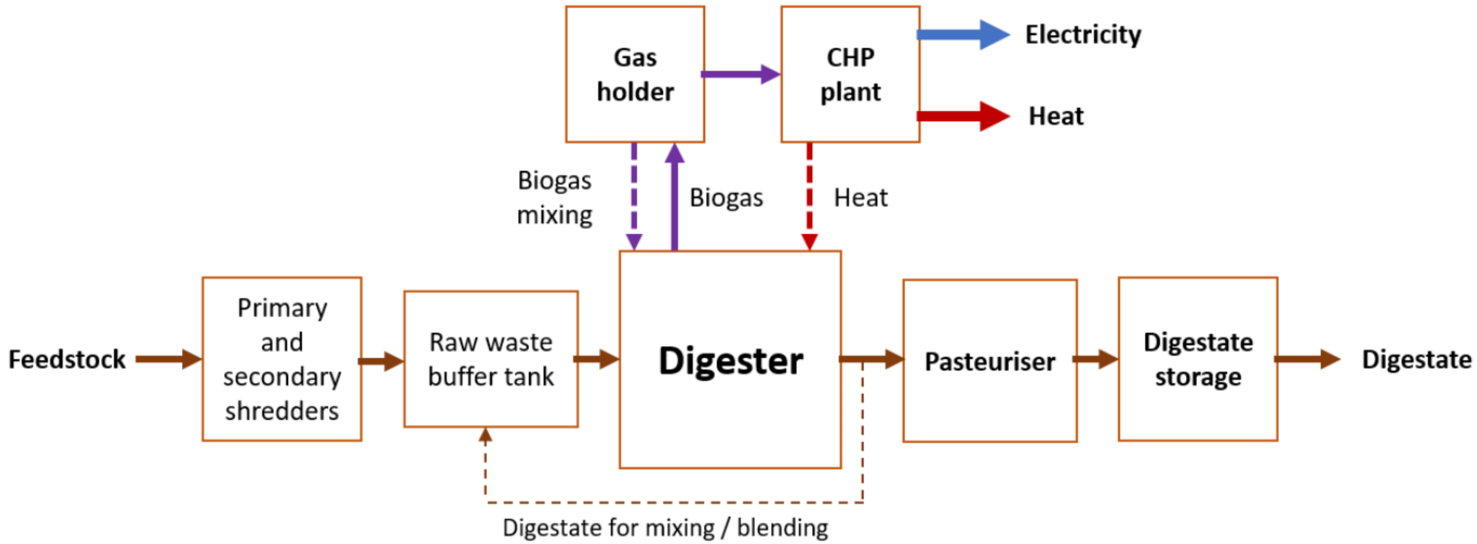
acetate and H_2/CO_2 convert into CH_4 and CO_2

Pretreatment of Waste

- Physical and mechanical pretreatment: separation, sorting

  Grinding, chopping, milling, ultrasound
- Physio-chemical and chemical pretreatment: use of chemical such as alkalis, acids and ozone
- Thermal pretreatment: Use of hot water and heat
- Biological and enzymatic pretreatment: using specialized micro organisms and enzymes

Schematic Diagram of Anaerobic Treatment



Limitations of AnaerobicTreatment

- Relatively high capital costs
- Long retention time
- Sensitive to certain key parameters (e.g., pH, temperature, feed rate, alkalinity)
- Higher concentration of free ammonia inhibitory for micro- organism activity.

Strategies

- Dilution of feedstock can bring the ammonia concentration down to threshold level
- A downstream treatment process can be introduced to strip ammonia before recycling.
- Digestate TAN concentration could be controlled by the degree of stripping applied.
- Stripping using a range of gases from air to nitrogen and CO_2 mixtures.
- Potential for recovery of ammonia for chemical fertilizer.

Mono Digestion of Food Waste

- Mono-digestion of source segregated food waste showed good gas productivity and high solids degradation.
- Reductions in the specific methane yield can be observed due to increase in VFA concentrations.
- Inhibition of AD process can be solved prompting the degradation of acetic acid through two-stage process

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Co- Digestion Processes

- Animal slurry , sewage or waste water sludge can be excellent co substrates with source separated food waste.
- Open gateway for new income streams.
- Probability of increase in the volumetric biogas production.
- Possibility to change economics of digester operation.
- Eligible for grant aid and renewable energy subsidies.

Ongoing research at Concordia

- Optimization of process conditions for food waste digestion
- Enhancement of methane yields
- Conversion of ammonia via annamox process after anaerobic treatment

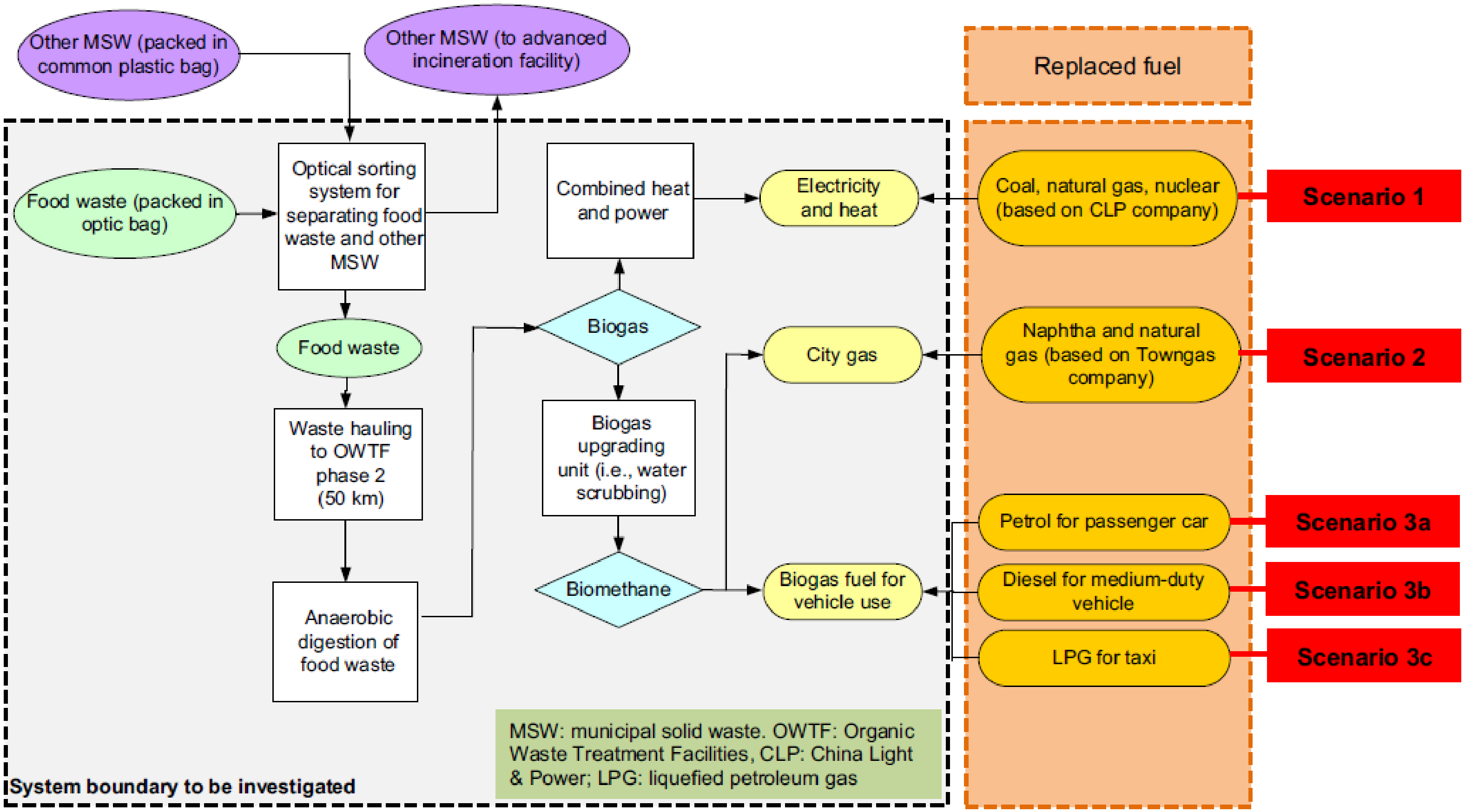

Fig. 1. Schematic process flow diagram of food waste valorization for various scenarios. Scenario 1 represents the valorization of food waste to electricity and heat; Scenario 2 represents the valorization of food waste to city gas (i.e., heating fuel for cooking purpose); Scenario 3a, scenario 3b, and scenario 3c represent the valorization of food waste to biogas fuel as a petrol substitute, as a diesel substitute, and as a LPG substitute for vehicle use, respectively.

Table 4
Number of vehicles and percentage reduction of GHG emissions due to fuel switching from petrol to biogas fuel for vehicle use in Hong Kong.

Criteria	Case 1	Case 2	Case 3
Amount of food waste valorized to biogas fuel as a petrol substitute for vehicle use (tpd)	1080	1800	3600
Number of vehicles fueled by biogas fuel[a]	12,209	20,348	40,696
Percentage of vehicles fueled by biogas fuel (%)[b]	2.63	4.38	8.76
GHG emissions reduction in transport sector (kilotonnes/year)	138	230	460
Percentage of GHG emissions reduction in transport sector (%)[c]	1.85	3.09	6.17

[a] Petrol is mostly used by the passenger cars in Hong Kong. Hence, the vehicle in this context is assumed to be the passenger cars of engine size in the range of 1501–2500 cc.

[b] There are 464,595 licensed private cars as at end June 2013.

[c] The percentage of GHG emissions reduction is quantified with reference to year 2005. This is the baseline year used by the HKSAR government to set the GHG emissions target by 2020. The GHG emissions in 2005 are 7460 kilotonnes CO_2e (HKEPD, 2014).

Anaerobic Treatment Plants across Canada

- Development of plants varies between 13 provinces in Canada.
- Three provinces British Columbia, Ontario and Quebec have the greatest opportunity for AD plants.
- There are very few plants that solely digest food waste. Most of the plants taking SSO co-digest it with other feedstocks.

Greenfield Global project

[SEMECS Varennes Anaerobic Digestion Project: Greenfield Global | Clean50]

- Greenfield Global developed an anaerobic digestion project with three regional municipalities to divert 40,000 MT of organic waste per year to produce biogas and biofertilizer.
- Biogas used by nearby Greenfield's ethanol plant to offset 4 million cubic meters of natural gas per year.
- Fertilizer is used by farmers replacing 10k MT of chemical fertilizers.
- First of its kind project in North America.

Process development

- Greenfield researched the composition of the feedstock over several seasons
- Evaluated all of the available technologies at an industrial scale by travelling to Europe (leaders in AD) 6 times over 2 years
- Determined need for a "Wet Pulper" technology for Quebec's type of waste stream,
- BTA (a German AD technology provider) was selected.

Design considerations

- Modifications to Greenfield's incoming gas train, and a long-term agreement with SEMEC
- Conceptual engineering followed by defining the capital and operational expenditures for the AD plant.
- A business plan used to seek grants and financial support for the project
- Parcel of industrial zoned land across the street from our Varennes ethanol plant was purchased.
- Land ideal for moving garbage trucks in, digestate out,
- Biogas transported across the road to the ethanol plant, via a short pipeline.

Results

- Diverting 40,000 metric tonnes of organics from landfill each year
- Displacing 4 million cubic meters (12%) of their natural gas consumption at their Varennes ethanol plant with clean, green biogas.
- Replacing 10,000 metric tonnes of chemical-derived fertilizer with biofertilizer from their digest from the plant, which in turn is being put on fields to grow more corn for the ethanol plant.
- This impact will increase threefold with Greenfield's expansion to 120,000 tonnes at the end of 2021.

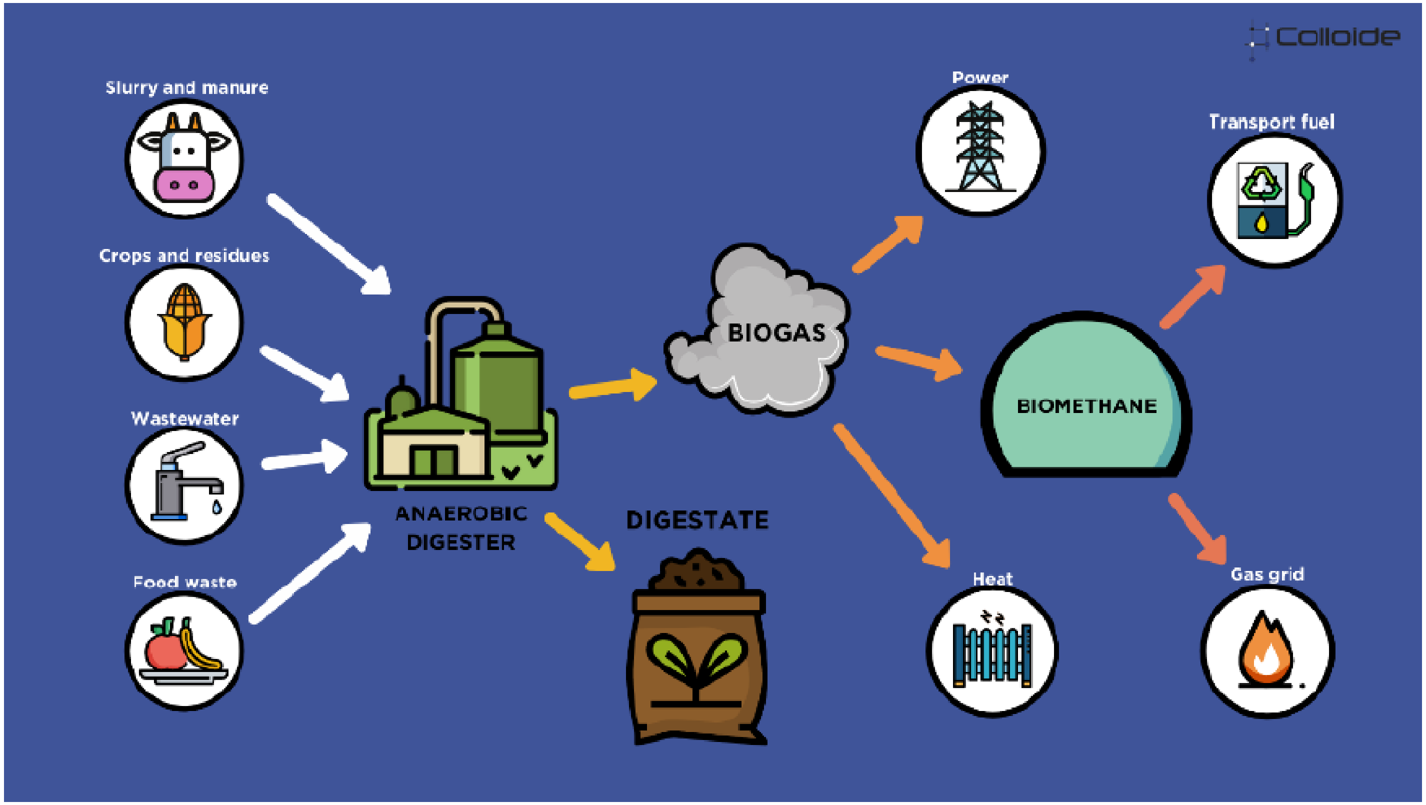

Figure 3: Biogas production from different sources [31]

31. https://www.colloide.com/what-is-anaerobic-digestion/

Integrated approach for sustainable management?

Manure production

Manure co-digestion

Compost production

Water treatment or field spraying

Electricity generation from biogas

Food waste digestion and circular economy

- The major plant nutrients nitrogen (N), phosphorus(P) and potassium (K) are generally regarded as being conserved
- In anaerobic digestion the feedstock characteristics can thus be used to predict digestate nutrient content.
- Recycling of scarce resources.
- Production of renewable energy.
- A sustainable alternative to fossil fuel

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Table 9: Direct greenhouse gas production and savings for digestion and composting of biowaste.

	AD electricity $kgCO_2/t$	AD CHP $kgCO_2/t$	AD transport fuel kg CO_2/t	Compost kg CO_2/t
Direction greenhouse gas production	255	255	255	365
Greenhouse gas from electricity[1]	0	0	0	0
Greenhouse gas production in "do-nothing" scenario dissipation of landfill to atmosphere	1,555	1,555	1,555	1,555
Net greenhouse gas production	−1,300	−1,300	−1300	−1,190
Greenhouse gas savings from displaced petrol[2]			151	0
Greenhouse gas savings from displaced electricity[3]	103	103	0	0
Greenhouse gas savings from displaced thermal[4]	0	76	0	0
Net greenhouse gas savings	1,403	1,479	1,451	1,190

[1]Based on CO_2 neutral supply of electricity.
[2]1 Nm^3 of CH_4-enriched biogas replaces 1 L of petrol, thus 70.9 L of petrol replaced per tonne of biowaste treated, petrol combustion produces 2.13 $kgCO_2/L$.
[3]The ESB (Irish electricity board) produce on average 0.734tCO_2/MW_eh; 140 kW_eh is the net production per tonne of biowaste.
[4]Combustion of kerosene for heat production in a boiler produces 280 kg/MW_th; 270 kW_th is the net production per tonne of biowaste.

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Concluding remarks

- Although composting has less equipment and operating costs, anaerobic digestion can have more benefits over the life cycle
- Savings of 1415 kg CO_2/t compared to 1,190 kg CO_2/t (Murphy and Power, 2006)
- A renewable energy source for heating, transportation fuel, combined heat and power (CHP) and fertilizers from the digestates can be produced.
- GHG emissions are reduced in energy, agriculture and waste management sectors
- Detailed studies such as LCA and EIA are needed to evaluate all factors

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