AUTOMATED BIODIGESTER FOR HOUSEHOLD WASTE TREATMENT

Laurent Gazaille	260 477 861
Antoine Malouin	260 539 225
Jean-Baptiste Trottier	260 573 780

Engineering Design 3

BREE-495

McGill – MacDonald Campus

April 15, 2016

Table of Contents

Executive summary

In western societies, organic wastes are managed by centralized and energy demanding processes. Biodegradable wastes are sent to landfills, incinerated or composted. Waste waters carrying feces are collected and treated, but often still contain pathogens. Efficient waste treatment systems are critical to maintain public health and thus necessary. However, the transportation of feces to centralized plants using water has negative environmental impact and necessitates large infrastructures. Alternative solutions should be investigated. We were asked to design a system that could shortcut the long treatment process of human wastes. A system using a biofilter made out of the carbon-rich material necessary to balance the composting was designed. The filter was tested by flushing semi-dissolved cow manure and showed promising capabilities. The effluent water to be redirected to sewage or septic system were brownish but showed no macroscopic evidence of solids. Further chemical analysis of the effluent water with more realistic inputs would allow stronger conclusions to be drawn. The guidelines of the engineering necessary for a full-scale system automation were discussed but not fully designed. This would have brought the scope of this project to a range out of this course. The design was limited to the actual physical system, including parts selection and sizing. The designers acquired a better feel of the necessary costs and technical challenges that come with the automation of small scale waste management systems, particularly when biological processes are included. It was concluded that our system could be refined and used in special situations or locations but is very unlikely to become a broadly used system. Still, we believe that we reached our objective of designing a biodegradable waste processing system that conveys to the western mentality of *Flush and Forget*. A special thank you goes to our advisor Grant Clark, composting specialist at McGill University, to our client, *Les Ateliers Hervé,* and to *Agrobiosol Inc*. for providing parts to build the prototype.

Introduction

Wastewater treatment plants saw major development in the late 20th century, leaving composting toilets behind in the research and development field. With the sustainability dilemmas of large industries and processes starting to rise and catch to world's attention in the 21st century, the status of composting toilets is now starting to be revisited.

Toilet flushing accounts for the highest percentage of water use in residential (27%), office (51%), school (60%) and hotel (33%) buildings. Water loss also happens in leaks and bursts in pipes of a rapidly aging infrastructure. Also, the processes in place to treat black water are highly energy intensive. The United-States annually use 3% of their total electricity to supply these processes (Anand & Apul, 2014). The current US water and wastewater disposal and treatment infrastructure annual expenditure can't sustain the necessary repair and rehabilitation needs. According to USEPA, the overall industry roughly falls short of $17 billion in required investments (Anand & Apul, 2014). This situation allows alternative treatment methods to be analysed as replacement system for the actual highly centralized wastewater handling infrastructure. Potable water is used to dispose and convey human faeces throughout the sewage systems and high-energy processes are required to treat black water. Resource and water management are at the heart of the McGill Bioresource Engineering department and drove this project forward from the start.

Les Ateliers Hervé Inc. is a small architectural design consulting company working mainly for architects and home builders in the field of Eco housing. The clientele for Eco housing do have an environmental consciousness and like to decrease their ecological footprint, but most of the time, their budget is limited. The projects onto which Les Ateliers Hervé work the most are around $150 000. To optimize their resource use, costumers tend to lower the surface area of the building and invest in resource-saving technologies. The company would like to propose to its clients an alternative to food and wastewater normal disposal by introducing a system that would treat and revalorize in-situ the household wastewater and the kitchen wastes by producing a useful compost. This would impact the current food, water and waste flow by:

- Reducing the amount of food waste being sent to landfills and incinerators;
- Reducing the need for landfilling and incinerating;

- Reducing considerably the amount of waste water contaminants;
- Reducing the load of every household on the waste water treatment facilities;
- Increasing the mass of organic matter being revalorized.

In order to reduce the cost and optimize its functionality, Les Ateliers Hervé requires a system that is compatible with current wastewater effluent infrastructure (leaching field, sewers). Additionally, the conventional levels of maintenance demand, ease of usage and peace of mind associated with the common *flush and forget* mentality should be attained. The company doubts that customers would be ready to invest considerable amounts of money for a complex food composting system. However, purchasing a waste water treatment or containment system is common and necessary if sewage collection is not an option. As such, a target cost comparable to existing composting toilet technologies would allow a competitive alternative against conventional wastewater management infrastructure.

Analysis and Specification

Characterization and quantification of inputs

As stated in the design requirements, the system needs to process wastes from the kitchen and the toilets. As such, inputs can be expected to consist of food wastes, feces, urine and toilet paper. The innovative feature of the design consists of using a filter made out of the carbon rich material necessary for composting to isolate solids from the toilet outflow. The filtering material therefore also needs to be characterized. Values for daily waste production per capita, waste nitrogen content, waste carbon to nitrogen ratio and water content need to be obtained in order to design the woodchip biofilter. Values found in scientific and governmental literature are presented below. Values used in the system design are collected in Table 4.

Feces and urine

Design values for the quantities of urine and feces generated per capita were taken from a recent extensive literature review published in *Critical Reviews in Environmental Science and Technology* aiming at providing design quantities for waste treatment technologies (Rose et al., 2015). Table 1 presents some of the values used in our design.

Table 1: Summary of feces and urine characteristics for design criteria (Rose et al., 2015)

Key design criteria	Median value
Feces	
Fecal wet weight (g/cap/day)	128
Fecal dry weight (g/cap/day)	29
Stool frequency (motions/24 hr)	1.1
Total solids (%)	25
VS (% of TS)	89
COD (g/cap/day)	71
Nitrogen (g/cap/day)	1.8
Protein (g/cap/day)	6.3
Lipids (g/cap/day)	4.1
Carbohydrate (g/cap/day)	9
Fiber (g/cap/day)	6
Calorific value (kcal/cap/day)	132
pH	6.6
Urine	
Urine wet weight (L/cap/day)	1.4
Urine dry weight (g/cap/day)	59
Urination frequency (urinations/24 hr)	6
Nitrogen (g/cap/day)	11
Calorific value (kcal/cap/day)	1701
pH	6.2

Important values to take away from Table 1 are fecal dry and wet weight, nitrogen content for feces, as well as urine dry and wet weight, and nitrogen content. Design values will be summarized in a table further on. Literature on carbon to nitrogen ratio of feces and urine must be looked upon carefully because different substances are often confounded. The term nightsoil is often used in literature to refer to the mixture of urine and feces recovered from composting toilets. The issue is that almost all values found referred to a 1956 textbook on organic waste composting by author Harold B. Gotaas (professor at UC Berkeley) who seems to have been a precursor and trailblazer in sanitary engineering. Two of the options when confronted to this issue are to disregard the values because they might be outdated or to assume that they are generally accepted in the field. It was decided to go with the latter and to use values of 5.5-6.5% for nitrogen content and 6-10 for C:N ratio (Gotaas, 1956). Table 2 presents a summary of the values collected for feces, urine and nightsoil in order to design the system.

Table 2: Summary of feces, urine and nightsoil properties

	*kg/(cap*day)*	*Moisture content*	*Nitrogen content*	*C:N*
Feces	0,128	77,00%	6,21%	-
Urine	1,459[a]	96,00%[c]	18,64%[e]	-
nightsoil	1,587[b]	94,47%[d]	17,64%[f]	8

a: $1.4\frac{L}{d} * 1\frac{kg}{L} + 0.059\frac{g}{d} = 1{,}459\ kg/d$, assuming solids add mass and no volume to urine.

b: $0{,}128\frac{kg}{d} + 1{,}459\frac{kg}{d} = 1587\frac{kg}{d}$

c: $\frac{1{,}400}{1{,}459} = 96\%$, moisture content of urine assuming 1,4L of water

d: $\frac{0.128*0.77+1{,}459*0.96}{0.128+1{,}459} = 94{,}47\%$, weighted average moisture content of nightsoil.

e: $\frac{11\frac{g}{d}}{59\frac{g}{d}} = 18{,}64\%$, urine nitrogen content as percentage of solid content.

f: $\frac{0.128*0.0621+1{,}459*0.08645}{0.128+1{,}459} = 17{,}64\%$, weighted average nitrogen content of nightsoil.

The value calculated for the nitrogen content of nightsoil of 17,64% differs greatly from the literature value of 5.5-6.5%. This difference is probably due to high nitrogen losses due to volatilization in the storage of nightsoil in traditional composting toilets. It was decided to use a design value of 6% instead of 17,64% because a volatilization phenomenon will probably also occur in our system.

Food wastes

Design values for the average of kitchen wastes were obtained from a report by the provincial government organization Recyc-Quebec (Taillefer, 2010). Their data on average organic wastes from households comes from a study from the consulting firms Dessau and NI environment. An average of 184 kg of organic wastes are generated per capita in Quebec which represents 44% of the total mass of wastes generated. Of this 44%, 52% are kitchen wastes, which represents 23% of the total waste mass. Thus, the average per capita mass of kitchen wastes in Québec is of 52%*184 kg which equals 96 kg. Data from the Cornell University composting website was used to further characterize food wastes. Food wastes form municipal wastes typically have a nitrogen content ranging from 1.9-2.9%, C:N ratio of 14-16 and moisture content of 69% (Cornell, 1996).

Biofilter material

Woodchips, cornstalk and straw were considered as filtering material. They are three readily available bulk carbon material from organic residue. The material chosen had to fulfill two roles in the system: filter out the feces of the flush water and add carbon to balance the composting mix. Nitrogen content, water content and C:N ratio values for the three materials were obtained from the Cornell University composting website (Cornell, 1996). Values found are presented in Table 3.

Table 3: Physical characteristics of woodchips, cornstalks and straw

	Moisture content	*Nitrogen content*	*C:N ratio*	*Carbon content*	*Density (kg/m^3)*	*Carbon (kg/m^3)*
Woodchips	12%	0,09%	500	45%	265[a] , 370[a] , 481[b]	216
Cornstalks	12%	0,70%	70	49%	127[c]	62
Straw	12%	0,40%	127	51%	53[d]	27

a: Cornell composting webstite (Cornell, 1996)

b: *http://www.engineeringtoolbox.com/density-materials-d_1652.html*

c: *Physical Properties of Corn Residues* (Zhang et al., 2012)

d: *Bulk Density of Wet and Dry Wheat Straw and Switchgrass Particles* (Lam et al., 2008)

Carbon content values estimations were calculated by multiplying nitrogen content by C:N ratio. Density values were obtained from various sources shown above and allowed the calculation of carbon density by multiplying density by carbon content. Analysis of these results led to the decision of using woodchips as filtering material for the bio-filter because of their much higher carbon content. A high carbon content would reduce the total mass of material needed so that the filter balances the compost C:N ratio.

Toilet paper

Because toilet paper is a carbon rich material, its significance to the effect on the C:N balance of the total mixture has to be investigated. The average consumption per capita of toilet paper in North America is estimated to be of 23.0 kg/y*cap (Collective, 2007). The average moisture content of toilet paper as measured by the ISO 287 procedure is of 6% (Goyal, 2009). Because of the absence of scientific literature on the nitrogen and carbon contents of toilet paper, values were estimated using the ones for newsprint provided by the Cornell Composting website. Office paper nitrogen content is estimated at 0.10% and C:N ratio at 170 (Angima, 2012). Office paper mass per area is of about 105 g/m^2 and that of toilet paper is about 28 g/m^2 (Goyal, 2009). It could be a safe assumption that area density is correlated with fiber density and thus carbon content. A linear fit of the C:N ratio of office paper with area densities yields a C:N ratio of 45 for toilet paper.

Table 4: Design values for biofilter size calculations

	*kg/(cap*day)*	*Moisture content*	*Nitrogen content*	*C:N*
Feces & urine (nightsoil)	1,587	94,47%	6,00%	8
Food wastes	0,263[a]	69,00%	2,40%	15
Toilet paper	0,063[b]	6,00%	0,10%	45
Woodchips	-	12,00%	0,09%	500

a: $\frac{96\ kg}{365\ d} = 0{,}263\ \frac{kg}{d}$, average daily food waste per capita.

b: $\frac{23\ kg}{365\ d} = 0.063\ \frac{kg}{d}$, average daily use of toilet paper per capita.

Carbon to nitrogen ratio balancing

The logical process underlying this calculation is that the C:N ratio that ends up composting at the end of the process is balanced. The challenge is that the input does not come at a constant rate and its composition cannot be precisely predicted without adding complexity and cost to the design. Feces and urine may be flushed alone or at the same time. Since all matter is expected to be collected in the digestion chamber and that the number of flush per day per capita can be estimated, a quantity of woodchips per flush can be determined. From there, the size of the biofilter can be determined through experimental analysis.

Balancing of daily outputs

The first step was to balance the daily inputs to the system per capita. To achieve this, the total nitrogen and carbon contents of the mixture were calculated using equations 1, 2, and 3. The amount of woodchips was calculated so that the C:N ratio of the total mixture reaches 30:1 using equation 4. The excel solver was used to determine the solution.

1. $\%C = \%N * \frac{C}{N}$
2. $C_T = \%C * M_d = \%C * (1 - \%M_W) * M_T$
3. $N_T = \%N * (1 - \%M_W) * M_T$
4. $C\!:\!N = \frac{C_T}{N_T}$

%C is carbon content, %N is nitrogen content, C_T is carbon mass content, N_T is nitrogen mass content, $\%M_W$ is moisture content and M_T is total mass.

The target value for the compost mixture C:N was set to 30:1, as it is the value suggested in the literature to stoichiometrically balances the inputs and outputs of the aerobic digestion (Haug, 1993). The same literature actually often suggests a range of 25-35 as being appropriate. Mass quantities of woodchips balancing the mixture C:N for 25, 30 and 35 were calculated to be of 0.24, 0.321 and 0.402 $\mathrm{kg_w/d * cap}$. Full calculation results for a C:N balanced at 30 are presented in Table 5.

Table 5: Balanced compost mixture

	*Input (kg_w/d*cap)*	*Moisture content*	*Nitrogen content*	*C:N*	*Carbon content*	*C (kg/d*cap)*	*N (kg/d*cap)*
Food wastes	0,2630	69%	2,40%	15	36%	0,02935	0,00196
Nightsoil	1,587	94%	6,00%	8	48%	0,04213	0,00527
Toilet paper	0,063	6%	0,10%	45	5%	0,00266	0,00006
Woodchips	0,321	12%	0,09%	500	45%	0,14431	0,00025
Mixture	2,23	77%	0,33%	30	10%	0,21845	0,00728

Biofilter design

The lifetime of the biofilter has to be determined in order to determine its proper size. Many factors may affect how long the biofilter will last, including its porosity, moisture content and decomposition stage. When subject to flush water, the pores in the filter will progressively be filled with feces, thus progressively lowering its porosity. Furthermore, its porosity may be affect by its moisture content. As the woodchip absorb water, the interstitial spaces may get occupied by the volume change of the substance. These two factors should be determinant in the number of flushes the filter may handle. Moreover, if the filter ends up lasting for an excessive period of time, decomposition may develop in the filtering chamber. The possibility of this situation occurring seems relatively low because we do not expect the biofilter to be used for more than a couple days, but it should be kept in mind as an upper bound to the utilisation timeframe.

Table 1 presents average values for number of urination and stool frequencies of respectively 6 and 1,1. If we assume that they are all separate events, we obtain a total of 7.1 flush per day per capita. Furthermore, if we assume that the average waste to be processed by the system over a prolonged period will be similar to the daily estimates presented before, we can calculate a mass of woodchips necessary to balance every flush from the toilet. Equations 5 and 6 determine the mass of woodchips per flush necessary to balance an average flush to C:N ratios of 35, 30 and 25.

5. $0.402\,\frac{kg}{d*cap} * \left[7.1\,\frac{flush}{day*cap}\right]^{-1} = 0.0566\,\frac{kg}{flush}$
6. $0.321\,\frac{kg}{d*cap} * \left[7.1\,\frac{flush}{day*cap}\right]^{-1} = 0.0452\,\frac{kg}{flush}$
7. $0.240\,\frac{kg}{d*cap} * \left[7.1\,\frac{flush}{day*cap}\right]^{-1} = 0.0338\,\frac{kg}{flush}$

Since the exact density of the woodchips cannot be determined exactly without the actual material to be used, a conservative estimate may be done using the density values presented above. One way of doing this is verify if the volume corresponding to the highest woodchip density and filter mass meets the mass requirement of the lower bound values. Densities ranging from 250 to 500 kg/m3 were used in the calculations to add safety to calculations. Equations 8 and 9 yield upper and lower bound volumes of woodchips per flush. Since the density of the woodchips will vary with particle size, which will also greatly affect porosity, the values calculated will be used as guidelines in prototype testing. Experimentation analysis will allow the determination of the proper volume to be added depending on the size grade of the woodchips.

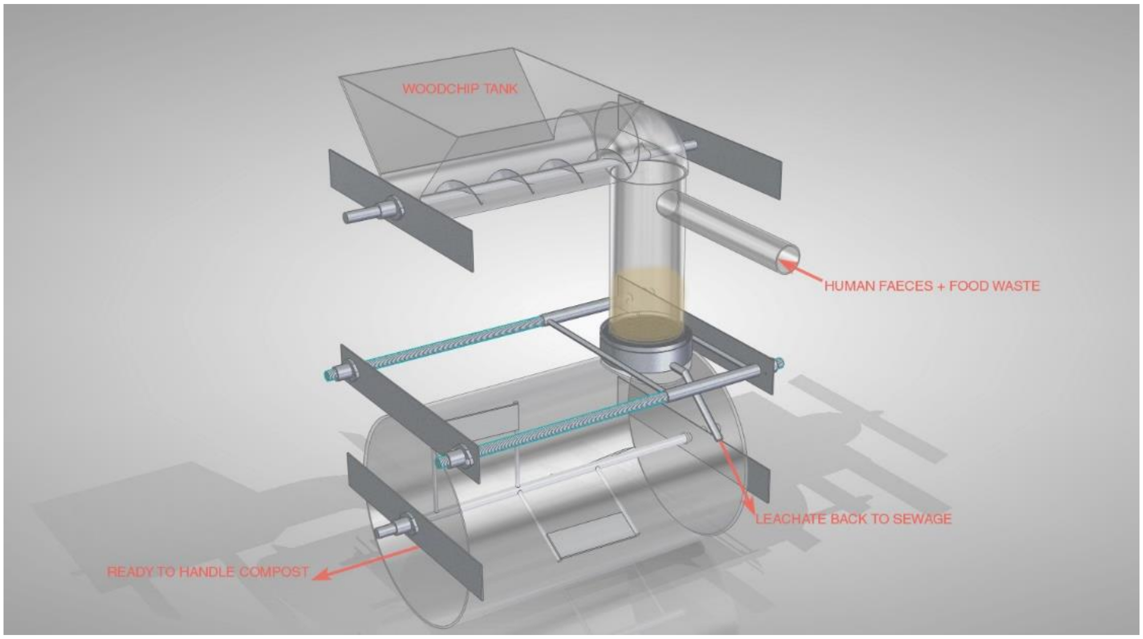
8. $0.0566\,\frac{kg}{flush} * \left[500\,\frac{kg}{m^3}\right]^{-1} * 1000\,\frac{L}{m^3} = 0.1132\,L$
9. $0.0338\,\frac{kg}{flush} * \left[250\,\frac{kg}{m^3}\right]^{-1} * 1000\,\frac{L}{m^3} = 0.1352\,L$

Based on the above calculation results, a design value of 0.125 $\frac{L}{flush}$ of different size woodchips will be used in the testing of the prototype. This value is the average of the results of equations 8 and 9. Prototype testing will allow the determination of the ideal type of wood residue for the filter, between fine sawdust and coarse mulch-like woodchips. This parameter will then affect the volume of woodchip per flush. The situation is thus quite self-determining, but the use of an estimated value of 0.125 $\frac{L}{flush}$ will allow an iterative solution process.

Design specifications

Our final design is a centralized system capable of connecting one or more toilets from different floors of a residential building. The system has two chambers: one for separating the solids and the liquids and the other chamber to compost the mix in thermophilic operating conditions. The separation (filtration) chamber receives the sewage outflow of the toilet. The flush passes through the woodchips where water drains itself to the bottom while the solid waste remains into the filtrate. A leachate collector below the filtration chamber allows the liquids to leave the system and flow back into the sanitation infrastructure in place (sewage or leaching field). The leachate collector being able to slide horizontally, a linear actuator can move the component to let the filtrated solids fall into the digestion chamber. Every time the filtration chamber is emptied, the woodchip tank ensures that the separation chamber receives a proper amount of fresh woodchip. The system therefore allows normal toilets and normal amounts of water to be flushed without affecting the composting operations. Finally, the digestion tank takes care of creating the best operation conditions for aerobic composting. Mixing, aerating and heating of the compost are powered by 120V electricity as well as the woodchip conveyor. The system is designed to sit outside at ground level alongside the building. There, the operator can collect ready-to-handle compost pushed outside of the digestion chamber by the tilted blades of the mixing rod. The biodigestor, with its envelope, measures 4 feet high by 4 feet long by 2 feet large.

Figure 1: 3D rendition of main component of final design



Pathogen Inactivation

It was initially planned to take advantage of the high amount of heat released during thermophilic composting to allow the system to reach the required temperature of 55 ^oC and time of 3 days recommended to safely assume pathogen inactivation (CCME, 2010). This idea was logical in a batch process and it was decided to increase the volume of the digestion chamber and run a continuous composting system. The main reason behind this decision was that our filter lifetime was observed to be much shorter than expected. We initially planned to run an inoculated compost for 7 days at a time with a filter change at the same frequency. However, the biofilter was observed to last for a set amount of flushing events rather than a length of time. Because of this, a batch process could no longer be ran and a continuous digester design was chosen. However, this also implies that it will be much more difficult to inactivate pathogens before emptying the digester. It was thus decided to install a heating system on the digestion chamber so that the heat could be generated externally and inactivate pathogen before servicing the digestion chamber.

The power requirement to size this component was estimated by calculating the power needed to heat a volume of half the digestion chamber (100L), with a moisture content of 100% from 5 ^oC to 55 ^oC over a period of 3 hours, as shown in equation 10

$$10.\ P = \frac{c_p * \Delta T * V * \rho}{\Delta t} = 4.18 \frac{kJ}{kg*K} * 50K * 100L * 1 \frac{kg}{L} * \left[3\ h * 3600 \frac{s}{h}\right]^{-1} = 1.94\ kW$$

This time period was chosen because a fast heating is not required since the temperature will have to be sustained over 3 days. Plus, since the power calculated is sufficient to heat the mixture to the required temperature, it will logically be enough to keep it at this temperature by lowering the voltage to the heating equipment. The part chosen to fulfill this heating requirement is an electric biodiesel 200L drum heater. Common models on eBay are rated at 750W, 1000W or 1500W. It was decided to use two 1000W heaters as they will release heat more evenly to the system.

Motor sizing

Mixing rod motor

The magnitude of the moment exerted on the mixing shaft in the digestion chamber in order to properly size the motor that would power it. As the mixture inside the digestion chamber is made of solids acting like a fluid, that the entire mass contributes to friction forces against the rotation of the shaft because of mixture cohesion, that gravitational forces are also involved, it was assumed that the torque applied on the shaft was equivalent to the weight of half the digestion chamber volume of water applied at the 2/3 of the radius of the shaft's arms. Compost only requires to be aerated and restructured once in a while, thus the speed of rotation can be very low. As a first estimate, 6 rotations per minute was chosen. Equation11 determine the torque applied on the shaft. Equation 12 determine the power required by the motor.

11. $\tau = F_g * d = \frac{V}{2} * \gamma * \frac{D}{3} = \frac{35in*\pi*\left(\frac{23}{2}in\right)^2*\frac{2}{3}*\left(0.0254\frac{m}{in}\right)^3}{2} * 9810\,\frac{N}{m^3} * \frac{23in}{3} * \left(0.0254\,\frac{m}{in}\right) = 227.61Nm$
12. $W = \tau * n = \tau * \frac{RPM*2\pi}{60s} = 227.61Nm * \frac{6*2\pi}{60s} = 143W \approx 0.192\ HP$

Linear actuator –Discharging gate

The magnitude of the forces involved when opening the discharging gate have to be quantified in order to properly size the linear actuator that will have to work against those forces. As the discharging gate can be seen as a horizontal sliding door, the main forces involved in its opening are the friction forces between the bottom part of the gate and the floor on which it slides (due to gravitational forces) and the friction forces between the gate and the parts that hold it against the biodigester (due to internal hydrostatic forces). Equation 13 determines the force exerted by gravity. Equation 14 determines the force exerted by hydrostatic pressure. Equation 15 determines the force required to move the gate. The static coefficient of 0.2 for wood on wood was taken from the engineering toolbox. Assumptions that the door would weight about 1 kg and that the hydrostatic force was exerted by a fluid of the same density than water without any cohesion were used to limit the need of safety factor.

13. $F_g = m * g \approx 1kg * 9.81 \frac{N}{kg} \approx 9.81N$

14. $F_h = V * \gamma * \frac{2D}{3} = 35in * \pi * (11.5in)^2 * 9810 \frac{N}{m^3} * \frac{2*23in}{3} * \left(0.0254 \frac{m}{in}\right)^4 = 455.22N$

15. $F = \mu_s * F_N = \mu_s * (F_g + F_h)$ = 0.2 *(9.81N+910.44N)=184.05N

Thus a linear actuator of 20 inches being able to pull 184.05N would be sufficient to open the discharging gate.

Linear actuator – Puck displacement

The magnitude of the forces involved when opening the puck have to be quantified in order to properly size the linear actuator that will have to work against those forces. As the puck can be seen as a horizontal sliding door, the main forces involved in its opening are the friction forces between the top part of the puck and the bottom part of the filtration changer (due to gravitational forces) and the friction forces between the sliding rods and the bottom part of the puck (due to gravitational forces). Equation 16 determines the gravitational force exerted by the content of the filtration chamber. Equation 17 determines the gravitational force exerted by the puck. Equation 18 determines the force required to move the gate. The static coefficient of 0.1 for polytetrafluoroethylene on steel and 0.6 for wood on a rough surface (i.e. the perforated plate) was taken from the engineering toolbox. Assumptions that the filtration chamber and the puck were filled with water were used to limit the need of safety factor. The cohesion forces inside the filtration chamber were neglected.

16. $F_{g1} = V * \gamma = h * \pi * \left(\frac{D}{2}\right)^2 * 9810 \frac{N}{m^3} = 18in * \pi * \left(\frac{8in}{2}\right)^2 * \left(0.0254 \frac{m}{in}\right)^3 * 9810 \frac{N}{m^3} = 145.45N$

17. $F_{g2} = V * \gamma = h * \pi * \left(\frac{D}{2}\right)^2 * 9810 \frac{N}{m^3} = 3in * \pi * \left(\frac{10in}{2}\right)^2 * \left(0.0254 \frac{m}{in}\right)^3 * 9810 \frac{N}{m^3} = 37.88N$

18. $F = \mu_{s1} * (F_{g1} + F_{g2}) + \mu_{s2} * F_{g1} = 0.1 * (145.45 + 37.88)N + 0.6 * 145.45N = 105.60N$

Thus a linear actuator of 10 inches being able to pull 105.60N would be sufficient to slide the puck from under the filtration chamber.

Woodchip auger

Since only 1.39L of woodchip are required at each refilling of the filtration chamber, the flow rate required by the woodchip auger is pretty low. On the other hand, since the woodchip's size goes up to 10mm there is a size limiting factor on the diameter of the auger. After talking with Louis-Philippe Guertin Eng. working for RAD equipment Inc., a leading manufacturer of bulk material handling equipment, it was decided that a 4-inches diameter auger would be sufficient and would not clog. To rotate the shaft of the auger, an electric motor from a drill (about 80 watts) would be more than enough.

Sensing and Automation

Only the necessary parts for automation of this project were chosen. As this is a very broad project, the focus was left on the design of the machine and composting process rather than on the design of the electronical automation.

Microprocessor and software

The recommended platform for the automation of this project would be an arduino mega. It is an inexpensive relatively powerful microcomputer used for small projects as this one with an extensive amount of open-source coding and information.

Temperature and humidity sensors

Temperature and humidity sensors are to be inserted in the digestion chamber. They will allow the monitoring of pathogen inactivation as well as humidity level in the compost. These sensors are relatively inexpensive and 3 are to be installed on the inner surface of the 200L digestion chamber. This will give a better idea of the physical processes happening in the vessel.

Level sensor

Water level capacitive sensors are important in this system. They give important information to the computer to decide when to operate the sliding puck and the woodchip-dispensing auger. The computer will be able to count the number of flushing event by monitoring variations on a capacitive level sensor placed in the filtering chamber. Another level sensor will be placed in the digestion chamber to indicate when it should be heated for inactivation and emptied.

Fault tree analysis

A failure tree analysis was performed using a top to bottom method. All the energy and mass flows of the system were looked upon to determine possible system problems or failures. The system was analyzed from the inflow of flush water to the outflow of compost and waste water. Potential failures and their solutions were reported in a bullet point style format.

Water flow

- The inflow pipe may get clogged or leak.
  - Two diversion valves are to be installed upstream on the inflow pipe. This will allow system flow diversion to the conventional waste disposal system in which our system already outflows.
  - A 4" pipe is to be used so that clogging is unlikely.
- The seal between the filtration chamber and the sliding puck may leak.
  - The sliding puck was designed wider that the filtration chamber, so that small leakages can be tolerated.
- The outflow pipe from the sliding puck may get clogged or leak.
  - A 4" flexible pipe is to be used so that clogging will be unlikely.
  - A screen it to be installed on the top of the puck so that only very small particles may flow through.
- The biofilter may clog unexpectedly.
  - An overflow outlet connected to the system water outflow is to be installed.

Woodchip and waste flow

- The woodchip feeder may fail or run empty.
  - Refill frequency guidelines will be given to system owners so that biofilter material shortage does not occur.
  - Corner pipe at the end of the dispensing auger will be oversized to avoid clogging.
- The biofilter may not fall into the digestion chamber.

    - Filtration chamber diameter will be made large enough compared to biofilter thickness so that cohesive forces in the highly humid filter do not overtake gravitational forces.
- The compost mixture may not exit the system properly.
    - The motor driving the mixing rod will be overdesigned so that it has enough power to push through clogs at the outlet door.

Energy and automation

- A system check button is to be installed so that the computer can try all its components and let the user know if the system is working properly. This checkup routine is to be performed at a certain frequency that will be determined by testing the reliability of the complete system.
- The motor and reduction system driving the mixing rod may fail.
    - If the level sensor reading in the digestion chamber does not respond to an expected reduction in level after a given period of time, the computer will know that there is a problem with the mixing system.
    - Wastes may still be accumulated until the digestion chamber reaches its maximal capacity, at which point the diversion valve to shortcut the system will be activated if no action has been taken by the user.
- The motor driving the woodchip dispensing auger may fail.
    - The level sensor in the filtration chamber is to be placed such that the computer can expect a certain range of response after replacing the filter.
    - If there is a problem, the system may continue to operate for a certain time with a lower filtration efficiency.
    - The user should be notified of the problem by the computer when adding woodchips to the system.
- The linear actuator driving the discharging gate may fail.
    - Limit switches are to be installed on the door, which will let the system know if the linear actuator is functional.
- The linear actuator moving the sliding puck may fail.

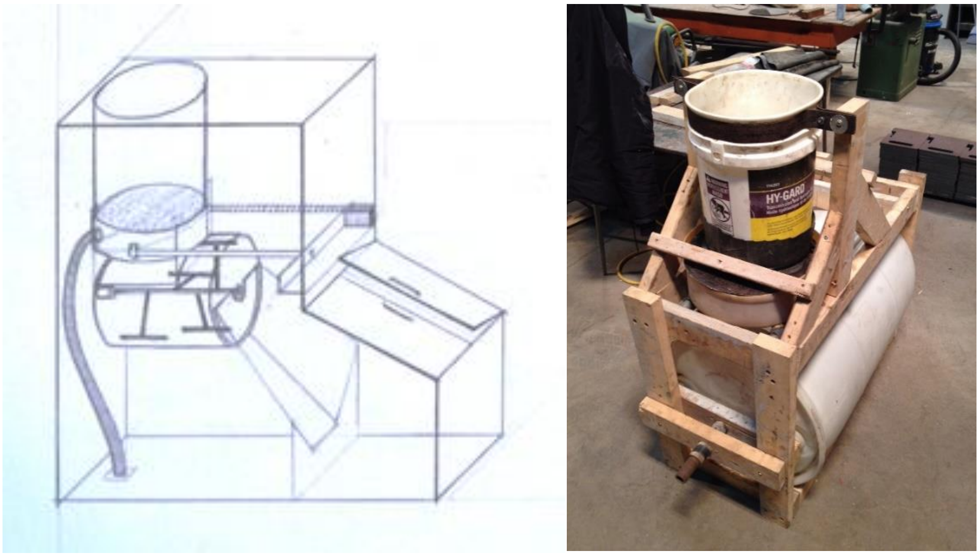
    - The level sensor in the filtration chamber is to be placed such that the computer can expect a certain range of response after sending signal to move the sliding puck.
    - If this actuator fails, the overflow will go to conventional system already in place.
- The automation system may fail.
    - The system is to be configured such that the diversion valve of the system to sewage or septic installation will be normally closed.
    - Only the running computer can open the system valve and shut the diversion valve.

Prototyping, testing, optimization

Prototype construction

The construction process took place in a bottom-up process where we first built the structure around the lower component and adapted the upper structure to host the rest of the system. The most voluminous part of our prototype was the thermophilic chamber. We used a high-density polyethylene (HDPE) barrel of 200L. Using wood as the structure, the main frame was first started by enclosing the thermophilic tank. Using steel parts and tubes, the mixing rod was welded together and inserted in the tank previously opened at both ends. Once the mixing rod was held in place in the wooden structure, we started building the sliding leachate collector. Made of the bottom of a small HDPE container and of a meshed steel plate, the collector was inserted into two steel pipes allowing it to move along the horizontal axis. A ¾ inch diameter brass fitting was inserted at the bottom of the container to allow a garden hose connection and easy disposal of the separated liquid. The final structure addition allowed a 5 gallons HDPE bucket (12" diameter) to self-stand above the leachate collector. Stripped of its bottom part, the bucket could now host solids while the collector could carry liquids out the system. A large opening made on the thermophilic chamber and aligned with the 5 gallons bucket ensured the solids would fall into the final tank every time the liquid collector would slide aside. Final adjustment were made using rubber bands and silicon to reduce the risk of leakage throughout the system.

Figure 2: Prototype sketched and built



Testing methodology

Keeping in mind that the trials were meant to test the filtration of a toilet effluent, results were taken regarding retention time of each flush and volume of leachate collected after each flush. Initially, we intended to design a batch system in which the filter would be added couple days and then completely composted. Thus, we estimated the necessary volume of woodchips in the filter for a household of 4 and a time length of 3 days. 3 adults were used to represent a household of 4 and it was estimated that 75% of their hygiene routine would be done at home.

19. $3\ persons * 3days * 7.1 \frac{flush}{day*cap} * 0.125 \frac{L}{flush} * 75\% = 9.3\ L$

Every flush was then simulated by adding cow manure mixed with 4 L of potable water to replicate the average volume of a toilet water tank. The quantity of manure added was determined visually as the equivalent volume to a human stool (to our knowledge and experience). It was observed that the flushing of water on the biofilter created a gash in the filter which created pathways of lesser resistance through the filter. It was thus decided to add a diffuser so that flush water would not degrade the performance of the filter and be distributed somewhat evenly over the surface. Timing stared after all the water was emptied on the biofilter. Timing was stopped when water stopped flowing out of the drainage pipe. Effluent volume was measured as the water column height in a 5 gallons collection bucket and calculated using the average diameter of the bucket (11"). After each testing session, the biofilter was disposed of in the digestion chamber by manually sliding the puck. Pictures of the filter were taken just after the effluent volume height measurements were taken. The flushing simulation is shown in Figure 3. Three series of test were ran, using three kinds of woodchips. Basic quantitative and qualitative description of woodchips used in testing are presented in Table 6.

Table 6: Properties of woodchips used in biofilter testing

Qualitative description	*Average size (mm)*	*Measured bulk density (kg/m3)*
Fine material for cattle bedding	< 5	101
Medium sized residue from woodwork	5-10	130
Coarse residue from wood chipper	> 25	247

Figure 3: Pictures of flushing simulation sequence

Test results

Results are presented in tables Table 7, Table 8, and Table 9. The quantity of water absorbed by the filter was calculated by subtracting the effluent volume to the input flush volume of approximately 4,5L.

Table 7: Test results for fine woodchips biofilter (<5mm)

Flush	*Retention time (minutes)*	*Effluent volume (L)*	*Absorbed water (L)*
1	5	2,5	2
2	11	3	1,5
3	25	4	0,5
4[a]	4	4	0,5
5	15	4	0,5
6	clogged	-	-

a: Filter was reconditioned by mixing before flushing.

Table 8: Test results for medium sized woodchip biofilter (5-10mm)

Flush	*Retention time (minutes)*	*Effluent volume (L)*	*Absorbed water (L)*
1	2	3,4	1,1
2	2	3,1	1,4
3	4	4,6	0
4	10	3,1	1,4
5	clogged	-	-

Table 9: Test results for coarse woodchip biofilter (>25mm)

Flush	*Retention time (minutes)*	*Effluent volume (L)*	*Absorbed water (L)*
1	5	2	2,5
2	10	3	1,5
3	25	4	0,5
4	clogged	-	-

Result analysis

Our hypothesis was that larger wood particulates would decrease the retention time of water because of the increased porosity. However, results show that the retention time pattern was similar for all woodchip sizes, approximately doubling every flush until clogging. Visual observations clearly show the solid faeces slowly filling all the interspaces in the filtrate and decreasing considerably the porosity in the filtration chamber to a point where the flush can no longer penetrate adequately and remains in the chamber without draining the excess water. This was confirmed by cutting a profile in the filter to observe the penetration of the solids in the filter. Only the top layer of about 5cm was filled with solids. Below that, there were only wet woodchips. This leads us to observe that only a limited thickness of the filter is actually efficient.

Furthermore, data from the test on medium sized woodchips presented in Table 8 allowed to choose this particular size of material for the biofilter. This test clogged after the 5th flushing whereas finer and coarser materials caused the filter to clog after the 4th test. Plus, retention times in the filtration chamber were significantly lower for this test, reaching a maximum of 10 minutes before clogging compared to 25 minutes for other materials. This allowed us to choose this type of woodchip material to compose the biofilter.

Because the content of each trial was emptied in the thermophilic chamber, the functionality of each component could also be tested. The sliding collector worked brilliantly allowing to dispose of all the drained water from the simulated flushes. The opening in the main tank was well dimensioned and all the solids could fall directly into it without any spill. Finally, the mixing rod behaved as planned, blending and aerating properly, but most importantly, moving the compost forward or backwards in the tank each time we turned the rod thanks to the angled blades design.

Design update

Data obtained through experimentation with the prototype allowed the biofilter to be designed. It was determined that the filter would have to last for a series of 4 flushes. It would consist of woodchips with a bulk density of $130\frac{kg}{m^3}$. Aiming for a C:N ratio of 30, the quantity of woodchips to be added was calculated to be of 0.0452 $\frac{kg}{flush}$. Equation 20 presents the calculation for the volume of this specific type of woodchips to be added to balance the compost mixture and obtain ideal biofilter performance.

20. $0.0452\,\frac{kg}{flush} * 4\,flush * \left[130\,\frac{kg}{m^3}\right]^{-1} * 1000\,\frac{L}{m^3} = 1.39\,L$

Our design uses a PVC pipe with inner dimeter of 8.125 inches. A volume of 1.39 L spread over the area of a circle of dimeter 8.125 inches has a height of 6.84 cm, as shown in equation 21.

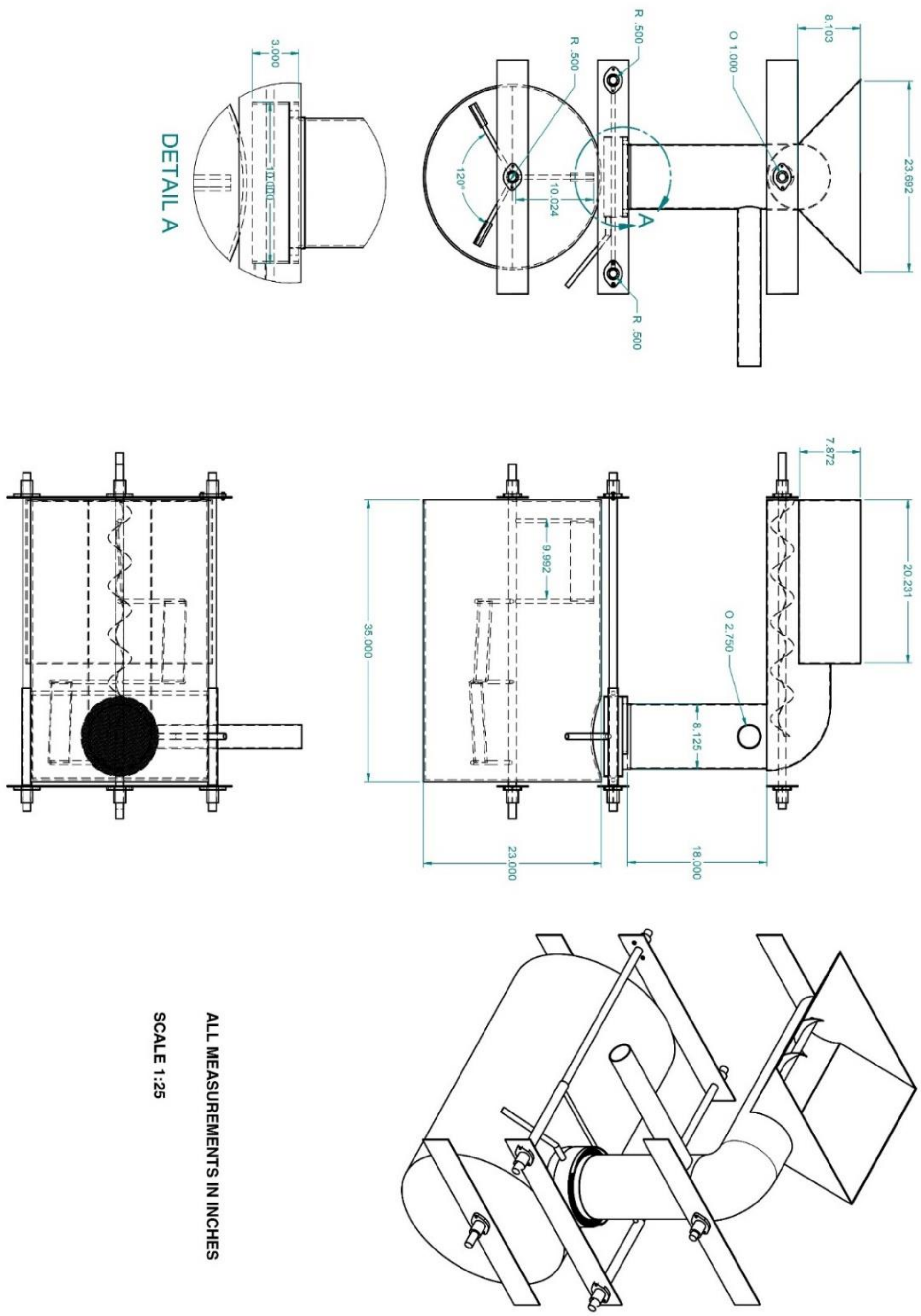
21. $\frac{1.39\,L}{\pi * \frac{(8.125\,in)^2}{4}} = \frac{1.39\,dm^3}{2.032\,dm^2} = 0.684\,dm = 6.84\,cm$

This design value will obviously be adjusted with more long term observations of the working prototype. Based on our observations, this height should be enough to filter solids out of the flush water. These values are specifications for system operations that can be adjusted once the actual system hardware is functional.

Final Design Specifications and Schematics

Final design overview

Figure 4: 2D CAD of final drawing



Bill of materials

Table 10; Bill of materials

Part	Material	Quantity	Unit Price	Price	References
Structural & insulation					
Structural lumber	2x4x8	8	3.00 $	24.00 $	homedepot.com
Plywood	1/2, 4x8	4	20.50 $	82.00 $	homedepot.com
Styrofoam	1,5'', 4x8	4	25.00 $	100.00 $	homedepot.com
Insulation	Glasswool	1	45.00 $	45.00 $	homedepot.com
Miscelaneous	Fittings, srews, glue...	100	1.00 $	100.00 $	eBay
Mechanical					
Aeration	fan 20cfm	1	10.00 $	10.00 $	eBay
Mixing motor system	200W electrical motor + gearbox	1	250.00 $	250.00 $	eBay
Mixing rod	Custom worked metal	1	150.00 $	150.00 $	eBay
Sliding axis	Metal tubing	2	25.00 $	50.00 $	Estimation
Door actuator	20" linear actuator	1	80.00 $	80.00 $	eBay
Puck actuator	10" linear actuator	1	50.00 $	50.00 $	eBay
Woodchip dispenser	Auger and motor	1	150.00 $	150.00 $	eBay
Reservoirs & tanks					
Digestion chamber	55 gallons drum	1	87.00 $	87.00 $	canadiantire.ca
Sliding puck	14'' PVC with flat cover	1	200.00 $	200.00 $	homedepot.com
Woodchip reservoir	Plastic bin	1	35.00 $	35.00 $	pvcfittingsonline.com
Filtration tank	2' of 12" PVC	1	50.00 $	50.00 $	homedepot.com
Automation & Safety					
Safety valves	4'' elecctro mechanical valves	2	150.00 $	300.00 $	Alibaba
Door position sensor	Limit switch	4	5.00 $	20.00 $	Sparkfun
Automation	arduino	1	15.00 $	15.00 $	Amazon
Compost monitoring	RH+T sensor	3	5.00 $	15.00 $	Sparkfun
Inactivation	heating element	2	125.00 $	250.00 $	eBay
Level sensor	capacitive sensor	2	40.00 $	80.00 $	Sparkfun
Drain pipe	Drain pipe Diam.: 2 inches	1	30.00 $	30.00 $	pvcfittingsonline.com
			Total	**2,173.00 $**	

Cost of the material was determined from different website according to their availability and/or the store's speciality: Home Depot, Canadian Tire, SparkFun, PVCFittingsOnline, eBay, Amazon and Alibaba.

Costs

Table 11: Running costs of the system

Consumable	qte	Basis	qte/yr	$/unit	$/yr
Woodchips					
Woodchips	351.41	kg/yr	351.41	0.33 $	115.85 $
Electricity					
Fan	0.005	kWh	43.8	0.07 $	3.07 $
Mixing motor	0.143	kWh	52.195	0.07 $	3.65 $
Woodchip dispencer	0.06	kWh	3	0.07 $	0.21 $
Gate actuator	0.06	kWh	0.6	0.07 $	0.04 $
Puck actuator	0.06	kWh	2.1	0.07 $	0.15 $
Automation	0.005	kWh	43.8	0.07 $	3.07 $
Heating					
Heating elements	2	kWh	2106*	0.07 $	147.42 $
				SUM	**126.03 $**

*** 2000W*3hr + 2000W*25%*(3d*24h-3h)**

The running costs include the woodchips, the electricity to automate the process and the electricity to kill the pathogens in the thermophilic phase. The mass of woodchip was calculated with the following equation:

$$m_{woodchip} = 0.0452\frac{kg}{flush} * 7.1\frac{flush}{cap * day} * 4\ cap * 365\frac{day}{yr} * 75\% = 351.41\ kg$$

The woodchip dispenser and the actuators found on the internet all had 60W motor. Its running time over the year was estimated to be of a total of 50 hours, which was determined by allowing about 15 seconds to the running time per filter refreshment.

The sensors and the Arduino board are expected to run constantly over the year, consuming about 5 Wh.

The heating elements were estimated to run a maximum of one cycle per week, which involves 3 hours at full power and the rest of the three day period at 25% power, for 2106 kWh yearly.

The price of 0.33$/kg was obtained from the approximate price of 6$ for a bag of 18.2 kg. Since, a cooling effect comes with the continuous running of a fan, its capacity was minimized to a 5W one, running 24h/day every day.

Determined previously, the wattage of the electric motor to mix the compost was 143 W. Running an hour per day every day demands 52.20 kWh per year.

Conclusion

From the macroscopic scale of waste water treatment infrastructures and operations to the microscopic scale of pathogen removal through composting, the residential biodigestor design project took our team on a path where three years of bioresource engineering studies could be leveraged like never before. As we learned, inserting a new element to an eco-system with the goal of creating a new dynamic is an ambitious enterprise. To make it so, our team spent one year understanding the waste water treatment cycle and the characteristics of residential waste effluents. Our individual knowledge on economics, building mechanics, biological processes and sociology was brought together with one precise goal: design the most accessible, efficient, reliable, user-friendly composting toilet there is. Our concept was first based on the science of pathogen removal of wastes through composting and slowly grew around it by adding compatibility to existing buildings, ease of maintenance and automation. Having a simple yet complete design allowed us to quickly enter the prototyping phase. Even though further analysis of the effluents and completion of the automation will help the product reach a market-ready stage, our design was proven functional. The biodigestor separated the liquid waste from the solid waste, the liquids got redirected to the regular sanitation infrastructure and the digestion chamber was filled with organic waste optimized in carbon/nitrogen ratio. We were asked to design a system that could shortcut the long treatment process of human wastes and that is what we delivered. We succeeded because each member of our team believes that, as future engineers, we must bring together scientific knowledge, proper technology and contemporary lifestyle together when designing for the latest challenges of the industrial world. People do not have to modify their homes nor lifestyle for their wastes to be handled differently. Why? Because it's 2016.

References

Angima, S. 2012. Master Composting Program. *Oregon State University Extension*.

CCME. 2010. A Review of the Current Canadian Legislative Framework for Wastewater Biosolids.

Collective, E. T. S. 2007. Per capita annual conumption of toilet tissure in North America. *World Watch Institute*.

Cornell, W. M. I. 1996. Cornell Composting. Ithaca, NY: Cornell University.

Gotaas, H. B. 1956. COMPOSTING Sanitary Disposal and Reclamation of Organic Wastes. *World Heatlth Organization*.

Goyal, H. 2009. Paper Properties. Available at: http://www.paperonweb.com/

Haug, R. T. 1993. The Practical Handbook of Compost Engineering. Boca Raton, Fl: Lewis Publisher.

Lam, P. S., S. Sokhansanj, X. Bi, C. J. Lim, L. J. Naimi, M. Hoque, S. Mani, A. R. Womac, X. P. Ye, and S. Narayan. 2008. Bulk density of wet and dry wheat straw and switchgrass particles. *Appl Eng Agric Applied Engineering in Agriculture* 24(3):351-358.

Rose, C., A. Parker, B. Jefferson, and E. Cartmell. 2015. The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology. *Critical Reviews in Environmental Science and Technology Critical Reviews in Environmental Science and Technology* 45(17):1827-1879.

Taillefer, S. 2010. Les Matières Organiques - Fiche informative. *Recyc-Québec*.

Zhang, Y., A. E. Ghaly, and B. Li. 2012. Physical properties of corn residues. *Am. J. Biochem. Biotechnol. American Journal of Biochemistry and Biotechnology* 8(2):44-53.