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Sustainable food processing systems - Path to a zero discharge: reduction of water, waste and energy

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Abstract

Since food processing systems consume extensive amounts of water and energy, the food industry has the incentive to reduce water and energy with the goal of developing a zero discharge process that utilizes substantially less water and energy, and generates no waste. The objective of this study is to evaluate water/energy consumption and to propose alternatives that reduce water and energy in the processing of three food products; 1) edible bean, 2) dairy products, and 3) corn masa. Three main approaches were; 1) plant-scale audit data collection to determine energy consumption, 2) laboratory scale experiments to assess product quality changes with a reduction in water and energy usage, and 3) computer-aided simulation to design systems for reduced water and energy consumption and wastewater generation. The results suggest that a zero discharge process is feasible by reducing water and energy. Modifications to the edible bean process reduced water input up to 55% and wastewater generation was decreased up to 91%. In dairy plant, the optimal heat recovery option could economically decrease the boiler fuel requirement by 50 times, and reduce the operating cost to 2.7% of the present cost. The water reuse process in redesigned corn masa process could reduce 90% of wastewater and 55% of water usage compared to the traditional process. The amount of energy required for heating was saved by 70% in the water reuse process. When scaling-up to plant-scale, reusing water could reduce water consumption by 95% and reduce energy requirement by about 80%.

Keywords: food process system; water and energy consumption; wastewater generation, zero discharge food process

1. Introduction

In the food industry, water has traditionally been a key processing medium throughout all steps in the food process as an ingredient and as a process aid. In addition, high levels of energy consumption are necessary for key operations such as food preservation, sanitation, and storage. About 5.4% of the United

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States's total waster consumption is utilized by food production and processing industries. For example, Blondin et al. [1] reported that the US fruit and vegetable industry annually generates nearly 11 million tons of by product wastes including 430 billion liters of effluent wastewaters. In addition, wastewater generated by food processing includes high biological oxygen demand (BOD) concentration, high levels of dissolved and/or suspended solids, nutrients, and minerals. Food industries generate approximately 20 percent of the total BOD in the nation, and are the primary source of biological pollutants [2]. When considering energy consumption, the US food industry consumes 7% of the total electricity used by the manufacturing sector requiring about 15% of the food industry's total energy needs is from electricity [3]. Moreover, the enforcement of wastewater discharge regulations and escalating sewage surcharges and energy costs have forced the food processing industry to find cost-effective technologies for providing pretreatment or complete treatment of their wastewaters. Increasing costs, and water rationing in certain areas are forcing industries to attempt to use less water and energy. As the industry expands to meet the needs of a growing population, these problems will only get greater. To accomplish getting by with less water and energy, more data is needed on how much water and energy is used by the various unit operations before food processors can develop processing operations that utilize less water and energy. To demonstrate the concept this paper will evaluate the water and energy consumption in 3 food processes; 1) edible bean process, 2) dairy products process, and 3) corn masa process. Based on these studies, a zero discharge food process that minimizes water consumption and energy requirement with no wastewater generation is achievable. This study used operating plant and laboratory data along with process simulation to evaluated the current water and energy consumption, and propose alternative process that reduces water and energy consumption.

2. Materials and Methods

Three common food processes were selected to determine water usage, wastewater generation and energy consumption in the food processing system. Our primary approaches categorized into three classes; 1) a plant-scale audit data collection and evaluation, 2) lab-scale experiments and 3) a computer-aided process simulation. For the edible bean process water balance data were determined at a local food manufacturing plant (Morgan Foods, Austin, IN, USA) around key process operations that included washing, soaking, inspection, fluming and blanching and filling (Fig 1) [4]. Operating conditions used in the unit operations in the edible bean process were identified and additional data was experimentally obtained to provide a complete mass balance. The parameters needed were flow-rates of material streams, moisture content of the solid, solid content of the wastewater, and operating conditions. SuperPro (Intelligen Inc., NJ, USA), a computer-aided designing software specific to food process, was used to execute process simulation and water reduction scenarios.

For the dairy products plant, energy consumption was measured based on performing a detailed audit on operating fluid milk plant [5] located in local area (Maplehurst, Indianapolis, IN, USA). Fig 2 shows HTST (high temperature and short time) unit for processing fluid milk in the plant. The data collection was conducted in two phases. Preliminary estimates were made concerning the approximate flow rates of utilities to the unit operations and actual meter installations. The utility billings were regularly monitored and after obtaining all flow information, energy balances were calculated for utility flows at the unit operations level. A central recording remote sensing system was installed in the plant to collect data using actual flow measuring devices. The collected data was used to evaluate the current operation and suggest alternative processes which could reduce energy.

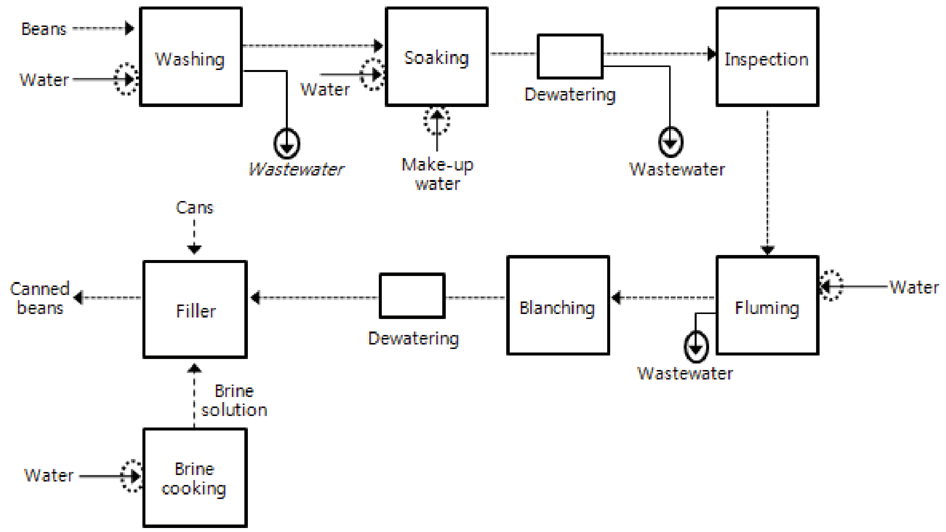

Fig. 1. Simplified beans processing flow diagram. The dashed lines represent the beans flow and the solid lines represent the water flow

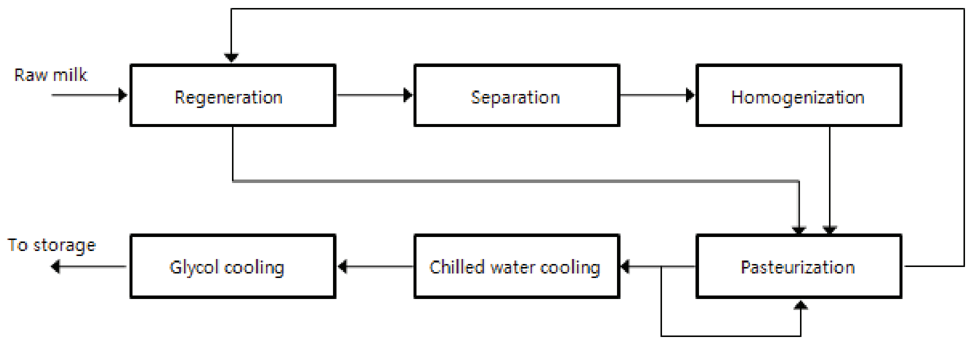

Fig. 2. HTST fluid milk processing system. Milk is pumped from the silos to the HTST balance tank. The milk is then standardized, homogenized, and pasteurized in the HTST unit and is pumped into large storage tanks prior to packaging

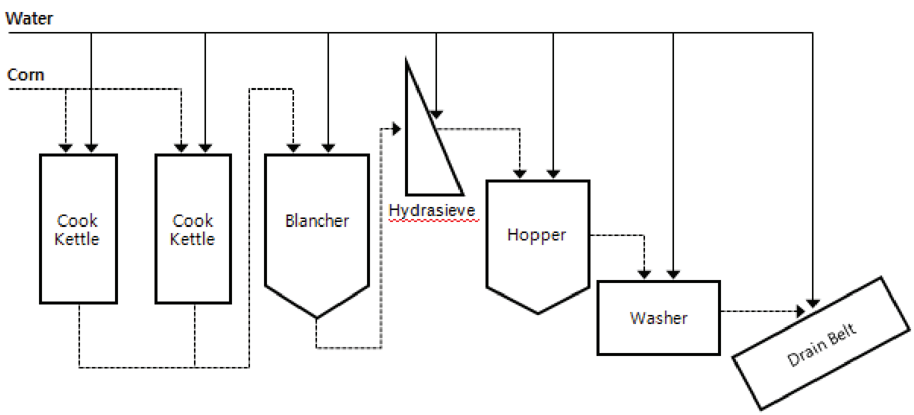

Fig. 3. Simplified masa corn processing flow diagram. The dashed lines represent the beans flow and the solid lines represent the water flow

For the corn masa process, a lab-scale experiment was performed to compare a traditional process and water reuse process in terms of the quality of the final product, the amount of wastewater disposed, and energy consumption. The experimental approximation of the water reuse process was achieved by cooking consecutive 500 g batches of food grade white dent corn in reused water comprised of 1% calcium hydroxide solution. The original water reuse process came from a modified lab scale nixtamalization procedure developed by Yglesias etal 2005 [6], which included the three main steps of processing: cooking, steeping, and washing. The water absorbed by the corn was replaced and moisture content of the nixtamal and dry matter content of the water were measured between each batch. Pasting characteristics and sensory properties of the final product were also investigated. Based on the experimental result, both water and energy balances were calculated and statistically compared. The plant-scale masa corn process (Fig 3) was examined to reduce water and energy consumption, and tested with water reuse in cooking operation.

3. Results and Discussion

3.1. Water consumption and wastewater generation in edible bean production

Water consumption and wastewater minimization in the edible bean food plant was evaluated by computationally modeling the current bean process and then proposing seven modified designs (4 for recycling wastewater and 2 for reducing water input) that reduce water and energy usage and wastewater generation; M1) counter flow of water through multiple washing stations, M2) Reuse washing wastewater for make-up water in soaking, M3) Reuse soaking wastewater for brine cooking, M4) Relocate inspection table, M5) Reuse soak water in soaking and fluming operation, M6) Replace the current blancher to steam blancher (remove fluming operation), and M7) a combination of all the modifications into one system, which modifies M1, M4 and M5 together. The modifications were designed to be consistent with the current bean process in terms of the product quality estimated by components composition and processing conditions.

Table 1. Simulation results for the current and modified designs in bean production process

Water input	Current (kg/batch)	M1 (ratio)	M2	M3	M4	M5	M6	M7
Wash	3018.090	0.097	1	1	1	1	1	0.097
Soak	5290.417	1	0.434	1	1	0.568	1	0.432
Flume/blanch	1001.362	1	1	1	0	0	0.18	0.000
Brine cooking	2985.379	1	1	0	1	1	1	1.000
Total	12295.247	0.778	0.756	0.757	0.919	0.733	0.933	0.452

Wastewater	Current (kg/batch)	M1 (ratio)	M2	M3	M4	M5	M6	M7
Wash	2994.088	0.090	0	1	1	1	1	0.090
Soak	3564.827	1	1	0.163	0	0.078	1	0.000
Flume/blanch	821.237	1	1	1	4.117**	1	0	0.456
Total	7380.152	0.631	0.594	0.595	0.864	0.555	0.889	0.087

*M indicated modifications and numbers in modifications were expressed as ratio compared to the current process.

** Flume wastewater includes soaking waste and fluming waste due to the relocation of inspection table.

Total water input and wastewater generated in the current bean process was 12295.25 and 7380.15 kg/batch, respectively, indicating that 60% of water input was discharged as wastewater. Soaking operation required the greatest amount of water input used for increasing moisture content of bean and generated the largest wastewater. In washing, 99% of input water was directly discharged as wastewater, while 67% and 82% of input waters were drained in soaking and fluming, respectively. Modified designs could reduce water input 7~27% and wastewater generation was decreased 11~45% (Table 1). Because of relocation of inspection table after blanching (M4) a new water input for fluming was not required, but flume wastewater increased since water used for soaking was discharged after fluming/blanching. The modification which combined 3 modifications, i.e., M1, M4 and modified M5, into one system could reduce water input and wastewater by 55% and 91%, respectively.

Solid concentration is one of key factor that determines water reconditioning. Solid concentrations in wastewaters for each operation were very low. Washing, soaking and fluming wastes were 0.28 g/L (= 0.03%), 0.51 g/L (= 0.05%) and 2.38 g/L (= 0.24%), respectively, suggesting wastewater may be recycled or reused without reconditioning. However, flume wastewater cannot replace the washing and soaking water input due to its relatively high solid concentration. We designed modifications such that the concentration of solid lost in wastewater essentially constant, corresponding to generally an equal amount of COD and BOD5 for each modification as shown in Table 2. The absolute amounts of wastewater were reduced, but concentration of solids remains almost constant except few cases. Recycling washing wastewater for replacing washing water input (M1) significantly increased COD and BOD5 since the modification was designed to reduce wastewater volume concentrating the solids lost. However, the absolute amounts of COD and BOD5 was unchanged in this case, suggesting treatment cost would less due to a reduction in volume as compared to the current process. We should note that the results were determined under the assumption that recycled wastewater was not purified and only used to replace water input in the operation thereby producing higher solid concentration.

Table 2. Estimated COD and BOD5 for the current and modified designs in bean processing system

COD (mg O/L)	Current	M1	M2	M3	M4	M5	M6	M7
Wash	476.7	4424.2	0	476.7	476.7	476.7	476.7	4424.2
Soak	880.3	880.4	880.7	880.3	0	880.9	880.3	0
Flume/blanch	4115.0	4115.5	4117.0	4115.0	1012.5	4119.0	0	1013.7
Total	5472.0	9420.2	4997.8	5472.0	1489.3	5476.6	1357.0	5437.9

BOD5 (mg O/L)	Current	M1	M2	M3	M4	M5	M6	M7
Wash	298.3	2643.1	0	298.3	298.3	298.3	298.3	2643.1
Soak	550.8	550.9	551.1	550.8	0	551.1	550.8	0
Flume/blanch	2574.7	2575.1	2576.0	2574.7	633.5	2577.2	0	634.3
Total	3423.8	5769.0	3127.1	3423.8	931.8	3426.7	849.1	3277.3

The modification (M7) can approximately reduce water cost by $40,000/year with assumption of $0.000674/kg of water. Since wastewater treatment cost is determined by the volume of wastewater and the total amount of COD/BOD5, modifications can reduce substantial amount of cost caused by wastewater treatment. With $0.44/kg cost of BOD treatment in wastewater, M7 can approximately save $142,000/year compared to the current process. However, it should be noted that the prices did not include capital investment and operating cost for the equipment needed for the modifications.

Minimization of wastewater has been suggested as a fundamental method for preventing high water demands [7]. However, unlike continuous systems, it is difficult to minimize wastewater in food plant because of its variability and uncertainties in wastewater generation. A computer-aided tool was used to propose possible scenarios. Modifications can be combined with to further minimization of water consumption and waste generation as shown in modification 7. However, practical issues such as water reconditioning and capital investment for constructing recycling system need to be considered to decide the best process for minimizing the water usage and wastewater.

3.2. Energy consumption and reduction in dairy production

Energy consumption in food processing was evaluated using a dairy multiproduct plant. The major demands for energy used in the dairy plant were steam, motors, liquid refrigeration energy (ammonia), and water. Based on the audit data, about 5.9 x 10^{10} BTU of fuel energy was yearly consumed. Fuel was mainly used in the boiler to produce steam, 58.9% of the fuel energy used in the boiler, which was equivalent to 3.35 x 10^{10} BTU, was yearly lost up by stack mainly due to low operating loads. Sanitation was the next largest user (17.0%) due to the large amount of hot water for clean-up, CIP, and case washing. Around 2.8% of the fuel was used for packaging and 0.7% was used for office heat. The fuel energy required for process equipment was only 6.2% of the total plant fuel input. The yearly consumption of electricity was determined to be 505.14×10^4 kWh. The largest single demand was from refrigeration compressors at 40.4%. The next largest user was process motors (homogenizer, separator, pumps, and packaging machines) at 21.9%. The yearly refrigeration energy usage was 1313×10^7 BTU. Most of the energy (87.9%) was used for the high temperature stage (10°F). Fluid processing was the biggest user (31.4%) in the high stage, and storage ranks as the next largest user (27.6%). The low stage (-40°F) accounted for 12.1% of the refrigeration energy. The largest consumer of refrigeration energy in the low refrigeration was storage. The annual water usage was 52.43×10^5 gallons. Water was utilized in three major areas: utilities, sanitation, and processing. Utilities accounted for 37.5% of the total water usage and include refrigeration and the boiler. Refrigeration consumed 23.3% of the total yearly water requirements. Sanitation required 24.4% of the total water usage. The biggest user in sanitation was fluid processing at in 10.6%, and the next largest user was packaging at 8.9%. Areas in processing other than simulation used 38.1% of the total water requirements. Fluid processing was the major user (19.7%) and receiving consumed 7.9% of the total water usage.

Table 3. Energy requirement and economics of the various plant steam systems

Option	Energy requirement (BTU/year)	Operating cost a ($/year)	Capital cost b ($)
Present system	57.0 × 109	386,147	-
New boiler (present process)	33.1 × 109	224,236	134,792
New boiler (process modifications)	9.78 × 109	66,255	763,281
Hot water heat recovery (new boiler)	3.75 × 109 c	29,408	768,171
Hot water heat recovery (hot water boiler)	0.96 × 109 c	10,384	798,994
Hot water heat recovery (heat pump)	0.74 × 109 c	8,894	859,709

[a] Operating costs was calculated based on industrial natural gas and electricity prices in 2009 and 2010 in Indiana (US Energy Information Administration). New boilers were operated by natural gas, while hot water heat recovery systems were operated by natural gas and electricity (for pumping).

[b] The Capital cost were converted to 2011 price using 2011 cost index (1475) compared to a cost index (650) since study had been priced all inputs, including energy and durable assets, at the 650 price level.

[c] Includes 0.34x10^9 BTU for pumping operated by electricity.

Since the plant is multiproduct, i.e., fluid milk, cottage cheese, and ice cream, several processes are common to all products. In order to properly allocate the energy required to process each product an analysis was made using the energy and production data. Ice cream was the product of the highest energy intensity at 5566.7 BTU/kg due to large amounts of low temperature refrigeration needed followed by cottage cheese at 2766.8 BTU/kg and then by fluid milk at 560 BTU/kg. However, fluid milk consumed the bulk of the process utilities due to the large volume produced.

Various heat recovery options [8,9] in plant steam system in which fuel was mainly used, were evaluated in terms of energy requirement and economics, i.e., operating and capital costs. The optimal option could decrease the boiler fuel requirement to less than 1 billion BTU per year, and reduce the operating cost to 2.7% of the present cost for operation (Table 3). The rate of return is quite good on all of the systems except heat pump option (Table 4), indicating that the operating cost can be reduced from $386,147 to $10,384 with an investment of $798,994 giving a very acceptable rate of return. Similarly it was found that 1.15 million kWh of electricity could be saved. Through use of more energy efficient motors, lights and by decreasing the load on the refrigeration system, approximately 1/5 of the electrical load can be saved.

Table 4. Plant system economics of incremental cost and savings, and rate of return [a]

Option	Incremental cost	Incremental cost savings	Incremental rate of return	Average rate of return [b]
	($)	($/year)	(%)	(%)
New boiler (present process)	134,792	161,911	120.1	120.1
New boiler (process modifications)	628,488	157,981	25.1	41.9
Hot water heat recovery (new boiler)	4,890	36,847	753.5	46.4
Hot water heat recovery (hot water boiler)	30,823	19,024	61.7	47.0
Hot water heat recovery (heat pump)	60,716	1,489	2.5	43.9

[a] The cost were converted to recent prices as did for Table 3.

[b] Over the present system

The energy use in the existing plant without investment alternatives is compared to the energy use in an existing plant with energy savings investment alternatives. It is found that an existing plant with energy savings investment alternatives uses 50% less fuel oil and saves over $200,000 annually. A 100% increase in fuel oil prices leads to only a 21% increase in energy costs in the existing plant with energy savings alternatives. Without these alternatives, the increase in energy costs for the same plant would be 62%.

Fluid dairy plants use a major portion of the total food processing energy, but very little information is available on how much energy is used by the various unit operations within the fluid milk process. With the recent escalation of energy prices and emphasis on reducing energy waste, this study provides an intensive analysis of the energy consumption at a medium sized fluid milk plant in the Midwest. In addition to energy consumption, energy saving options and alternatives were analyzed and presented.

3.3. Water and energy usage and reduction in masa corn process

Water and energy consumptions in traditional method and water reuse process for producing masa corn were studied as an example of a process modified to decrease both wastewater and energy that changes final product characteristics. Moisture content of nixtamal experimentally showed a decreasing trend as the amount of water reuse increased (Fig 4, left). After five reuses the average nixtamal moisture content for a traditional process was 55.6% compared to 47.6% for the water reuse process. This could be caused by the increased amount of dry matter in the water which caused water absorption into the corn kernels to decrease. Dry matter content of the re-used water increased from 2 to 7% over the five batches, and was projected to level off at 13%. The range of moisture contents of nixtamal obtained by the reused water process was 48-55%, which is within the range of 48-50%, optimal moisture content to achieve desired quality characteristics [10]. Changes in the pasting profile between reuse process and the traditional process were determined to be insignificant. However, solids composition in wastewater from the water reuse process significantly increased. BOD (>7236 mgO2/L) was within the range of values reported by [11], while both suspended solids and dissolved solids significantly increased by 80% in water reuse process (Fig 4, right). This may suggest the final waste treatment is important in the water reuse process.

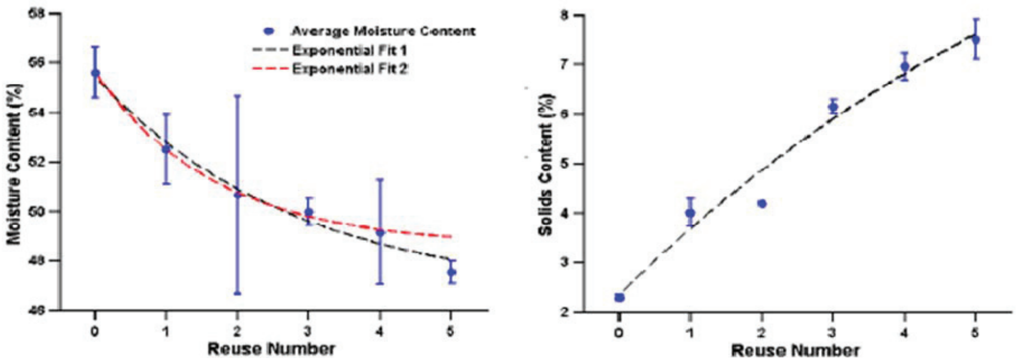

Fig. 4. Cooking corn (nixtamal) moisture content (left) and solid (dry matter) build-up in waste (right), showing exponential decay in moisture content and exponentially increase in solid content as reuse number increases

The amount of water used and disposed for both processes were compared. Water reuse process after five reuses was able to significantly reduce the amount of wastewater compared to the traditional process (Table 5). For processing 3kg of dry corn, the water reuse process resulted in 88% reduction in the amount of wastewater and a 55% reduction in the amount of water used during processing. The amount of energy saved for the water reuse process was calculated based on a temperature profile that obtained from heating used for the cooking process. Comparing to the traditional process, the energy input for heating determined by the energy needed to heat water was reduced by 70% in the water reuse process.

Table 5. Water usage and disposal laboratory comparison between traditional and water reuse corn masa processes

Process	Water used (mL)	Water disposed (mL)
Traditional	9000	5856
Water reuse	4018	1070
Reduction	**55.4%**	**81.7%**

Results from the experiments demonstrated an 82% reduction in the amount of wastewater, a 55% reduction in the amount of water used, and a 70% reduction in the amount of energy consumed for the process when wastewater was reused for 5 iterations. Even more reuses would result in even greater water, waste, and energy savings, but the absolute limit for the number of reuses has not been determined. This finding has implications for improved the sustainability of the masa production process. By reducing water and energy consumption, and limiting disposal of waste products, use of the water reuse process will greatly reduce the impact of masa production facilities on the environment, and water supplies.

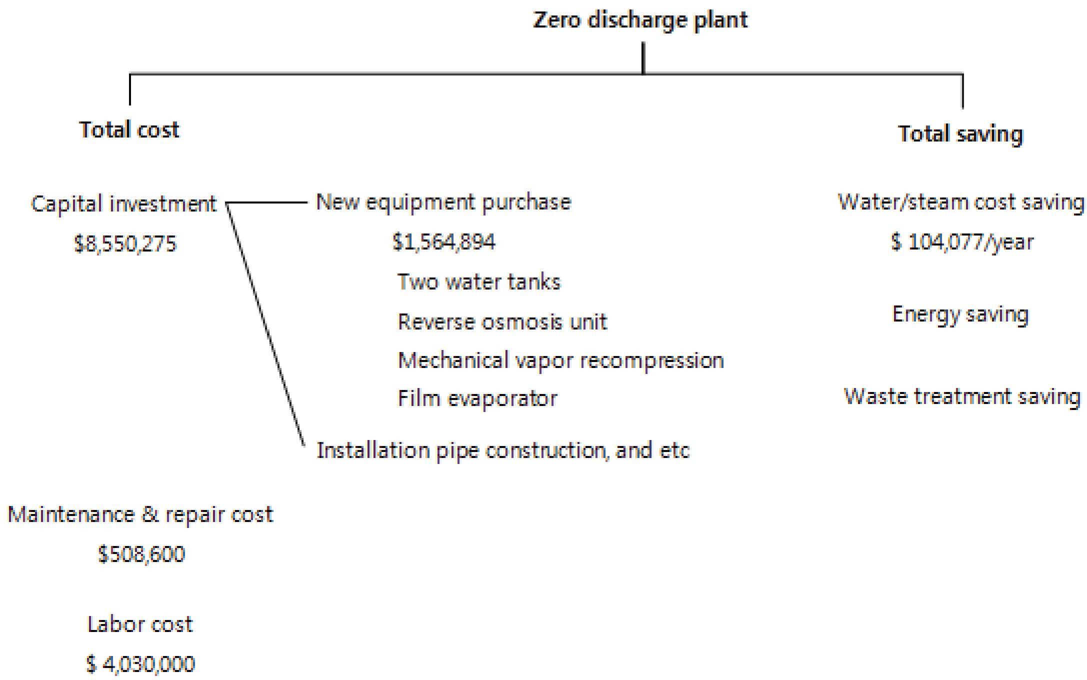

Fig. 5. Cost and saving diagram for zero discharge masa corn processing plant. Equipment cost and capital investment were estimated using Peters et al. (2003)

At the plant-scale a possible process redesign was evaluated. The current masa producing industry daily uses about 450,000 kg of water and generates more than 400,000 kg of wastewater. In the cook operation completed 40 cooks each day in industrial masa corn processing, reuse of water from the fist cook could reduce water added to the next cook by 95% (from 1,226 to 60 kg), while energy used for 40 cooks were reduced by about 80% (from 43,470 to 7,855 MJ). Likewise, a zero discharge masa processing plant is feasible with the above modification combined with reuse of the hydrasieve water to compensate for absorbed water during the cook step. The hydrasieve water can be used to quench the hot corn, and the combined hopper, washer, and drain belt water in the hydrasieve. We estimated that about $100,000/year could be saved with a zero discharge masa corn process based on water savings alone and that the rate of return rate will be supplemented with other savings, e.g., energy and waste treatment, suggesting that up to $750,000 can be used to obtain a 10% return rate for the capital investment (Fig 5).

The lab-scale experimental result showed that water and energy consumption and wastewater were reducible by water reusing, and plant-scale investigation showed how much amount and cost could be actually decreased with process modification. It was found that a zero discharge plant is more than likely feasible with water reusing, but future work, e.g., investigating the effect of water reuse on product quality in plant-scale, will be necessary to verify the industrial application of water reuse process.

4. Conclusion

Because of the resource intensive nature of food processing systems, the limited availability of resources and increasing cost, we have shown that the reduction in water usage, wastewater production and energy consumption is economically feasible. Further investigation which collectively considers resource consumption, waste generation and economics in a food processing system is necessary to completely develop a zero discharge food processing system. The impact of the reduction in water, waste and energy in food processes can potentially be a huge advantage environmentally and economically.

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