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Life Cycle Sustainability Assessment of Single Stream and Multi-Stream Waste Recycling Systems

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Abstract: An increasing trend of moving towards single-stream waste management systems is occurring in many municipalities. This is because of the ability to process greater quantities of materials, minimize material management costs, and maximize recycling convenience and participation. Research on evaluating comprehensive sustainability (economic, environmental, and social) of the two streams is very limited. This study looks to gain an in-depth understanding of two waste management systems and assist in the decision-making processes of municipalities. To achieve this, the study provides a framework for evaluating economic, environmental, and social impacts as well as a sustainability assessment of single- vs. multi-stream waste management systems within the scope of a typical North American college town. A life cycle assessment framework was employed. The scope of the assessment includes production of materials, collection, sorting, and processes included in a material recovery facility (MRF). The functional unit is 1 ton of municipal solid waste. The case study was conducted on a North American college city during its transition from multi-stream recycling to single-stream recycling. The sustainability assessment result of the case study reveals that the single-stream recycling collection cost is slightly lower (USD 86.96/ton) than the multi-stream recycling collection cost (USD 89/ton). Additionally, the GHG emissions for the single-stream recycling system (10.56 kg CO_2eq/ton) are slightly higher than for the multi-stream recycling system (9.67 kg CO_2eq/ton). This is due to the complexity of the processes involved in the MRF. Nevertheless, recycling rate is the determining factor for life cycle GHG emissions and costs. Municipal solid waste policymakers could benefit from this study by using the framework and study results for tactical and strategic decision-making.

Keywords: life cycle sustainability assessment; recycling; waste management; single-stream recycling; multi-stream recycling

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1. Introduction

The increase in municipal solid waste (MSW) has become a global issue in the last century. Along with the growing volume of waste, there also comes the decreasing availability of areas and traditional methods such as landfilling to dispose of the waste in certain locations [1]. The various issues that arise due to the escalating amount of waste have forced modes of alternative disposal, such as recycling, that is enforced by the United States government. The Environmental Protection Agency (EPA) of the United States annually releases the expected goals, policies, and current statistics regarding recycling in a document called Sustainable Materials Management: Fact Sheet [2]. This document contains data regarding MSW generation, recycling, combustion with energy recovery, composting, and landfilling data. Recycling opens up the opportunity to stall the creation of new landfills and attempt to maintain the size of current landfills while also conserving natural resources that would be used to manufacture new materials or products. The two recycling methods included in this study are single-stream recycling (SSR) and multi-stream recycling (MSR). Single-stream recycling is a method of disposal in which all recyclables are placed into a single bin, then collected by a truck that also has one main compartment [3]. Multi-stream recycling, or dual-stream recycling, is another method of disposal that entails separation of the type of recyclable material prior to collection and transport. The objective of this study is to evaluate economic, environmental, and social impacts of two waste managing systems—the single-stream system and the traditional multi-stream waste management system—including waste collection, transportation to the materials recovery facility (MRF), and processing at the MRF. The study results contribute to the current knowledge on sustainability understanding of the two streams and can assist governmental decision-making at all levels.

In this article, a literature review will firstly be provided to consolidate current knowledge on this study. In Section 3, a sustainability assessment that includes techno-economic assessment, life cycle assessment, and social impact assessment is conducted. Assessment results are presented in Section 4 and are used as the baseline for sensitivity analysis of multiple variables in Section 5. At the end of this article, insights and understandings from this study will be provided in the Sections 6 and 7 to assist practitioners and policy makers in decision-making.

2. Literature Review

This section reviews the current literature on practices, challenges, and studies around single-stream and multi-stream recycling systems. In the end of this section, we highlight the gaps in economic, environmental, and social sustainability of the two systems.

In the single-stream recycling system, once recyclables are collected, the materials are taken to a materials recovery facility (MRF) to be separated using various operations and technologies [4]. The recyclables are separated using physical or chemical features. The various technologies and processes in a MRF involve conveyor systems, magnetic separation, screening, air classification, non-metal separation, and balers or compactors [5]. Single-stream is more often seen in residential areas [6]. The benefits of adopting a single-stream recycling system include convenience, higher volume of recycled materials, decrease in collection fees of traditional waste, and lower transportation costs due to a smaller single compartment collection truck [7]. Despite the appealing advantages of SSR, this method does result in higher levels of cross-contamination [8]. This occurs because the recyclables are all placed into one container and mixed with the previous residues on the used waste. There is also an increased chance that glass will become broken during the recycling operations [8]. The level of recycling education/awareness plays a role in controlling the contamination of wastes for SSR [9,10]. Higher levels of contamination reduce the resale price of the repurposed materials due to poor quality [11]. In a multi-stream waste recycling system, there will be multiple bins that correspond with specific recyclables, such as paper or plastics, that require the consumer to separate their waste by type of recyclable material [6]. This system is most used in urban areas (some scenarios that are good to use multi-stream). The benefits of a multi-stream system include a decreased possibility of contamination, lower processing cost, and higher quality and value of the recycled material [12]. Therefore, multi-stream is the most financially advantageous method of recycling [6]. Despite lower contamination levels, multi-stream recycling methods consequently result in higher collection costs due to the necessity to maintain separation of the materials [13]. Although dual-stream recycling is effective in various ways, there are limiting factors, such as the collection equipment, including side-loading collection trucks and curbside containers. Side-loading trucks have nearly half the space for recyclables when compared to single-stream collection trucks. The small and numerous containers discourage recycling. The containers make it a tedious task to collect, which adds a tremendous amount of time, making the dual-stream collection process less efficient [6]. Also, there is a lower level of household participation with the requirement to separate prior to pickup, which takes extra time, effort, household space, and additional bins rather than just one. Presently, it is more and more common to find cities and towns with larger populations adopting a single-stream system or switching from multi-stream to single-stream recycling. This trend is occurring in order to increase public participation to meet, maintain, and increase the mandated recycling rates [3]. Transitioning to or adopting a single-stream recycling disposal system most likely entails adopting a bi-weekly garbage collection schedule. Additionally, there are also changes in materials processing and the efficiency of curbside collection [6]. Currently, there is a lack of knowledge about environmental, economic, and social impacts of both single-stream and multi-stream recycling systems, which is necessary when adopting a recycling system. Therefore, an assessment of all aspects is imperative.

While the two methods are used widely these days, a comparison of sustainability (environmental, economic, and social) performance between the two has rarely been studied. There are more often studies and research found regarding only one of the sustainability aspects [10,14–24]. Wang assessed participation and recycling rates after switching to a single-stream collection system but lacked an environmental or economic evaluation [3,25] and focused on the cost–benefit analysis, with a small evaluation of the social costs of switching to an automated collection with single-stream [3,26]. Fitzgerald examined the greenhouse gas impacts of both methods while missing the full evaluation of sustainability [27]. Chester et al. centered on environmental consequences of recycling, more specifically, a curbside recycling program [28]. Using a more social evaluation, Bell et al. focused on the potential increase in recycling rates of single-stream programs [29]. In addition to a cost examination, Lakhan assessed the overall difference in recycling performance between single- and multi-stream methods [6]. Similarly to Lakhan's report in 2015, we also addressed the differences in performance of the two current methods. Based on the available literature, it is evident that assessments are lacking. The present assessments of recycling, more specifically of single- and dual-stream methods, are limited in that they lack complete and thorough evaluations of both methods regarding sustainability, which includes environmental, economic, and social assessments. Therefore, there is a need for a study that includes all three perspectives.

3. Methodology

This study follows the life cycle sustainability assessment framework, which includes a life cycle assessment (Figure 1) [30], a life cycle techno-economic assessment [31], and a social impact assessment [32].

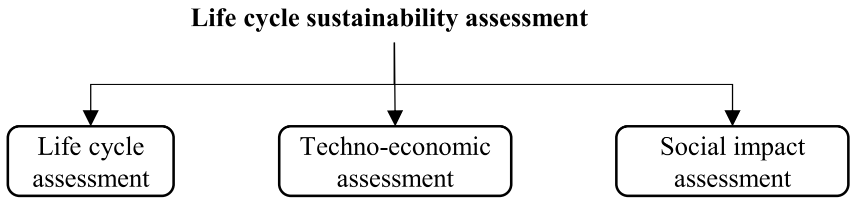

Figure 1. Life cycle sustainability assessment framework [30].

This study was conducted on a North American college city with a population of approximately 40,000. The MSW management system is transitioning from multi-stream recycling to single-stream recycling. The city collects waste from residents, businesses, and industrial facilities. The university, however, currently maintains its multi-stream recycling system and operates a separate MSW management system. Sustainability assessment conducted in this section presents the results based on the two systems in this case with different waste composition. A general comparison of single-stream and multi-stream recycling systems is presented in the sensitivity analysis section.

3.1. Life Cycle Assessment

The life cycle assessment (LCA) environmental impact assessment method has been widely used by practitioners to investigate environmental impacts associated with a product or system over the past twenty years. According to ISO 14040, the method comprises four stages: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (Figure 2) [30].

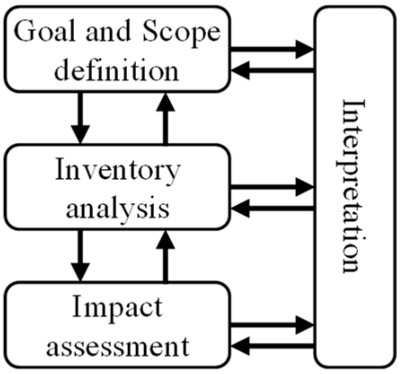

Figure 2. Four phases of life cycle assessment [30].

3.1.1. Goal and Scope Definition

The goal of this analysis is to understand economic, environmental, and social performance of the two systems. The scope of the assessment begins at the collection of waste and continues until the end of life for the waste. Analyzing the different kinds of recycling will provide insight into the two different recycling methods, particularly which method recycles more. Our system boundary encompasses the direct inputs into the system, as well as the variables that enter or exit the system until the end of life for the waste. This system boundary can be visually represented by Figure 3 below. Although the operations within each stage can be different, the wastes go through the same processes involved in the two recycling systems. The "end of life" stage means the wastes will be repurposed to different raw material processing facilities (e.g., steel scraps to steel making manufacturers).

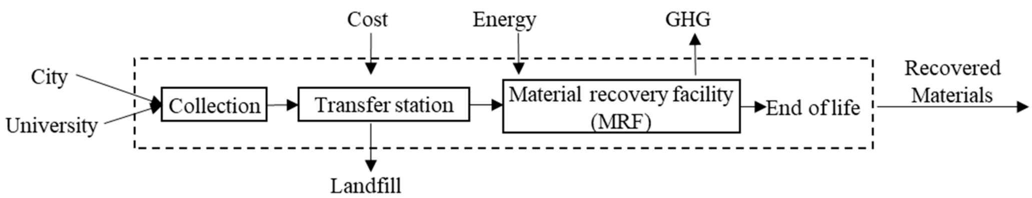

Figure 3. System boundary: Both systems involve the same life cycle stages.

The functional unit for the techno-economic assessment and life cycle assessment is one ton of municipal solid waste.

3.1.2. Life Cycle Inventory

This inventory encompasses the energy inputs, GHG emissions, and materials required for the operation of the entire waste management system [33]. Most of the data used in this study is primary data collected from the Municipal Waste Department of Harrisonburg, Virginia, USA as well as the James Madison University Waste Management Department. Data used for the materials recovery facility and data used for the emission factors were secondary data collected from literature sources such as the EPA and Entec, UK Ltd.

a. Waste Component

The waste management of the city is divided in to two different systems. The university, located inside the city, has adopted a multi-stream system characterized by four main components: paper, plastic, organic waste, and recyclables. On the other hand, the city itself uses a single-stream system, in which each waste component is divided into recyclable and non-recyclable. Table 1 below shows the components for the city and the university, and this kind of waste composition is based on one unit of municipal solid waste. The moisture content of the waste is considered to be 29.4% [34].

Table 1. Waste composition.

Materials	Waste Component	City (%) (Single-Stream)	University (%) (Multi-Stream)	Single-Stream Waste (ton)	Multi-Stream Waste (ton) *
Paper	Recyclable paper	8.7	15	3844.1	582.9
	Non-recyclable paper	7.2		3181.3	
Plastics	Recyclable plastics	3.3	18	1458.1	699.5
	Non-recyclable plastics	14.3		6318.5	
Organic waste	Compostable organic waste	36.3	48	16,039.2	1865.3
	Non-compost organics	4.4		1944.1	
Recyclables	Glass	2.3	2	1016.3	77.7
	Electronics	2.2	1	972.1	38.9
	Household hygiene	9.2	8	4065.1	310.9
	Bulky objects	1.6	1	706.9	38.9
	Fines	1.1	1	486.1	38.9
	Household hazardous	1.4	1	618.6	38.9
	Building materials	3	1	1325.6	38.9
	Beverage containers	1	3	441.8	116.6
	Metals	3.9	1	1723.2	38.9

*: Due to different data documentation systems, in multi-stream waste, only recycled materials are shown in the table. A total of 4946 tons of waste went to the landfill. _: underlined materials are non-recycled materials.

b. Collection and Transportation (City Single-Stream vs University Multi-Stream)

The city uses a single-stream management system, and the university uses a multi-stream waste management system.

Tables 2 and 3 present the city waste collection and the city's transportation to the MRF [35]. The key elements to the city collection are not only the waste collection that the city has to do, but also the transportation to the MRF [36]. The city collection program utilizes eight trucks that drive an average of 56 miles per day. The waste collection factor for the city was calculated based on an average distance traveled per day by the eight trucks, as the density of households varies among communities. It represents one-way collection distance for each truck per day. When calculating total travel distance, this factor will be multiplied by 2. On the other hand, the city has to transfer the waste to the MRF, which it does approximately 2 times per day, with the only difference being that the MRF is 74.3 miles south of the city, which makes the average miles driven daily by the truck about 6 times higher than just doing the collection around the city. The city collects waste 300 days a year. For the remaining 65 days there are no collections because of the limited area of their service.

Table 2. City waste collection—single-stream.

Parameters	Amount	Unit
Number of trash trucks	8	
Truck cost	250,000	USD/truck
Waste collection factor (one way)	3.5	miles/truck/day
Distance traveled per day	56	miles
Distance traveled per year	16,800	miles/year
Diesel consumption	4200	gallons/year
Diesel cost	9618	USD/year
Labor	480,000	USD/year
Landfill	32	USD/ton
Total landfill fee	352,396.16	USD/year

Table 4 shows the characteristics of university collection. With 8 pickup trucks having to collect the waste only around the university campus, there is only a need for 10 workers within the system, and the pickup trucks go to campus about twice a day being only 2.8 miles away from campus. As mentioned above, the university makes a profit mainly from paper cardboard, glass, and organics. Only when they receive enough waste do they bring it to materials handlers, with the paper being 86 miles away and the organics disposal being 117 miles away.

Table 3. Transportation to MRF—single-stream.

Parameters	Amount	Unit
City transfer to MRF	74.3	miles
Number of transports per day	2	
Total miles traveled per day	297.2	miles
Diesel consumption per day	74.3	gallons
Diesel consumption per year	27,119.5	gallons
Diesel cost	62,103.6	USD/year

Table 4. University waste collection and transportation to MRF—multi-stream.

Parameters	Amount	Unit
Number of times/day	2	
Number of workers	10	
Distance within campus	2.8	miles
Distance to Royal Oak (organics)	117	miles
Distance to Sonoco (paper glass cardboard)	86	miles
Miles per gallon (MPG)	41	miles/gallon
Diesel consumption	11.2	gallons/day
Emission factor	10.2	kg CO_2eq/gallon

The main difference in the collection and transportation of the two systems is that the city has a much larger collection and has to cover a greater area. This also means having a much greater mileage consumption and therefore diesel consumption. The main cause of this is that the city also has to transport the waste to the MRF twice a day.

c. Material Recovery Facility

The material recover facility is where the collected wastes are received, sorted, and treated to be ready for end buyers. For both systems, the waste components get put on a conveyer and if they cannot be treated, they get thrown in the trash pile [37]. After identifying the components, the waste gets separated onto the different conveyers appropriate for the waste materials. For example, the single-stream cardboard gets transferred to a second conveyer and then baled, while paper goes through a new combination screen, where it is manually removed to ensure that there are no contaminants. A process flow diagram for single-stream MRF is shown in Figure 4.

Figure 5 shows the waste process in the material recovery facility for a dual-stream recycling system [38]. Some university wastes that are supposed to be sorted during collection but ended up in the general bin are sent to this facility for further processing. This process is characterized by two main operations the waste goes through: the fiber stream and the container stream. In the fiber stream, the waste enters the machine through a feeder where it goes from a conveyer to a disc screen. While on the screen lines, the waste also gets checked by a worker to make sure clean material goes to the final conveyer to then be baled. On the other hand, after being put on the conveyer, the waste goes through a set of air knives, which separates the glass material and moves it through a glass breaker. The rest of the waste then goes through an optical scanner, which identifies light plastics that go straight to the baling process. The rest of the waste then goes through another optical scanner, whose job is to identify heavier plastics and send them straight to baling. The rest of the waste then goes through a magnet, which attracts all steel and metals that are sent to the balers. Finally, the rest of the waste goes to the last conveyer to be baled together [39].

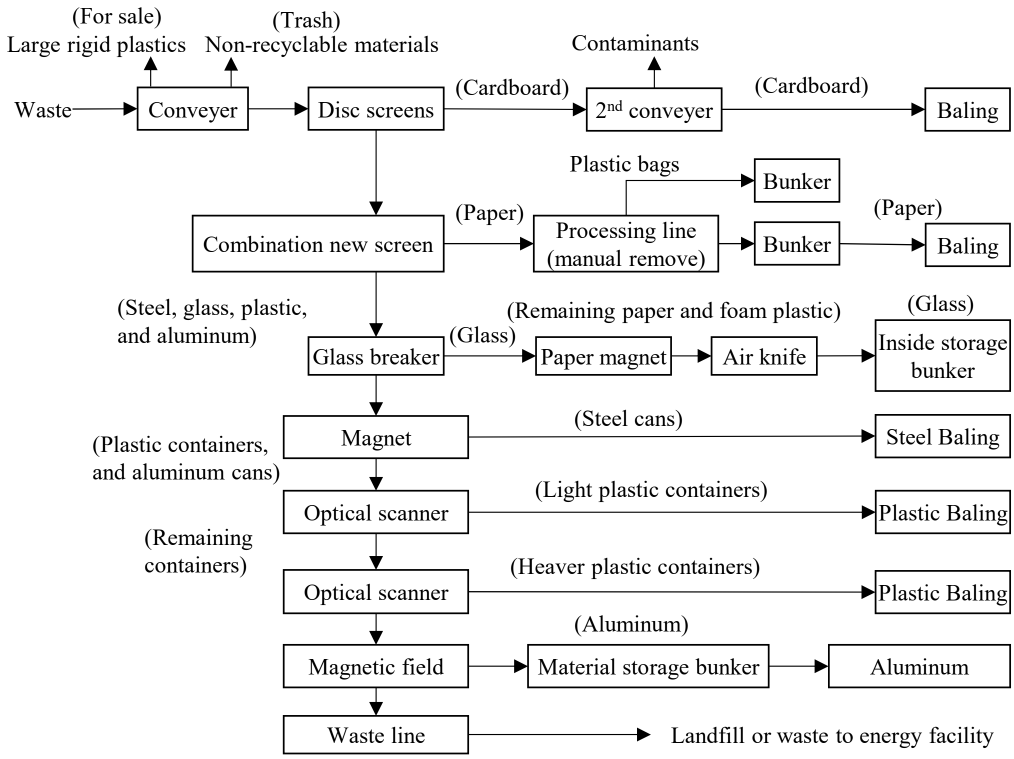

Figure 4. Single-stream MRF processes.

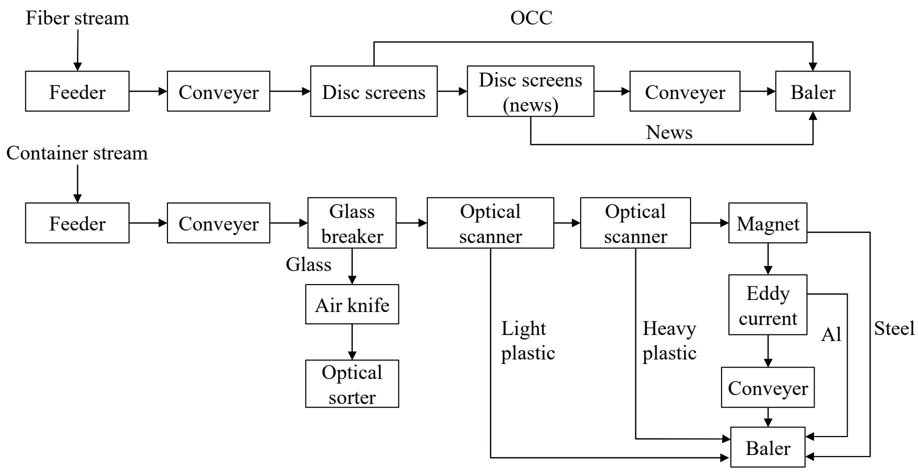

Figure 5. Dual-stream MRF processes for the multi-stream waste system.

The main difference in the MRF process for the two systems is that single-stream MRF requires a higher level of mechanization and human work to sort the materials, while the dual-stream MRF is only required to be sourced in two different operations. This is because the material is also being sorted, so there is a reduced possibility of the waste being contaminated [37].

Table 5 shows energy consumption by the MRF [38,39]. The energy consumption is how much electricity is being consumed hourly per one ton of waste that is being processed. There are several factors that cause electricity consumption. For each material, there are different operations that the waste must go through, and these operations are performed by specific equipment for each waste category. Categories include power consumption, processing time, and throughput. These will determine how many tons can be processed in that time. The equipment also must be operated and maintained over the years, and each machine has an end-of-life of approximately 10 years.

Table 5. MRF energy consumption and equipment use.

Operations		Throughput (ton/h)	Power (kw)	Utilization	Process Time (h)	Energy (kwh/ton)	Cost (USD)	Life (Year)	O&M (USD/Year)
Cardboard	Feeder	30	15	1	0.033	0.50	150,000	10	100
	Conveyer	30	5.6	0.85	0.033	0.16	46,000	10	10,000
	Disc screens	45	8.5	0.85	0.022	0.16	175,000	10	10,000
	2nd conveyer	30	5.6	0.85	0.033	0.16	46,000	10	10,000
Paper	Combination new screen	7	10	0.85	0.143	1.21	280,000	10	13,000
	Vacuum	10	5	0.85	0.100	0.43	150,000	10	100
	Processing line	10	5.6	0.85	0.100	0.48	46,000	10	10,000
Glass	Glass breaker	9.9	30	0.85	0.101	2.58	220,000	10	10,000
	Paper magnet	2	4	0.85	0.500	1.70	35,000	10	5000
	Conveyer	30	5.6	0.85	0.033	0.16	46,000	10	10,000
Steel	Magnet	2	4	0.85	0.500	1.70	35,000	10	5000
Plastics	Optical scanner	10	13	0.85	0.100	1.11	225,000	10	5000
Heavier plastic	Optical scanner	10	40	0.85	0.100	3.40	450,000	10	10,000
Aluminum	Magnetic field (Eddy current)	12	9	0.85	0.083	0.64	128,000	10	5000
	Balers	30	59	1	0.033	3.93	530,000	10	5000

Table 6 shows the energy consumption of the MRF for the dual-stream system [38,39]. Just like in Table 5 above, the energy consumption is characterized by the same factors, and the main difference is that the dual-stream system has only two main operations: the fiber stream and the container stream. Within them, there are multiple different sub-operations adopted by the machines.

Table 6. MRF energy consumption and equipment use for fiber and containers.

Operations		Throughput (ton/h)	Power (kw)	Utilization	Process Time (h)	Energy (kwh/ton)	Cost (USD)	Life Time (Years)	O&M (USD/ Year)
Fiber stream	Feeder	30	15	1	0.033	0.50	150,000	10	100
	Conveyer	30	5.6	0.85	0.033	0.16	46,000	10	10,000
	Disc screen (OCC)	45	8.5	0.85	0.022	0.16	175,000	10	10,000
	Disc screen (News)	7	10	0.85	0.143	1.21	280,000	10	13,000
	Conveyer	30	5.6	0.85	0.033	0.16	46,000	10	10,000
	Baler	30	59	1	0.033	3.93	530,000	10	5000
Container stream	Feeder	30	15	1	0.033	0.50	150,000	10	100
	Conveyer (manual sort)	30	5.6	0.85	0.033	0.16	46,000	10	10,000
	Glass breaker	9.9	30	0.85	0.101	2.58	220,000	10	10,000
	Optical scanner	10	13	0.85	0.100	1.11	225,000	10	5000
	Optical scanner 2	10	13	0.85	0.100	1.11	225,000	10	5000
	Magnet	2	4	0.85	0.500	1.70	35,000	10	5000
	Eddy current	12	9	0.85	0.083	0.64	128,000	10	5000
	Conveyer	30	5.6	0.85	0.033	0.16	46,000	10	10,000
	Baler	30	59	1	0.033	3.93	530,000	10	5000

d. End of Life

At the end of life, waste will be going to separate processing facilities to generate new raw material for production [6]. During this process, environmental impact credit is gained and, in calculation, the saved impacts are negative values. In Table 7, emission factors for different recycled wastes are presented, as well as recycled cost rates in the market. The emission factor is the amount of GHG emissions in kg of CO_2eq per ton. In this study, emission factors are from the U.S. EPA WARM model [2]. The category of waste also impacts the emission factor and overall revenue greatly because of reprocessing technologies. The price per pound of recycled waste changes, however, causing the overall revenue received to vary. The more valuable materials, such as metals, increase the overall revenue and greatly lower the emission factor per ton of MSW.

Table 7. Recycling price and emission factors.

Waste Component		Price (US Cents/lb)	Emission Factor (ton CO_2eq/ton)
Paper	Recyclable paper	4.75 [1]	−3.53
	Non-recyclable paper		0.02
Plastics	Recyclable plastics	7 [2]	−1.02
	Non-recyclable plastics		0.02
Recyclables	Glass	0.5 [3]	−0.28
	Electronics	32 [4]	−2.5
	Household hygiene	20 [5]	−0.07
	Bulky objects	20 [5]	−0.07
	Fines	100 [4]	−4.71
	Building materials	20 [5]	−0.01
	Beverage containers	33 [4]	−9.11
	Metals	5 [4]	−4.34

[1] [40]; [2] [41]; [3] [42]; [4] [43]; [5] average of all recycled wastes.

This study focuses on wastes except organic waste because the purpose is to compare the GHG emissions primarily from collection, transportation, and processes in MRFs. Organic waste recycling costs and benefits as well as emission factors are not included because organic waste emissions often depend on the treatment method. According to the EPA WARM model, the emission factor is −163.29 kg CO_2eq/ton if it is composted, while the emission factor is −54.43 kg CO_2eq/ton if it is anaerobically digested. Assumptions are made that household hygiene and bulky objects are counted as mixed MSW from the WARM model.

4. Results

4.1. Life Cycle Impact Assessment Results

The life cycle impact of the waste depicts the effect that the system has on the municipality. Based on the process discussed above, such as collection of waste and MRF of the waste life, Figure 6 shows the life cycle GHG emissions of the two systems. The life cycle GHG emissions calculations for each of the two systems were based on the following data.

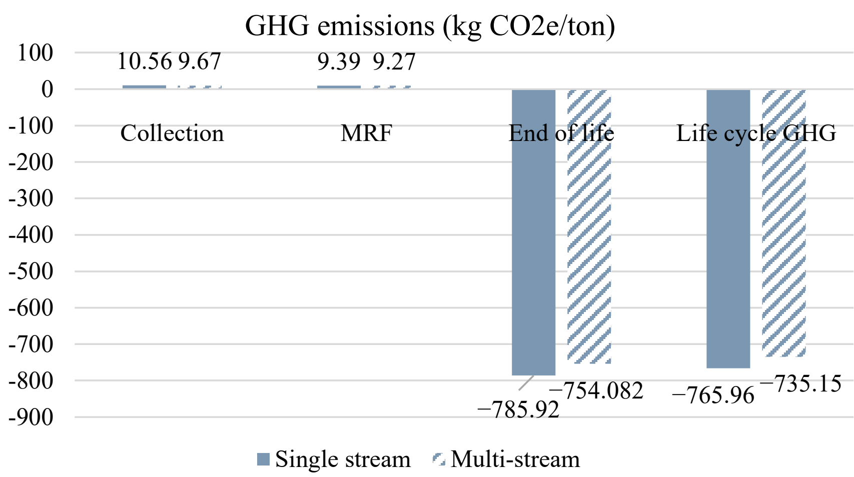

Figure 6. Life cycle GHG emissions.

In the multi-stream system, there are three stages of GHG emissions: collection, MRF, and end of life. The collection stage includes a diesel consumption of 11.2 gallons/day, with an emission factor of 10.21 kg CO_2eq/gallon. GHG emissions from campus collection were 34,305.6 kg CO_2eq/year, and GHG emissions from transportation were 3261.62 kg CO_2eq/year. In the MRF stage, electricity consumption was 18.00 kwh/ton with an emission factor from electricity of 0.82 kg CO_2eq/kwh. Diesel consumption was 0.7 L/ton, with an emission factor from diesel of 10.21 kg CO_2eq/gallon. In the end-of-life stage, the total GHG from recycling was −2930.36 tons CO_2eq.

The single-stream recycling system was also composed of the same three stages where GHG emissions took place. The collection stage had a diesel consumption of 4200 gallons/year, and GHG emissions from city waste collection were 42,882 kg CO_2eq/year. Diesel consumption per year was 74.3 gallons, and GHG from transportation was 276,890.1 kg CO_2eq/year. The emission factors for electricity and diesel at the MRF stage are 0.82 kg CO_2eq/kwh and 10.21 kg CO_2eq/gallon, respectively. Electricity consumption was 18.3 kwh/ton, and diesel consumption was 0.7 L/ton. In the end-of-life stage, total GHG emissions from recycling in the single-stream system were −34,725.88 tons CO_2eq/year.

The collection of the waste for the single-stream is 10.56 kg of CO_2eq per ton, while for multi-stream is 9.67 kg of CO_2eq per ton. This difference is minor because the single-stream collection has a higher annual truck diesel consumption with more mileage. For the MRF, the GHG emissions for the single-stream (16.9 kg CO_2eq/ton) are slightly higher than the multi-stream system emissions (16.65 kg CO_2eq/ton). This is because the single-stream utilizes more machinery and processes to separate the waste. For the end of life of the waste, the single-stream saves more GHG emissions than the multi-stream because the variation of waste composition between the two systems affects GHG emission credits.

The life cycle GHG emissions show that both systems result in net negative emissions, which indicates that both recycling systems can effectively save GHG emissions, with single-stream recycling slightly higher than multi-stream recycling.

4.2. Techno-Economic Assessment Results

Table 8 and Figure 7 shows the values for the costs and revenues of the different components of the different waste management systems and what impacts they have on both the cost and emission factors of the wastes. These values display an overall impression of the differences between each waste management system.

Table 8. Life cycle costs and benefits.

Stages	Multi-Stream			Single-Stream		
Collection	Diesel cost	7694.4	USD/year	Overhead	1,032,685	USD/year
	Labor cost	306,300	USD/year	Solid waste collection	1,339,448	USD/year
	Equipment cost	8.6	USD/ton	Equipment cost	8.6	USD/ton
	Collection cost	89.4	USD/ton	Collection cost	86.96	USD/ton
MRF	Equipment cost	5.3	USD/ton	Equipment cost	5.8	USD/ton
	Wire cost	1.2	USD/ton	Wire cost	1.3	USD/ton
	Fuel electricity cost	1.91	USD/ton	Fuel electricity cost	1.93	USD/ton
	Building and land capital	12.3	USD/ton/year	Building and land capital cost	12.3	USD/ton/year
	MRF cost	20.71	USD/ton	MRF cost	21.33	USD/ton
End of life	Total recycling revenue	416,287	USD/year	Total recycling revenue	5,076,635	USD/year
	Revenue per ton	107.13	USD/ton	Revenue per ton	114.9	USD/ton
Life cycle	Life cycle cost	2.99	USD/ton	Life cycle cost	−6.61	USD/ton

There is a clear difference between multi- and single-stream when it comes to the life cycle costs for the system [44]. During the collection and MRF there are slight differences between the costs for single- and multi-stream. These differences arise from the increased transportation costs that must be allocated for multi-stream to account for the different types of materials. During the MRF, the cost of single-stream is greater than multi-stream because of the increased energy costs that are associated with operating the system for a period longer than that of multi-stream to separate the waste components. The end-of-life revenue is largely dependent on the waste composition of the two systems. The single-stream from the city waste comprises more “valuable” waste (e.g., fines, electronics) compared to the multi-stream system in the university.

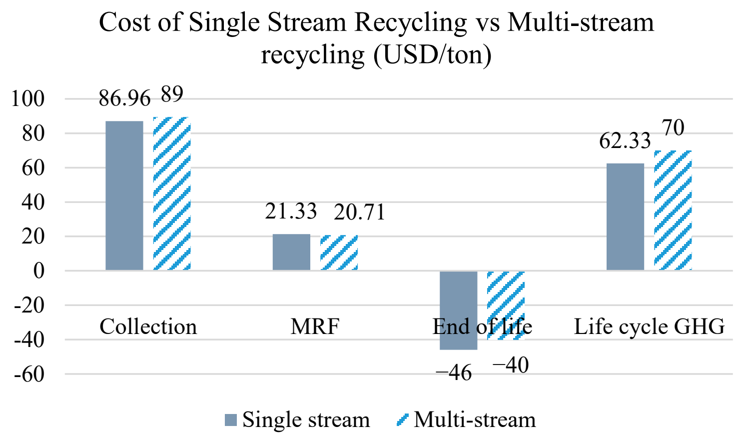

Figure 7. Cost of single-stream recycling vs. multi-stream recycling (USD/ton).

4.3. Social Impact Assessment Results

There are several factors playing an important role in the transition from one recycling system to another. They include: recycling participation, public acceptance, and transition plan [45].

Recycling participation rate is a key factor in triggering the transition from multi-stream to single-stream. The recycling rate is increased due to the ease of disposal into one sole container rather than several containers [46]. Recycling participation is crucial to preserve the recycling services at hand. Decreased participation gravely affects the other aspects of the process. Fewer recyclable materials that are collected result in shorter or decreased collection routes and a decreased need for labor. Vice versa, increasing recyclable materials poses a capacity issue, which might introduce the need for additional collection trucks and employees. Any fluctuation in participation affects the economics and environmental aspects of the whole process [45].

Public acceptance affects local government decision-making on waste management system selection. During the transition, residents expressed controversial opinions such as going back to the old system without recycling or that the new system will make it easier to deal with trash. Such discussions still exists one year after single-stream recycling system adoption. This indicates that educating residents on two recycling systems is critical to public acceptance [46].

During the system transition, several factors will need to be considered. In transitioning from multi-stream to single-stream, the categorized recycling bins will be replaced with a single recycling bin at residential, business, and industrial areas. Nevertheless, collection schedules, truck routes, and waste managing fees are also key factors involved in making a system transition plan. In transitioning from a single-stream to a multi-stream system, categorized recycling bins and signs shall be created. It is also suggested that educating residents on how to recycle waste before, during, and after the adoption of the system should be set into place to optimize success. Sometimes, certain verifications and fees need to be designed to ensure that residents and industry will respond to the changes.

5. Assessment of Alternative Scenarios

In order to analyze the sustainability impact of recycling rate, energy cost, and recycling cost of metals, sensitivity studies were conducted on some key factors that affect the overall sustainability performance.

5.1. Waste Composition

In the above study, waste components were different due to the natural activities of the city and university systems. Here, in the sensitivity analysis, the same waste composition is assumed to be consistent with residential wastes. The recycling rate is assumed to be 40% for single-stream and 35% for multi-stream. Therefore, in a typical residential area, for every one ton of waste, 0.4 tons were recycled in single-stream recycling and 0.35 tons were recycled in multi-stream recycling. Table 9 shows the sensitivity analysis results of GHG emissions and cost comparison of the two systems.

Table 9. GHG emissions and costs at different recycling rates.

Scenarios		GHG Emission (kg CO_2eq/ton)				Cost (USD/ton)			
System	Recycling Rate	Collection	MRF	End of Life	Life Cycle	Collection	MRF	End of Life	Life Cycle
Single-stream	0.4	10.56	21.33	−318.9	−291.5	10.56	21.33	−46	62.33
Multi-stream	0.35	9.67	20.71	−279.1	−252.8	9.67	20.71	−40	70
Multi-stream	0.4	9.67	20.71	−318.9	−292.63	9.67	20.71	−46	64
Single-stream	0.35	10.56	21.33	−279.1	−251.61	10.56	21.33	−40	68.1
Multi-stream	0.4	9.67	20.71	−318.9	−292.63	9.67	20.71	−46	64
Single-stream	0.4	10.56	21.33	−318.9	−291.5	10.56	21.33	−46	62.33

Table 9 indicates that, given the same waste composition and amount, recycling rate plays a key role in the life cycle of total GHG emissions and life cycle costs during the end-of-life stage. For stages of collection and MRF, recycling rate does not affect GHG emissions or cost of the two stages. For single-stream recycling, given recycling rates of 40% and 35%, end-of-life GHG emissions change from −318.9 kg CO_2eq/ton to −279.1 kg CO_2eq/ton reduction. This proves that waste recycling GHG avoided emissions and that the recycling rate significantly affects the waste life cycle. Collection and MRF processing do not have a significant impact on waste life cycle GHG emissions. Similarly, the life cycle cost is largely affected by the end-of-life value of the recycled materials. For both recycling systems, the recycling rate dropping from 40% to 35% will result in USD 6 reduction of end-of-life cost. The reduction is due to the reduction in collected recycled material from one ton of waste. However, the cost difference from the recycling change is not as significant as GHG emissions changes. This is because, for some materials, end-of-life treatment causes more GHG emissions, but the process itself is not very expensive.

5.2. MRF Process Efficiency

In order to find the impact of MRF process efficiency on GHG emissions and costs, three separate changes were made: (1) increasing single-stream MRF equipment efficiency by 50%, keeping multi-stream recycling MRF efficiency the same; (2) increasing multi-stream MRF equipment efficiency by 50% while keeping single-stream MRF efficiency the same; and (3) increasing both single-stream and multi-stream MRF equipment by 50%. The results are shown in Table 10.

There are two findings from this analysis. First, by increasing equipment efficiency, GHG emissions are reduced from their original emission amount. This is reflected by changes 1, 2, and 3. The GHG emissions were reduced from 16.9 to 9.39 kg CO_2eq/ton for single-stream MRF and from 16.65 to 9.27 kg CO_2eq/ton for multi-stream MRF. This is due to the reduced use of energy (electricity and diesel) to process the same amount of waste. Second, increasing equipment efficiency does not change MRF cost significantly. This is reflected by changes 1, 2, and 3. The single-stream MRF cost decreased from 21.33 to 20.71

USD per ton, and multi-stream MRF cost decreased from 20.71 to 20.10 USD per ton. This is because MRF costs include components such as electricity cost, equipment cost, wire cost, and land and capital cost. The cost details for the original MRF system are shown in Table 11.

Table 10. Sensitivity analysis on MRF process efficiency.

	Cost (USD/ton)				GHG Emission (kg CO_2eq/ton)			
	Baseline	Change 1	Change 2	Change 3	Baseline	Change 1	Change 2	Change 3
Single-stream	21.33	20.71	21.33	20.71	16.9	9.39	16.9	9.39
Multi-stream	20.71	20.71	20.1	20.1	16.65	16.65	9.27	9.27

Table 11. MRF costs for the single stream recycling system and the multi-stream recycling system.

	Electricity (kwh/ton)	Diesel (L/ton)	Wire (kg/ton)	Equipment Cost (USD/ton)	Wire Cost (USD/ton)	Fuel Electricity Cost (USD/ton)	Building and Land Capital Cost (USD/ton/Year)	Total (USD/ton)
Single-stream	18.30	0.7	0.6	5.8	1.3	1.930	12.3	21.33
Multi-stream	18.00	0.7	0.6	5.3	1.2	1.910	12.3	20.71

5.3. Recycling Price

The life cycle costs for the two systems are only 9.6 USD/ton different. From the life cycle perspective, however, single-stream recycling is a net benefit, while multi-stream recycling is a net cost. Therefore, the economic benefit for the waste recycling life cycle is not as much as GHG emissions savings. The waste collection stage contributes to most of recycling cost. Therefore, to reduce the total recycling cost, efforts need to be focused on reducing collecting system efficiency. One important factor that affects life cycle cost is the recycling price. For example, if the paper recycling price changes from 4.75 US cents/lb to 0.955 US cents/lb, the single-stream recycling cost will result in a zero balance of life cycle cost–benefit (Table 12). On the other hand, if the paper recycling price increases to 7 US cents/lb, the multi-stream recycling system will result in a zero balance of life cycle benefit. Similarly, price changes of other recyclables will also affect net life cycle costs.

Table 12. Paper recycling price change impact.

	Baseline (USD/Life Cycle)	Change 1 Paper Cost 0.955 US Cents/lb	Change 2 Paper Cost 7 US Cents/lb
Single-stream	−6.61	0	−10.52
Multi-stream	3	9	0

6. Discussion

The results show that there is no significant cost difference between the two recycling systems. Single-stream recycling collection cost is slightly lower (USD 86.96/ton) than multi-stream recycling collection cost (USD 89/ton) due to the simplicity of the equipment and facility requirement. This difference, however, could be sensitive to the complexity of waste management system at different locations. For example, another study done comparing single- vs. dual-stream recycling systems in Ontario, Canada, showed similar results for the cost of collection per ton (CAD 194.68/ton for single-stream and $200.66/ton for dual-stream). However, their total net cost per ton was much higher for single-stream than multi-stream due to a larger processing cost [6]. In our case, the single-stream MRF cost is slightly higher (USD 21.33/ton) than the multi-stream recycling MRF cost (USD 20.71) due to more processes involved in the waste separation stage. This study also finds that the end-of-life benefit does not have a difference between the two systems as long as they have the same waste composition. In the case study, because the city waste composition has more valuable recyclable components, it presents a higher benefit than multi-stream. The determining factor for recycling benefit, with the same waste composition, is the recycling rate. The result from the recycling rate change is discussed in the sensitivity analysis of this study. An environmental impact assessment was conducted to evaluate GHG emissions during the collection, MRF, and end-of-life stages. The results reveal that GHG emissions for multi-stream recycling are slightly lower (9.67 kg CO_2eq/ton) than single-stream recycling (10.56 kg CO_2eq/ton). For the MRF process, GHG emissions show a similar result for cost assessment: namely, that single-stream is slightly higher (16.9 kg CO_2eq/ton) than multi-stream (16.65 kg CO_2eq/ton) because of the complexity of the MRF process. These results vary from the results found in a different case study by Fitzgerald et al. (2021). Their data were composed of fuel consumption, number of recyclables collected, and emissions from three different counties. They concluded that single-stream offers a great deal of benefits when it comes to GHG emissions. The variation could possibly be explained by the travel distance of the multi-stream recycling system in this case study being relatively shorter than the city's single-stream recycling travel distance. A sensitivity analysis was conducted to study the MRF system efficiency. It shows that due to the multiple components of MRF cost, improving MRF efficiency does not reduce cost as much as GHG emissions reduction. From the life cycle perspective, both systems show a significant GHG savings by recycling wastes. Collection and MRF GHG emissions are significantly lower than end-of-life GHG savings. Finally, a social impact assessment was conducted to discuss recycling participation, public acceptance, and the transition plan during the transition phase of the two systems. It shows that it requires more effort to educate citizens on the benefits and operations of the new system to increase public participation and acceptance. Nevertheless, an operational transition plan needs to be made to systematically conduct this transition.

7. Conclusions

With the current trend of cities moving to single-stream recycling systems, this study aims to understand the economic, environmental, and social impact of this transition and the two systems. A case study was conducted on a small North American college city with a mixed-stream recycling system during the transition. A life cycle cost assessment was carried out to analyze activities involved in waste management states, including waste collection, transportation to MRF, MRF processing, and waste end of life.

This study focused on a small college city with a population around 40,000. Although the result of this study is limited to this scope, it is consistent with Lakhan's on larger cities as described in the literature review section, which shows that single-stream collection cost is lower than multi-stream recycling cost and that MRF processing cost is higher for multi-stream recycling. The life cycle cost in this study, however, is different, showing that both systems have a positive net cost (USD 298.87/ton and USD 232.50/ton) during the recycling life cycle. In this study, the net life cycle costs are close to zero because of the low waste management cost during collection and MRF. There are two possible reasons for this difference. First, larger cities require more complex management systems and higher overhead costs. This proves prior assumptions that MSW collection cost and MRF cost vary with location and size of the city. Second, this study focuses on the technical aspect of the two recycling systems. There are some overhead costs (e.g., MRF human capital) in MRF that are not included. This could be another reason that the MRF cost in this study is lower than Lakhan's study. It is suggested that in order to reduce life cycle GHG emissions and cost, efforts should be focused on increasing the recycling rate at the collection stage so that a higher percentage of the municipal waste can go to the MRF. Practitioners also need to focus on reducing collection cost to make the total life cycle cost more economic. Future research will be extended to produce a more technical cost analysis of management and overhead costs than were given assumption in this study. In addition, this study only examined the two systems in one city and one university. In order to draw concrete conclusions about the comparison, more case studies need be conducted to get bigger sample sizes from the two systems.

The result of this study can assist municipal solid waste management policy and decision-makers with economic, environmental, and social assessment data. Policy makers, especially in small cities and college towns, however, should integrate individual case situations with the results of this study before making strategic decisions because of variations in the systems discussed above.

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