

Sustainable life-cycle assessment of mixing approaches in water storage tanks

Mohammad Alizadeh Fard and Brian D. Barkdoll

ABSTRACT

Poor mixing in water storage tanks can cause stagnant zones that could pose negative public health effects. The present study uses Life Cycle Assessment to decide among the only three mixing options available, namely sprinkler, multiple inlets, and a mechanical mixer for the first time. These options were compared using different life-cycle assessment (LCA) tools using an 80-year lifetime as the functional unit while assuming that all three options result in acceptable water quality. Using SimaPro modeling software as well as the IPCC 2013 GWP 100a V1.0 and Cumulative Energy Demand methods, these three mixing approaches were compared with and without waste recycling. Results showed that application of a sprinkler is the least expensive option. Damage-cost analyses for categories of human health, ecosystem quality, and resources showed that a sprinkler caused the least damage and cost, while a mixer resulted in the most damage and cost.

Key words | cost evaluation, life-cycle assessment, mixing, storage tanks

Mohammad Alizadeh Fard
Brian D. Barkdoll (corresponding author)
Department of Civil and Environmental
Engineering,
Michigan Technological University,
Houghton, MI 49931,
USA
E-mail: barkdoll@mtu.edu

HIGHLIGHTS

- LCA proved effective in analyzing tank mixing technologies.
- Sprinklers caused the least environmental damage and cost.
- Mechanical mixers resulted in the most damage and cost.
- Multiple inlet mixing had high damage but medium cost.

INTRODUCTION

Microbial contamination of drinking water supplies can lead to waterborne diseases worldwide (Alizadeh Fard *et al.* 2013; Aghdam *et al.* 2015; Alizadeh Fard & Barkdoll 2018). The World Health Organization (WHO) emphasizes that water for human consumption should be free of microbial agents that are pathogenic (Filion *et al.* 2004). In a water distribution network, the water storage tank can be a source of microbial contamination (Grayman *et al.* 1996). When storage facilities are kept full and water is underused, stored water ages and water quality is decreased

(Grayman *et al.* 2004). This can end in losing disinfectant agents which in turn leads to bacterial growth in the tank (Kennedy *et al.* 1993). To keep the quality of water acceptable, the concentration of the residual disinfectant needs to be in a suitable range (AWWA 1986). Long detention time has been considered as one of the main reasons for decreased residual disinfectant and increased microbial contamination (Mau *et al.* 1996; Zhang *et al.* 2014).

Increased water temperature can also exacerbate the problem (Alizadeh Fard & Barkdoll 2018). Many studies have shown that significant microbial growth can happen in water of 15 °C or higher (LeChevallier *et al.* 1996; Kirmeyer *et al.* 1999). LeChevallier *et al.* (1996) found that coliform bacteria occurred more frequently when water

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temperature was increased from 5 °C to >20 °C. Higher microbial growth in storage tanks can also be observed because of tank design as the tanks are usually over-sized to accommodate emergency supplies, resulting in stagnant, microbe-present water that may only be used in infrequent emergency situations. This stagnation may also allow for sediment accumulation that can work as a growth medium for bacteria (Boulos *et al.* 1996; Clark *et al.* 1996; Edwards & Maher 2008).

There are three existing water mixing technologies, namely mechanical mixers, multiple-inlet mixers, and an internal-pipe sprinkler system. Related studies have shown that lack of sufficient mixing can cause the aforementioned problems leading to bacteria growth. For example, Alizadeh Fard and Barkdoll (Alizadeh Fard & Barkdoll 2018) studied the feasibility of an internal piping configuration consisting of a sprinkler-type inlet that distributes the incoming flow evenly across the water surface and a corresponding upside-down sprinkler drain at the tank bottom (Alizadeh Fard & Barkdoll 2018). They conducted experiments on seven types of inlet and outlet configurations. Their results indicated that the novel sprinkler system resulted in parallel downward streamlines that removed most of the stagnation zones in the tank. Another example of a proposed mixing system is using a multiple-inlet system, consisting of an internal pipe with multiple outlets into the tank (Beatrix 2016). Such a system can provide enough mixing with a properly designed passive mixing system, which has often 10 percent volume turnover or less. In this system, mixing in the tank occurs during the fill cycles, occurring from momentum of flow being injected into the tank water. The velocity difference between the inlet jet and tank water creates turbulence, which develops circulation patterns throughout the tank. Another effort to increase the level of mixing is using a mechanical mixer, consisting of a mixing arm being rotated by an electric motor (Fisk 2014). Using a mixer can significantly improve the degree of mixing in storage tanks. The mixer is an active, submersible mixing system for acceptable drinking water quality in storage tanks and reservoirs. The mixer can rapidly eliminate stratification, uniformly distribute disinfectants and prevent water quality deterioration. Efficient and effective mixing of large volumes is made possible by the mixer, which establishes a stable flow structure throughout the storage volume.

Design of tanks for particulate contaminant behavior can also have an effect (Won *et al.* 2019). Tank mixing has been studied experimentally (Alizadeh Fard & Barkdoll 2018) as well as numerically (Huang *et al.* 2020).

Life Cycle Assessment (LCA) and Life Cycle Costs (LCC) are powerful tools to decide between project options and have been used as decision-making tools in the context of water supply. For example, Lundie *et al.* (2004), performed LCA to examine the potential environmental impacts of Sydney Water's total operations in the year 2021. They provided base case results for the comparison of alternative future scenarios and for decisions to be made regarding potential environmental enhancements. LCA can also be used for asset management (Alegre *et al.* 2016).

In another case, Vince *et al.* (2008) developed an impact assessment tool using LCA for the environmental evaluation of drinking water production. LCA allowed for quick and easy assessment of both energy and environmental performances to determine the weak points of drinking water production. According to their results, the main source of impacts is electricity consumption for plant operation (Vince *et al.* 2008). In addition, De Gussem *et al.* (2011) found that LCA can be used for cost optimization of environmental impact for waste water treatment plants.

Since no studies of the environmental impacts of mixing approaches have been performed, this paper describes life-cycle environmental and cost assessments that were performed for the aforementioned mixing approaches to enhance the level of mixing in storage tanks. The goal of this study is, for the first time, to inform the decision-makers about different aspects of these three studied systems to aid in selection of a mixing system that includes not only initial costs, but also ongoing costs and environmental impact. Thus, the analysis and the life-cycle assessments are broadly applicable to municipal authorities and water utilities.

PROCEDURE

The main goal of this analysis is to evaluate and compare the environmental impacts of three approaches to minimize stagnation in water storage tanks. A functional unit with an operational life span of 80 years was used in this LCA analysis. Eighty years is a typical design life for these types

of systems (Maupin *et al.* 2014). This is justified, since the current analysis assumes all mixing options provide the conditions necessary to achieve the same level of mixing in the tank. A tank size of 5,725 m³ (27 diameter × 10 m height) was used for all devices to ensure comparability. The effect of the mixer materials of plastic, steel, and rubber on the water quality are not considered here since these materials are commonly used with water and, therefore, are not considered dangerous to water quality. The cost and environmental impact of the manufacturing of the

materials is, however, considered thereby necessitating an LCA approach. This study investigates the environmental impacts of the three technologies related to overall energy consumption, greenhouse gas emissions, human health, ecosystem quality, and resources. This study also compares their life-cycle assessment results to identify the most sustainable mixing approach for water tanks suffering from stagnation. The system boundary is defined as extending from raw materials' acquisition to the manufacturing and usage of the final product (Figure 1).

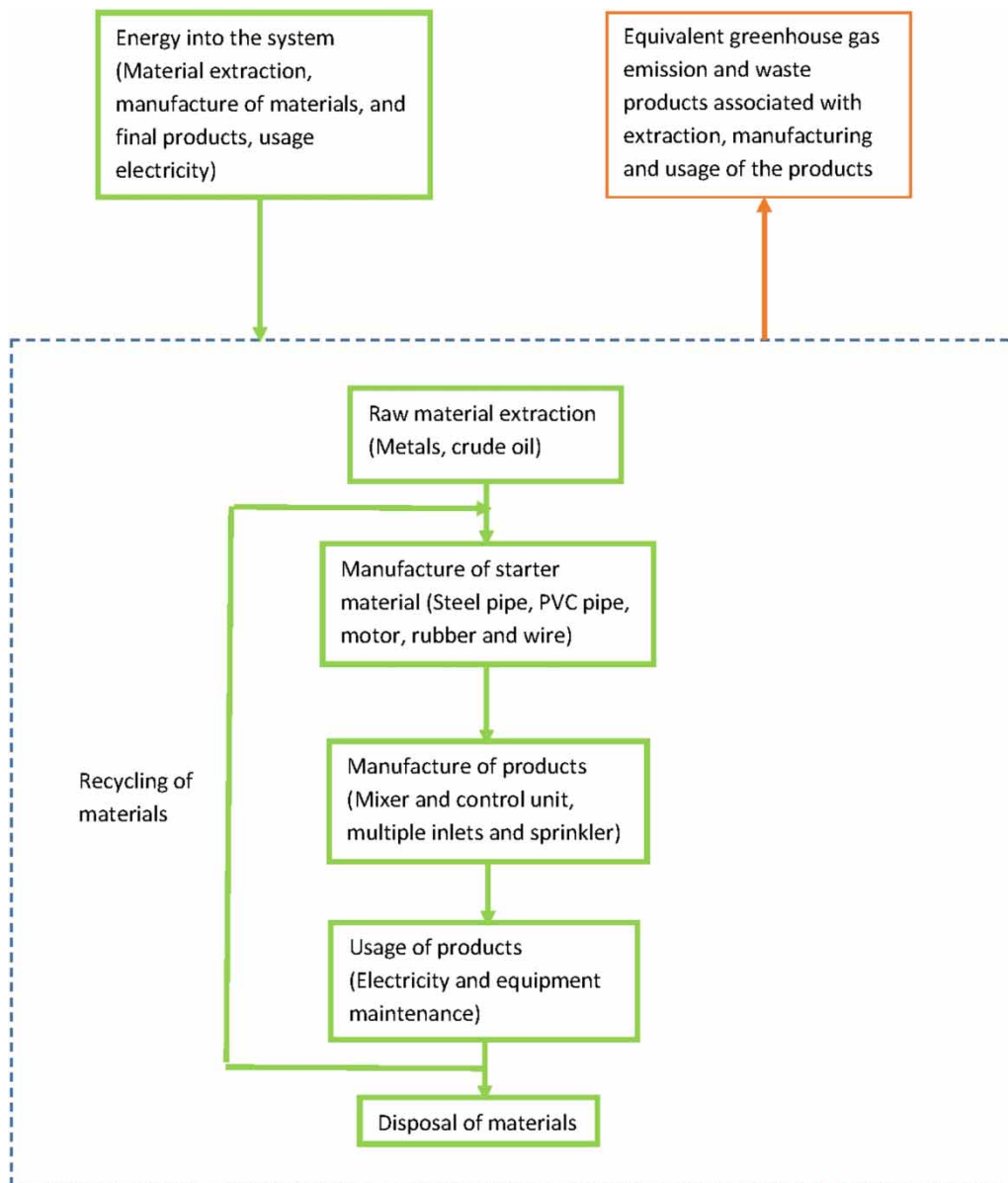


Figure 1 | General life-cycle diagram for mixing approaches studied in this study.

Figure 2 shows the methodology of this study. Phase one includes energy inputs and materials used. This phase was used as inventory for LCA and LCC. Phase two assesses the impacts of the process/system/activity on human health, ecosystem, and resources. In this stage, the Cumulative Energy Demand method was utilized to evaluate the environmental effects based on the energy consumption in different materials/stages. The forms of energy considered here are renewables (hydropower and wind), fossil fuels (natural gas and coal), and the US energy grid mix. In the third stage, a sensitivity analysis was performed to identify the critical role of the energy source.

Environmental life-cycle assessment

All major life-cycle stages are considered for each mixing option, including the production of construction materials, equipment, and operation and maintenance. The specific construction processes considered for the existing tank are preparing the site, and disinfecting the tank before use. Steel and PVC pipes from the old mixing systems would be sent to the recycler. The operation and maintenance stage consists of draining and disinfecting the tank and the replacement of equipment. Energy consumption by the municipal pumping station was omitted from the analysis because there were no differences between the options.

Comparative life-cycle assessments rely on a measure of the function of the studied system and provides a reference on which the inputs and outputs can be related. This study uses a functional unit that assumed 80 years of operating time for all three options and equipment replacement was calculated based on this period. Each mixing system was considered for a tank with a volume of 5,725 m³ (27 m diameter × 10 m height) and it is assumed that all systems can provide the highest-quality of finished drinking water. In other words, all material inputs and emissions are normalized based on the capacity of the highest-quality water each approach can provide. As there is no technical (water quality) comparison between these options in the literature, this study assumes that all these mixing options are able to provide the same degree of mixing in the studied tank. In addition, as access to clean energy is not possible everywhere, a US mixed energy grid was assumed for energy source and the results were presented based on this assumption in the previous sections.

Input data

Mixer system

Product manufacturing: This system consists of two major parts, a mixer which is installed in the tank and a control

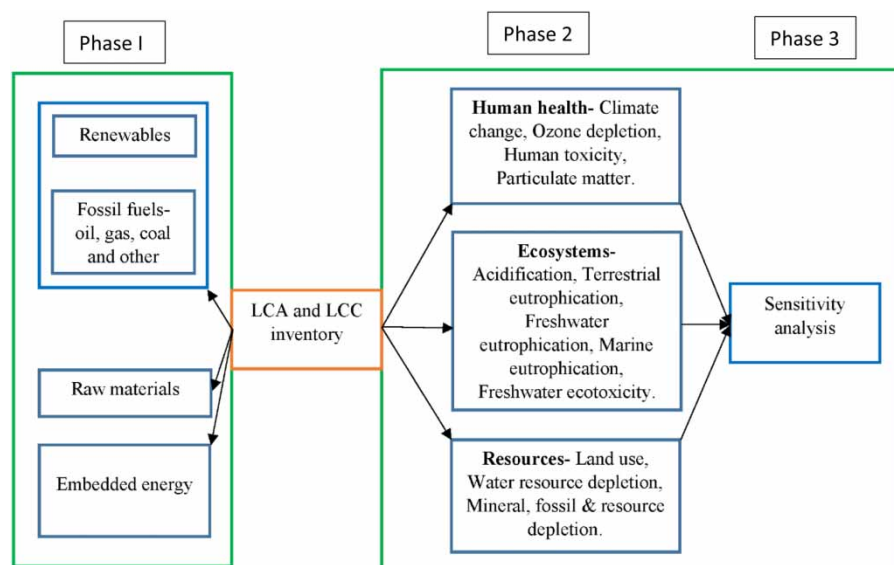


Figure 2 | Methodology of LCA and LCC of this research.

system connected to the mixer from outside the tank. For the mixer case, stainless steel and rubber are the main materials and for the case of the control unit, stainless steel and wire (including copper and plastic) were included.

Product usage: Product usage refers to all materials and resources being used in the operating time of the product. For this case, electricity consumption and equipment replacement (for maintenance) were considered as the main parameters. The mixer's motor replacement was included every five years for the 20 year lifetime.

Waste materials and waste scenarios: For this system, the main source of waste was from stainless steel and copper, and rubber. Two waste scenarios were considered. In the first one, all materials were considered recyclable and in the second one nothing was recycled. A summary of the materials used for mixer system is tabulated in [Table 1](#).

Multiple inlet system

Product manufacturing: This system consists of two main parts: first, the main steel pipe, which is transporting inflow inside the tank; second, the rubber inlets, which provide turbulent flows at multiple locations.

Product usage: It is estimated that rubber inlets need to be replaced with new ones after 10 years of service. As this system is not a mechanical system, it does not consume energy.

Table 1 | Initial LCA parameters defined for the mixer ([Fisk 2014](#))

Manufacturing		
Mixer	Stainless steel	19 kg
	Rubber	5 kg
Control unit	Stainless steel	13.4 kg
	Copper	15 kg
	Plastic	4 kg
Usage		
Mixer	Stainless steel	21 kg
	Electricity	67,452 kWh
Waste		
Stainless steel	53.4 kg	68.99%
Rubber	9 kg	11.63%
Copper	15 kg	19.38%

Waste materials and waste scenarios: The main source of waste considered is from stainless steel and rubber inlets. Two waste scenarios were considered, both recyclable and non-recyclable. In the first one, all materials were considered recyclable and in the second one non-recyclable. Summary of used materials for multiple-inlet system is described in [Table 2](#).

Sprinkler system

Product manufacturing: In this system, the main inlet riser steel pipe transports water from outside of the tank to the top sprinkler distribution system; then, the PVC sprinkler systems work as a distribution system.

Product usage: Replacement of PVC pipes every 10 years was included, but the riser pipe was not replaced. No electricity was included due to the passive nature of the sprinkler system.

Waste materials and waste scenarios: In this system, the main source of waste comes from PVC pipes and the steel riser pipe. Two waste scenarios were considered: all materials recycled and nothing recycled. The summary of the used materials for the sprinkler system is described in [Table 3](#).

Impact assessments

SimaPro modeling software was used for the impact assessment. IPCC 2013 GWP 100a V1.0, Cumulative Energy Demand (CED), and Eco-indicator 99 were used to study all mixing approaches. The first two methods were chosen

Table 2 | Initial LCA parameters defined for the multiple inlet system ([Krugger 2012](#); [Beatrix 2016](#))

Manufacturing		
Main pipe	Stainless steel	3,665 kg
Inlet	Rubber	15 kg
Usage		
Inlet	Rubber	15 kg
Waste		
Stainless steel	3,665 kg	99.12%
Rubber	30 kg	0.81%

Table 3 | Initial LCA parameters defined for the sprinkler system (Alizadeh Fard & Barkdoll 2018)

Manufacturing		
Riser pipe	Stainless steel	1,221.7 kg
Sprinkler	PVC pipe	1,617 kg
Usage		
Sprinkler	PVC pipe	200 kg
Waste		
Stainless steel	1,221.7 kg	40.2%
PVC pipe	1,817 kg	59.8%

since they are the common types of comparable sustainable measurements that relate not only actual materials used but the processes used to produce the final product, whether injection molding, extrusion, or metal working. The IPCC 2013 GWP 100a V1.0 method accounts for the total equivalent greenhouse gas emission in kilograms of carbon dioxide equivalent and uses a 100-year global warming potential definition. On the other hand, the CED method can quantify energy consumption. There is a clear correlation between these two methods, since energy consumption and greenhouse emissions are proportional. For the third model, Eco-indicator 99, the damage to health, ecosystem quality, and resources were compared.

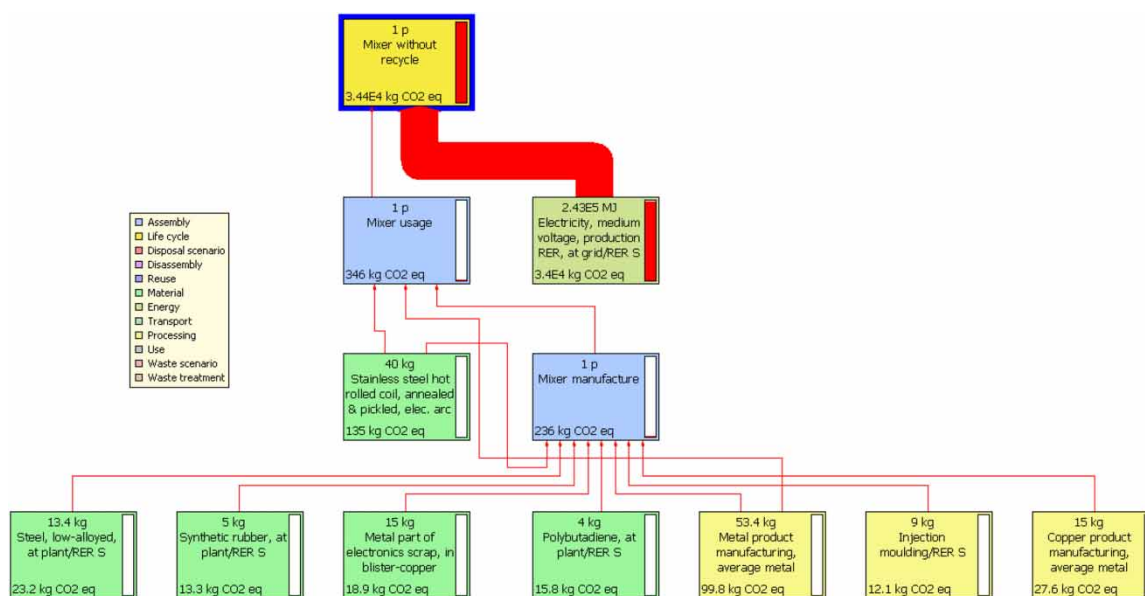
All mixing approaches are studied in the case of the damage they pose to three categories. These categories are human health, ecosystem quality and resources.

Two waste scenario models were created for each product: in one scenario, no materials were recycled and in the other one scenario materials were recycled. It is important to model both scenarios to see the effects of the ideal and worst-case scenarios. It should be noted that recycling all materials would not be possible in some areas as recycling facilities may not be available.

RESULTS AND DISCUSSION

Environmental LCA

Material Flow Sheets using the IPCC 2013 GWP 100a V1.0 method are documented in Figures 3–5. Results for cases without recycling showed similar results. According to the results, electricity consumption had the highest impact in greenhouse gas emission for the mixer case. However, materials and manufacturing processes are the main sources of greenhouse gas emissions for both the multiple inlets and sprinkler options. The CED method assessments are documented in Figures S1–S6 (Supplementary materials). The

**Figure 3** | Material flow sheet for tank mixing – mixer with no recycle. The thick line shows the highest impact is from electricity consumption.

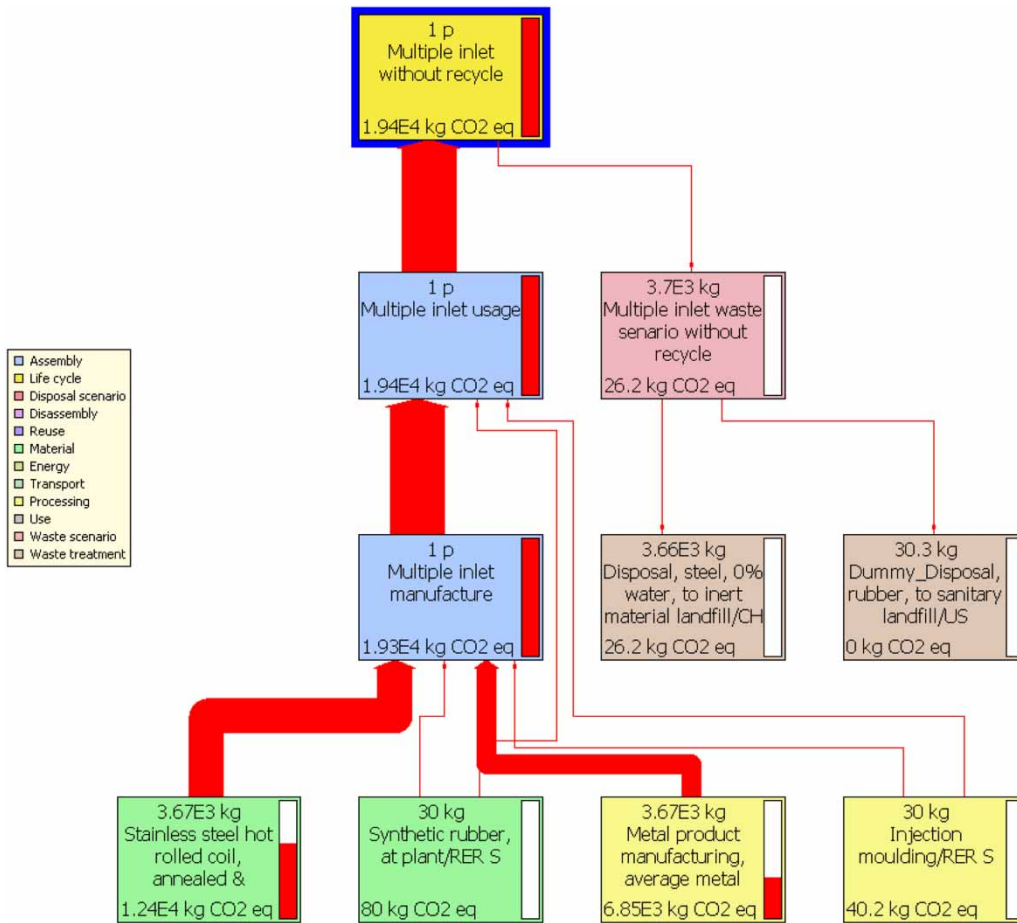


Figure 4 | Material flow sheet for tank mixing – multiple inlet system with no recycling. The thick line shows the highest impact is from raw materials.

overall energy consumption and greenhouse gas emissions measured by the methods are summarized in Table 4.

As can be seen in Table 4, the mixer option has the highest total energy consumption at 4.2E5 MJ and this value is the same for the cases whether materials are being recycled or not. In accordance with these results, it was revealed that the mixer option emits the highest amount of greenhouse gases, contributing to 3.44E4 kg CO₂ equivalent during manufacturing and use. This value was the same for both waste scenarios. The sprinkler option showed the least amount of carbon dioxide emission among all three options. Results indicated that both energy consumption and carbon dioxide emissions decreased when the materials were recycled for the sprinkler option.

In another study, human health, ecosystem quality, and resource damages were modeled for all three options. Figures 6 and 7 show the results of this method for the

waste scenario with material recycle and waste scenario without material recycle, respectively.

It can be seen from these results that the mixer had the highest impact on human health and the sprinkler had the lowest. Further studies revealed that in the mixer option, a considerable amount of carcinogens are released, thereby increasing the impact significantly. Both mixer and multiple inlets had almost the same impact on ecosystem quality. Finally, resource damage results showed that the mixer had the lowest impact and multiple inlets had the highest.

A sensitivity analysis (Table 5) describes the relative impacts of LCA for the studied mixing approaches. Among the 13 major impact categories listed here, climate change has the most significant impact. The second-most impactful category is freshwater ecotoxicity. Thirdly, terrestrial eutrophication impact is higher than the other impact categories.

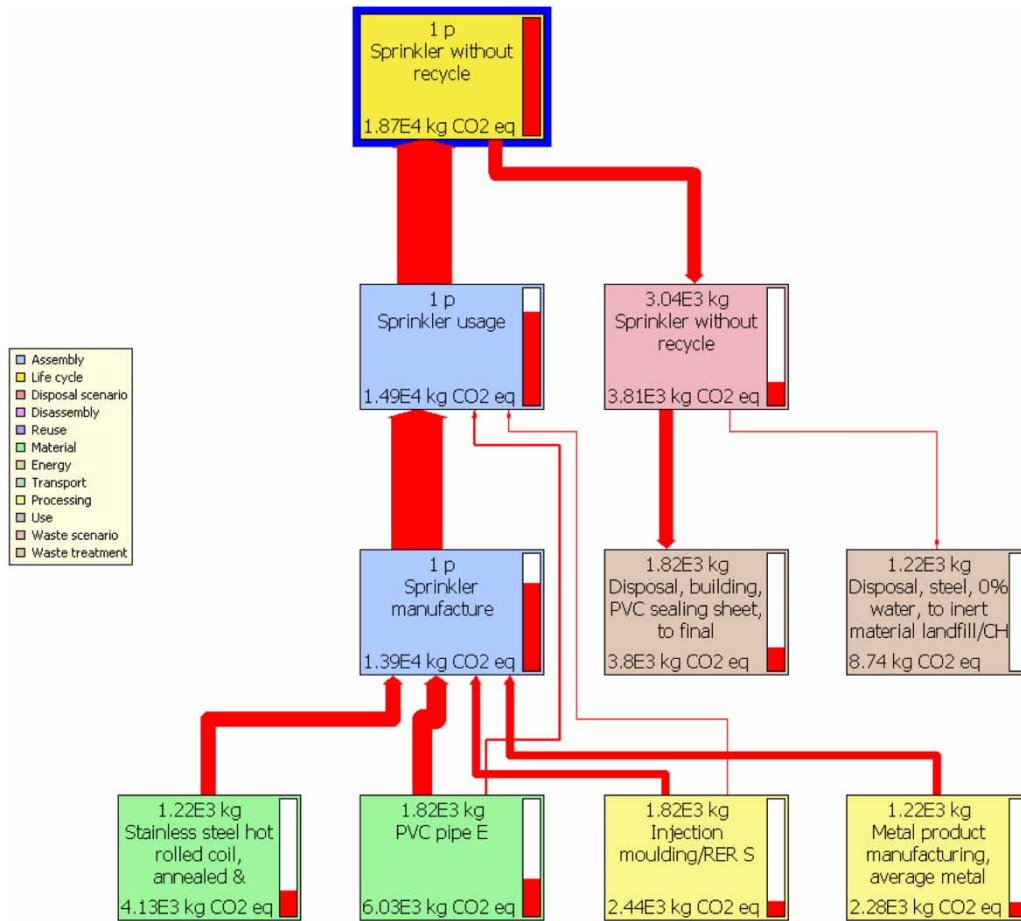


Figure 5 | Material flow sheet for tank mixing – multiple inlet system with no recycling. The thick line shows the highest impact is from raw materials.

Table 4 | Total green house gas (GHG) emissions and energy usage values obtained from method analysis

Waste scenario	Mixer total energy use (MJ)	Total GHG emissions (kg CO ₂ equivalent)	Multiple-inlets total energy use (MJ)	Total GHG emissions (kg CO ₂ equivalent)	Sprinkler total energy use (MJ)	Total GHG emissions (kg CO ₂ equivalent)
Recycling all materials	4.2E5	3.44E4	1.89E5	1.94E4	2.06E5	1.49E4
Without recycling	4.2E5	3.44E4	1.89E5	1.94E4	2.14E5	1.87E4

Cost analysis

Alongside the preceding technical analysis, it is important to estimate the life-cycle cost for each product. Table 6 provides the associated cost for each approach (Pax Water Technologies 2020; Red Valve 2020).

The mixer's manufacturing cost is the highest of all three systems. This high cost emanates from the fact that the mixer's motor, stainless steel equipment, and control unit are expensive. The operating cost of the mixer is also the

highest one, as the motor needs to be changed every five years. In addition, the electricity cost of the mixer adds to the motor cost and makes the mixer the most expensive option considered.

Damage-cost analysis

It is important to compare all options from both cost and life-cycle assessment points of view. Competitive maps are useful tools for decision making. These maps have two

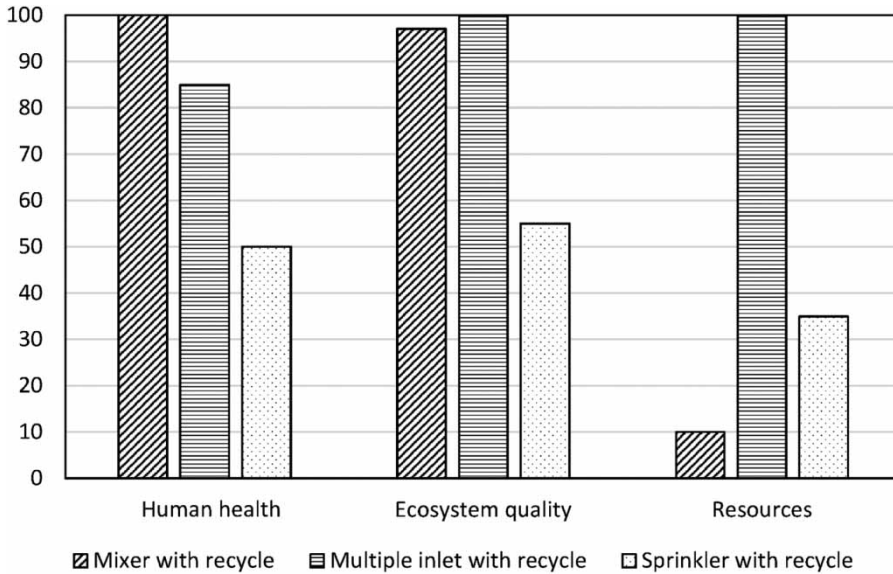


Figure 6 | Eco-indicator 99 analysis results with material recycle. (The scale shows a relative environmental impact factor. An impact factor value of 100 is assigned to the highest impact option and the other values are relative to that.)

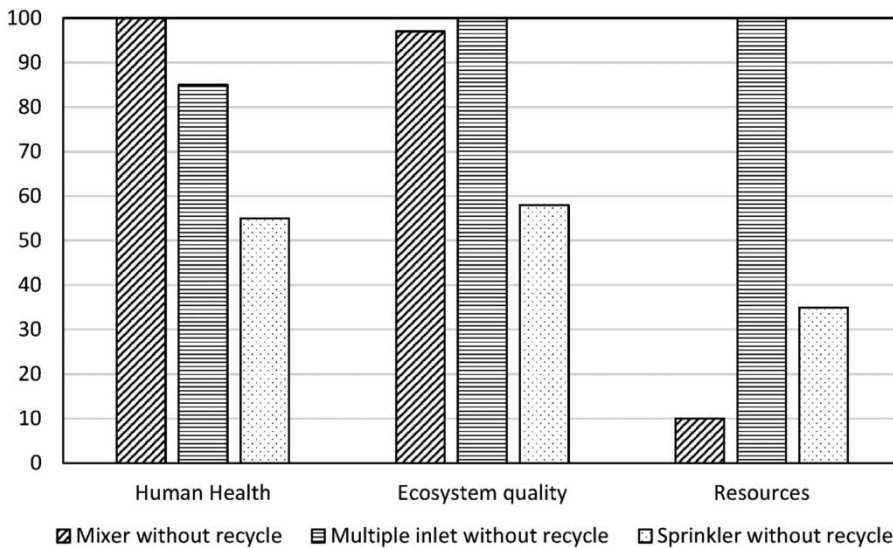


Figure 7 | Eco-indicator 99 analysis results without material recycle. (The scale shows a relative environmental impact factor. An impact factor value of 100 is assigned to the highest impact option and the other values are relative to that.)

axes, one is for cost and the other one is for a qualitative factor. In this analysis method, the higher the value of cost or the qualitative factor, the less favorable is the process or product. In fact, each option has a coordinate on the map and the closer the coordinate to the origin the better the option is. It means this option has the minimum

damage and cost in comparison to other options. Table 7 and Figures 8–10 show competitive maps for health damage-cost, ecosystem quality-cost, and resource-cost, respectively.

According to the results, the sprinkler system is the best option based on all three analyses and the mixer option was

Table 5 | The relative life-cycle impact analysis results for the studied mixing approaches

Parameter	Unit	Mixing approach		
		Mixer	Multiple inlets	Sprinkler
Climate change	kg CO ₂ eq	32.12	22.24	21.27
Ozone depletion	kg CFC-11 eq	4.3E-06	2.84E-06	2.33E-06
Human toxicity, non-cancer effects	CTUh	5.06E-06	3.92E-06	3.61E-06
Human toxicity, cancer effects	CTUh	2.60E-08	2.03E-08	1.83E-08
Particulate matter	kg PM _{2.5} eq	0.042	0.028	0.029
Acidification	molc Hp eq	0.601	0.349	0.314
Terrestrial eutrophication	molc N eq	3.19	2.27	2.09
Freshwater eutrophication	kg P eq	8.69E-06	6.45 E-06	6.14 E-06
Marine eutrophication	kg N eq	0.32	0.21	0.19
Freshwater ecotoxicity	CTUe	19.51	10.89	9.41
Land use	kg C deficit	2.89	1.25	0.42
Water resource depletion	m ³ water eq	0.009	0.031	0.012
Mineral, fossil & resource depletion	kg Sb eq	0.87E-13	1.49E-13	0.73E-13

Table 6 | Life-cycle costs including manufacturing and usage, for all mixing approaches

System	Manufacturing cost (\$)	Usage cost (\$)	Total cost (\$)
Mixer	16,094	8,000	24,094
Multiple inlets	10,275	150	10,425
Sprinkler	2,125	123	2,248

Table 7 | Relative ratios for all mixers (ratio = value divided by maximum value for any of the mixers).

System	Relative cost ratio	Relative human health damage ratio	Relative ecosystem quality damage ratio	Relative resource damage ratio
Mixer	1.00	1.00	0.95	0.10
Multiple inlets	0.43	0.85	1.00	1.00
Sprinkler	0.09	0.50	0.55	0.35

the worst case in cost vs. ecosystem quality damage and cost vs. human health damage analyses.

Discussion regarding the source of energy

Chart Modeling for Eco-indicator 99 method assessments are documented in Figures S7–S10 (Supplementary

materials). There is no material recycle considered for the waste scenario. Four resources for electricity were considered. According to the results, when a clean source of energy (like wind or hydropower) is considered, the mixer option has the minimum damage to all three categories. Since electricity generation does not pose significant damage to the three categories for the case of clean energies, material usage is the main factor to be considered for life-cycle assessment. On the other hand, when fossil fuels (coal or natural gas) were considered as the main source of energy, the sprinkler option had the minimum damage for most of the categories. Therefore, the source of electricity can significantly change the results.

Sensitivity analysis

To lessen the uncertainty in the electricity source, a sensitivity analysis of three different scenarios was performed. The three sources were as follows:

Scenario 1- Energy demand was only supplied from US mixed energy grid.

Scenario 2- Energy demand was only supplied from hydropower.

Scenario 3- Energy demand was supplied equally from a US mixed energy grid and hydropower.

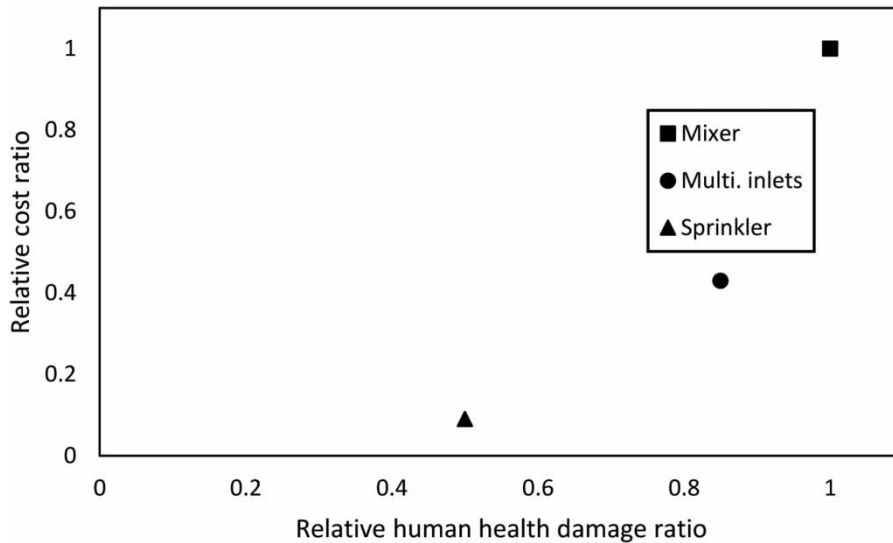


Figure 8 | Human health damage vs. cost graph for all three options.

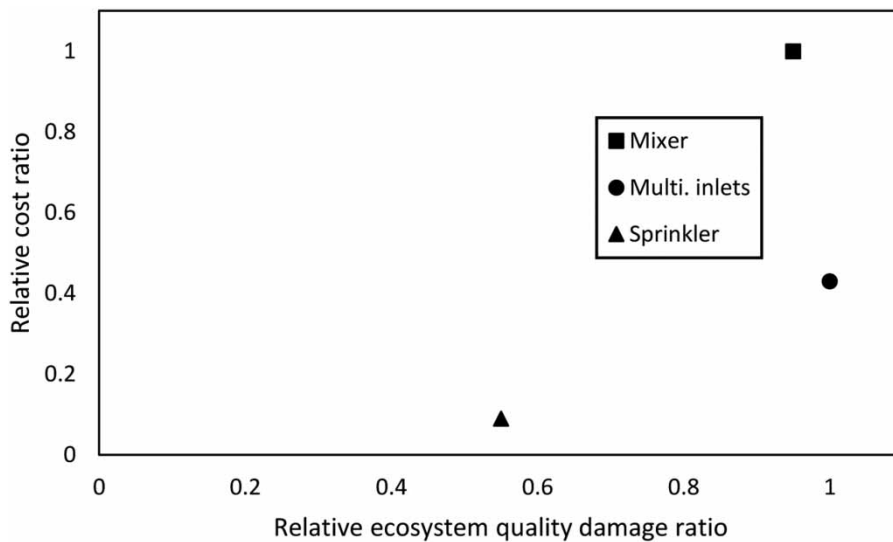


Figure 9 | Ecosystem damage vs. cost graph for all three options.

According to the results from Table 8, for a US grid energy mix (Scenario 1), the mixer has the highest impact in all categories except land use, water resource depletion, and mineral, fossil and resource depletion and this is due to the fact that the mixer needs the lowest amount of resources to manufacture and use. On the other hand, when the energy source changes from the US energy grid mix to hydropower (Scenario 2), then the multiple-inlet

option becomes the worst option and the mixer the best in all categories. For the last scenario in which the energy source is an equal combination of hydropower and the US energy grid mix (Scenario 3), the multiple-inlet option has the highest impact in all categories while the sprinkler has the lowest impact in climate change, ozone depletion, acidification, terrestrial eutrophication, marine eutrophication, and freshwater ecotoxicity.

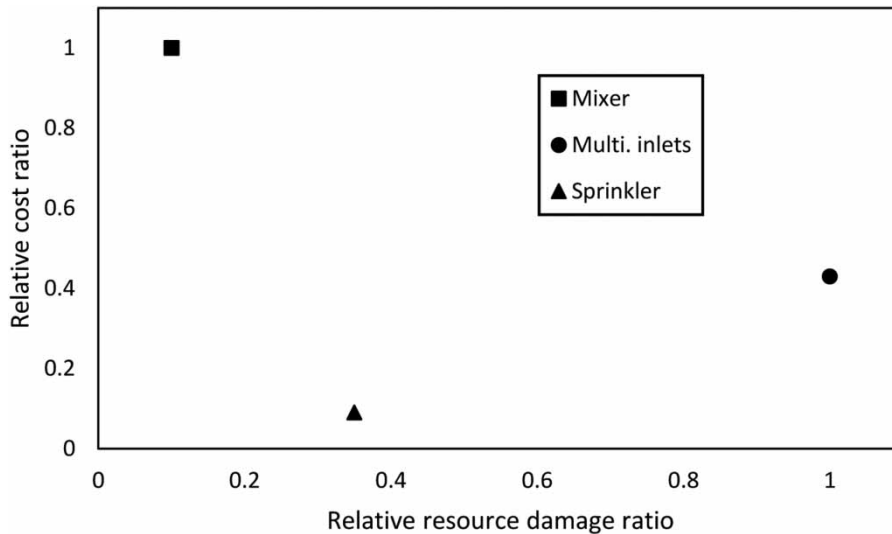


Figure 10 | Resource vs. cost graph for all three options.

Table 8 | Sensitivity analysis results for mixing options based on three different energy

Parameter	Scenario 1			Scenario 2			Scenario 3		
	Mixer	Multi. inlets	Sprinkler	Mixer	Multi. inlets	Sprinkler	Mixer	Multi. inlets	Sprinkler
Climate change	100	69.23	66.23	21.34	100	56.21	68.24	100	60.12
Ozone depletion	100	66.14	54.21	25.29	100	50.54	58.36	100	51.23
Human toxicity, non-cancer effects	100	77.48	71.26	19.91	100	78.56	48.24	100	75.21
Human toxicity, cancer effects	100	78.12	70.52	18.41	100	82.4	46.27	100	75.23
Particulate matter	100	67.14	69.23	20.01	100	56.21	61.35	100	61.38
Acidification	100	58.19	52.18	24.33	100	52.35	66.28	100	52.22
Terrestrial eutrophication	100	71.25	65.46	23.67	100	54.23	71.25	100	61.45
Freshwater eutrophication	100	74.21	70.66	14.19	100	61.59	59.12	100	64.28
Marine eutrophication	100	67.12	60.42	18.55	100	54.38	62.58	100	56.92
Freshwater ecotoxicity	100	55.80	48.26	9.52	100	41.25	51.69	100	45.74
Land use	23.05	100	34.29	10.09	100	29.45	17.36	100	33.55
Water resource depletion	27.43	100	38.39	16.73	100	37.15	20.23	100	37.65
Mineral, fossil & resource depletion	58.15	100	49.16	8.48	100	29.45	32.39	100	38.59

The scale shows a relative environmental impact factor. An impact factor value of 100 is assigned to the highest impact option and the other values are relative to that.

CONCLUSIONS

When comparing a mixer with multiple inlets and sprinkler systems, the mixer consumes more energy, thereby significantly emitting more greenhouse gases. According to the results, the mixer system can emit 34,351 kg CO₂ to the

environment while the multiple inlets and sprinkler systems emit 19,359 and 18,689 kg CO₂, respectively. On the other hand, the sprinkler system had the highest amount of waste production. Damage-cost analysis showed that the sprinkler is the best option considering minimum cost and minimum damage that it poses to the environment.

RECOMMENDATIONS FOR FUTURE IMPROVEMENT

In the current study, the same degree of mixing was assumed for all options. However, further analysis is necessary to compare these options when they have different mixing efficiencies. Such an analysis can be done by EPANET software. In addition, by modeling the water distribution network in EPANET software, other important health factors (like chlorine concentration) in the network can be calculated. Therefore, we can perform a broad analysis not only with the available indicators in Simapro software, but also with other health indicators. As a result, a comprehensive analysis could be performed comparing these options to enable making a conclusion about the feasibility of each one.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories in Alizedah Fard (2018) found at <https://digitalcommons.mtu.edu/etdr/706/>.

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