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Environmental and Financial Analysis: Single-Use Plastic versus Reusable Recycling Bags

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by

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ENVIRONMENTAL AND FINANCIAL ANALYSIS:
SINGLE-USE PLASTIC VERSUS REUSABLE RECYCLING BAGS

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The Bren School of Environmental Science & Management produces professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principle of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions. The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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I. Introduction

An important factor of many companies' environmental strategy is an effective campus recycling program. Poor recycling practices can result in a company's recyclables ending up in landfills; therefore, companies must dispose of recyclable waste in an effective manner to lessen negative environmental impacts and achieve corporate sustainability goals. Environmental consulting firms, such as WSP's Sustainability, Energy & Climate Change division, provide strategic advice to help clients across all industries and economic sectors achieve sustainability goals[1]. WSP works to develop comprehensive and sustainable environmental solutions, including innovative waste management strategies to bolster their clients' zero-waste initiatives and reduce environmental impacts (S. Katz, personal communication, June 2, 2021).

For WSP and its clients, a challenge to effective recycling is contamination caused by single-use plastic garbage bags (SUPGBs) used to line recycling receptacles (bins)[2]. While WSP has looked into alternatives to SUPGBs, there is a lack of environmental and financial information available to make an informed decision. Currently, WSP is helping Company X[3] achieve their goal of zero-waste; however, a barrier to reaching this goal are SUPGBs used to line recycling receptacles on Company X's corporate campus. SUPGBs are not recyclable in Company X's recycling program, and disposing of SUPGBs in recycling bins can result in contamination charges due to the bags jamming recycling equipment and decreasing the value of recycled products (Albeck-Ripka, 2018). Therefore, SUPGBs and, sometimes, recyclables are disposed of in the trash, contributing to Company X's landfilled waste. WSP recognizes, for Company X to reach their zero-waste goal, it is critical for them to eliminate SUPBGs from their landfill waste stream.

With consultation from WSP, Company X is currently searching for an alternative solution to SUPGBs to meet these goals. WSP is considering a reusable recycling bag (RRB)—distributed by Zorch International and produced by Factory Direct Promos—as a replacement for SUPGBs used to line recycling receptacles and as a potential solution to reduce recycling contamination and plastic waste generation. Before considering implementing RRBs as an alternative to SUPGBs, WSP and Company X need to understand the financial viability of an RRB system and have a detailed cost comparison between use of each bag option at Company X's corporate campus. Additionally, for WSP to effectively advise Company X to reduce their environmental impact and meet zero-waste goals, WSP needs to understand the environmental tradeoffs between SUPGBs and RRBs. However, WSP does not currently have detailed information on the environmental and financial tradeoffs of switching from SUPGBs to RRBs at Company X's corporate campus.

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[1] WSP's Sustainability, Energy & Climate Change division is the client for this project.

[2] We will refer to containers that hold recyclables as receptacles and bins, interchangeably.

[3] WSP's client cannot be disclosed at this time and will be referred to throughout this report as 'Company X' for confidentiality purposes.

Furthermore, the RRB has not been previously instituted at a corporate campus or a comparable institution; therefore, WSP also lacks information on how the janitorial process will be impacted by the use of RRBs.

To help WSP and Company X properly evaluate the RRB, our project assessed the environmental and financial tradeoffs between SUPGBs and RRBs used to line recycling receptacles on Company X's corporate campus. We conducted a Life-Cycle Assessment (LCA) to assess the environmental impact of RRBs in comparison to SUPGBs and created a financial model to analyze and compare the costs of implementing each bag type. We also organized a field test piloting the RRB on UCSB's campus to assess the bag's durability, the janitorial staff's experience, and the on-site operations and logistics needed to effectively implement RRBs. This information is essential for WSP to effectively communicate the environmental and financial tradeoffs and janitorial feasibility of switching from SUPGBs to RRBs and ultimately make an informed recommendation to Company X. WSP can use the results of the LCA and financial analysis to incentivize Company X and other clients to choose the bag option that best reduces the environmental damages and financial impact of their recycling program. To help WSP communicate the results of this project with other clients, we created a conference style presentation to synthesize key environmental and financial tradeoffs between the bags. Additionally, we developed a web accessible, user-friendly financial savings and environmental impact calculator to help businesses assess the tradeoffs of using SUPGBs versus RRBs.

II. Objectives

The objectives of this project all contributed to evaluating a RRB as an alternative to a SUBGB to line recycling receptacles on Company X's corporate campus. This project intended to assess the financial and environmental tradeoffs between SUPGBs and RRBs and how the janitorial process is impacted by RRB implementation to identify the recycling bag option most viable for Company X's corporate campus. Further, this project aimed to make the results communicable to WSP's broader corporate client base. Our project objectives are as follows:

1. Field-test the RRB to help WSP understand the feasibility of implementing RRBs in place of SUPGBs to line recycling receptacles in commercial campus recycling programs.
2. Conduct a Life-Cycle Assessment (LCA) to identify the bag option—SUPBGs or RRBs—with the lowest environmental impact.
3. Create a financial model to identify the monthly, annual, and multi-year costs of lining recycling receptacles with SUPGBs versus RRBs.

4. Develop a Shiny App Impact Calculator using the results of the financial analysis and LCA to allow WSP's clients to compare the financial cost and environmental impact of SUPGBs and RRBs.

III. Background & Significance

The Problem with Plastic

All plastic eventually becomes waste that is reprocessed or recycled, thermally destroyed, or disposed of in open dumps, landfills, or the natural environment (Geyer, 2020). As plastic production—specifically single-use plastics—has grown, the amount of plastic waste disposed of in landfills has increased, while the amount of plastic recycled has remained relatively small. More than 8.3 billion metric tons of plastic are estimated to have been produced between 1950 and 2017, with only nine percent of this plastic recycled (Geyer, 2020). The lack of plastic recycling has contributed to intensive landfill accumulation and ecosystem degradation due to emissions from plastic waste incineration, plastic pollution entering the oceans, and increased land-use for landfills. In 2018, the U.S. generated around 35,680 million tons of plastic waste, with 26,970 million tons sent to landfills, 5,620 incinerated for energy recovery, and only 3,090 million tons recycled (*Plastics: Material-Specific Data*, 2021).

In the United States, plastic recycling rates are low due to the recycling infrastructure being ill-equipped to process many plastics, specifically single-use plastics and film plastics (Elejalde-Ruiz, 2015). Non-recyclable plastics are often improperly disposed of, creating a large contamination problem for U.S. recycling operations. SUPGBs used to collect recyclables and subsequently disposed of in recycling dumpsters are not recyclable and are the main contaminant in recycling facilities across the U.S. (Elejalde-Ruiz, 2015). Contamination in recycling increased in the early 2000s when the U.S. recycling industry switched from a sorting system to a single-stream system, where all recyclable items are placed in one container to later be sorted at recycling facilities (S. Bell, 2019). Because single-stream recycling is more convenient for businesses and individuals, recycling increased in popularity, and the proportion of commercial businesses participating in recycling significantly increased as well. However, single-stream recycling has allowed for high levels of contamination because many customers attempt to recycle non-recyclable materials they believe are recyclable (B. Bell, 2018). Contaminants were accepted by recycling facilities for many years because the recycling market would pay for recycled material regardless of the quality (B. Bell, 2018). However, in 2018 China—the world's largest recyclable materials buyer—implemented the National Sword Policy, banning the importation of contaminated recyclables (*National Sword*, 2018). Since then, SUPGB contamination, mainly from commercial businesses, has severely affected recycling facility operations.

Although SUPGBs are recognized as one of the main contaminants in commercial recycling, businesses continue to use SUPGBs as liners for recycling receptacles because there are limited viable and cost-effective alternatives on the market (B. Bell, 2018). SUPGBs are convenient because they allow janitorial teams to easily carry items from recycling receptacles to recycling dumpsters. Many janitorial teams then dispose of the entire SUPGB containing recyclables in outdoor dumpsters; however, film plastic—such as SUPGBs—is not currently recyclable at general recycling facilities, such as Material Recycling Facilities (MRFs) that service commercial businesses and neighborhoods (Davis & Joyce, 2019). U.S. recycling facilities are often not equipped to remove recyclables from SUPGBs, meaning large amounts of recyclable material disposed of in SUPGBs are sent to landfills (Elejalde-Ruiz, 2015). SUPGBs also jam recycling equipment and interfere with the machines' ability to separate recyclables, resulting in work stoppages (Elejalde-Ruiz, 2015). This puts the safety of the recycling workforce at risk as the staff are required to climb onto the equipment to remove the plastic (Elejalde-Ruiz, 2015). Additionally, SUPGBs that do make it through the recycling equipment impact the quality of sorted recyclables (Semuels, 2020). Recyclables contaminated with SUPGBs lose value and have less or no appeal to buyers (Semuels, 2020). As a result of this contamination, recycling becomes more expensive and recyclable commodities become less valuable to end buyers (S. Bell, 2019).

To avoid contamination, recycling facilities usually send recyclables contained within SUPGBs to landfills where they lose their marketplace value and contribute to ecological harm (Albeck-Ripka, 2018). Waste Management, the largest recycling company in the U.S., estimates it sends 25% of its recyclable goods to landfills due to contamination primarily caused by SUPGBs (Albeck-Ripka, 2018). This accelerates the rate at which landfills reach capacity, contributing to environmental and social harm (Dengler, 2017). Landfills change and eliminate ecological habitat space and emit harmful gasses and substances, such as carbon dioxide and methane, which contributes to climate change and leachate that contaminates groundwater (Knoblauch, 2020; Danthurebandara et al., 2012). With the addition of SUPGB-contaminated recyclables, landfills fill up faster and release more harmful substances (Knoblauch, 2020; Danthurebandara et al., 2012). The environmental and societal externalities of SUPGB contamination in recycling are vast; however, there is no direct government policy initiative or broad social movement targeting corporate business use of SUPGBs or SUPGBs as a contaminant in general.

Several U.S. government regulations and private initiatives aim to combat recycling contamination but these efforts have been insufficient in solving the magnitude of the problem. While plastic grocery bags have garnered significant scientific and media attention, leading to widespread plastic bag taxes and bans across the world, SUPGBs have had virtually no mainstream media or policy opposition in light of the environmental damages they cause. Recently, the EPA updated the U.S. Recycling Goals, which includes measures to reduce contamination in recycling by calculating the percentage of contamination and targeting the reduction of main contaminants through public education and outreach (*U.S. National Recycling Goal*, 2021). Although the EPA's goals represent an intensified focus on contamination in recycling, there is no direct government policy initiative targeting SUPGB use. Additionally, private initiatives seek to address recycling contamination within specific municipalities, corporations, and economic sectors. Corporate initiatives, such as the Closed Loop Fund, have invested millions in providing loans to municipalities seeking to upgrade recycling facilities (Humes, 2019). Cities across the U.S., such as San Francisco, have implemented strategies to achieve zero-waste, including mandatory recycling laws for businesses and residences, as well as a city-wide three-bin system (Rysavy, 2016). Some prominent examples of successful plastic reduction initiatives include the plastic bag bans at grocery stores and plastic bag taxes that have been implemented at many retail stores (*State Plastic Bag Legislation*, 2021). However, these private initiatives also fail to directly address the incorrect use of SUPGBs in commercial recycling programs and prevent further SUPGB contamination.

Although many large corporations have established waste reduction goals, there are no widely adopted solutions to eliminate the use and incorrect disposal of SUPGBs from corporate business recycling. Many large companies, such as Company X, have implemented waste-reduction strategies with the intention of reaching zero-waste in the near future (*Landfill Waste Diversion Validation*, 2021). However, Company X has not yet found an effective solution to reduce SUPGB contamination in its recycling program and ultimately eliminate SUPGBs from its landfilled waste stream. This project aims to find a financially and environmentally viable replacement to Company X's use of SUPGBs to line recycling receptacles on their corporate campus, with the goal of reducing their total waste output and contribution to recycling contamination.

Business and Sustainability Strategies

In recent years, corporate strategies have prioritized reducing environmental impacts, requiring companies to make decisions about sustainability that encompass both environmental and financial tradeoffs (B. Bell, 2018). As companies' environmental impacts are increasingly exposed to the general public, stakeholders have urged companies to mend such issues and work towards more sustainable practices (*Reducing Env. Impact*, 2020). Companies who place profit ahead of the environment or have subpar environmental performance are seen as environmental laggards and lose credibility, access to market growth, and access to valuable stakeholders, such as investors concerned about environmental, social, and corporate governance performance (Herremans et al., 2009).

However, companies who do improve their environmental performance may benefit financially from cost reductions, improved employee retention and motivation, enhanced credibility, and further stakeholder approval and connections (Henisz et al., 2019; *Feeling the Heat?*, 2019). Consumers and stakeholders have shown an increasing desire for companies to exhibit environmental stewardship; therefore, pursuing environmental improvements can help protect a company's environmental image and ensure their success as a business.

Managing environmental-related costs and implementing best practices can also contribute to a company's competitiveness. To avoid falling behind their competitors, companies must include sustainability as a part of their business strategy and not solely a corporate social responsibility consideration; however, many companies still hesitate to implement sustainable changes due to financial motivation. All corporate environmental initiatives have financial implications; therefore, companies are often concerned about the financial implications of implementing environmental improvements, including the cost, potential cost savings, and the return on their investment. Companies are often motivated to switch to more sustainable practices if environmental initiatives result in cost savings.

Research has shown improved environmental performance can positively impact a firms' financial performance, and there are many instances where companies have saved money by becoming more sustainable (Dreyer et al., 2019; Ellsmoor, 2019; Guenster et al., 2011; Hang et al., 2019; Scarpellini et al., 2017; Tang et al., 2016; Trabelsi & Chikh, 2018). For example, Coca-Cola's effort to reduce material use in their packaging saved an estimated $100 million (Hope, 2014). Bank of America's campaign to reduce the amount of resources used to produce receipts saved $500,000 annually (Hope, 2014). And, Patagonia's sustainability-focused marketing strategy resulted in a $543 million sales increase, allowing the company to open 14 new stores in 2012 (Hope, 2014). It is increasingly evident that it pays to go green. Many companies investing in sustainability initiatives are not only performing better financially, but improving their reputation and strengthening stakeholder and investor trust in the company (Guenster et al., 2011).

This project seeks to understand if the most environmentally friendly option for lining recycling receptacles—SUPGBs versus RRBs—is also the most cost-effective option. The results of this project will inform Company X of the solution for lining recycling receptacles that will improve both their environmental and financial performance. Company X has a diverse portfolio of sustainability and corporate social responsibility goals, and the results of this project will provide Company X with the necessary information to improve their waste management strategy and achieve their zero-waste goals. In 2020, Company X set a goal to reach 'zero-waste' and UL certification for their direct operations, products, and packaging by 2030, which includes diverting at least 90% of their solid waste from landfills and incineration (*Landfill Waste Diversion Validation*, 2021). UL certification—a highly regarded and competitive third-party sustainability certification—will validate and provide credibility to Company X's waste diversion efforts.

Company X's use of SUPGBs to line recycling receptacles on their corporate campus is one of the barriers to reaching zero waste and the UL certification. Currently, Company X is lining recycling receptacles with single-use HDPE (High Density Polyethylene) bags—which are not recyclable in U.S. recycling facilities—and therefore are landfilled or incinerated (Elejalde-Ruiz, 2015). A RRB offers an alternative solution to SUPGBs, potentially reducing Company X's recycling contamination, increasing their current waste diversion rate, and strengthening their credibility as an environmentally conscious company.

WSP will use the results of this project to help Company X, as well as other corporate clientele, make informed decisions towards reducing the environmental impact and financial implications associated with corporate campus recycling programs. WSP's global presence and collaboration with industry leaders across multiple sectors allows them to influence industry trends and widely adopted sustainable changes. With this widespread influence in waste management and corporate sustainability strategies, the results of this project can be impactful on a broad scale. If the RRB proves to be a financially viable, sustainable, and effective solution, WSP will communicate the results of this project to evangelize the RRB for their clients.

Environmental Impact Evaluation

Assessing the environmental impacts of SUPGBs and RRBs from raw materials to ultimate disposal is necessary to further understand the direct and downstream consequences of both bag types (Unruh, 2015). Life-Cycle Assessment (LCA) is an important decision-making tool used in corporate sustainability to quantify the environmental impacts of processes and goods from "cradle to grave" or over the entire life of a product (Unruh, 2015). A LCA comparison of SUPGBs and RRBs has not previously been conducted; however, LCA analysis has been used to assess the environmental implications of replacing other commonly used single-use plastic bags with reusable bags, including plastic grocery bags.

Using plastic grocery bags as a proxy for SUPGBs, LCA results indicate traditional disposable, single-use polyethylene (PE) plastic bags have a greater environmental impact than reusable polypropylene (PP) bags. A LCA performed in 2021 comparing the environmental impacts of common reusable bags (cotton, non-woven PP) and common single-use bags (HDPE, biodegradable plastic, kraft paper), found reusable non-woven PP bags produce an overall lower environmental impact (Ahamed et al., 2021). Furthermore, a study comparing single-use plastic grocery bags and reusable grocery bags found if PP reusable bags were made with post-consumer resin (PCR) in concentrations of 40% to 100%, the use of PCR could offer significant environmental benefits, including a reduction in the carbon dioxide emissions, amount of solid waste, and pollution (Greene, 2021).

Overall, studies agree reusable PP plastic bags have less severe environmental impacts than single-use PE grocery bags (Civancik-Uslu et al., 2019; Saibuatrong et al., 2017). Evidence from a LCA of reusable grocery bags suggests a RRB has the potential to lower Company X's environmental impact by reducing waste production and contamination in their campus recycling programs. Further, a LCA that compares SUPGBs and RRBs is necessary to provide evidence of the potential environmental tradeoffs for Company X and other organizations. The goal of this project's LCA is to evaluate the tradeoffs of each option and help WSP's future clients reduce their SUPGB consumption and contamination.

IV. Deliverables

The deliverables for this project align with the previously stated objectives. Each contributes to our overall analysis of the environmental and financial tradeoffs associated with implementing RRBs in replacement of SUPGBs to line recycling receptacles in corporate campus recycling programs. The following deliverables are presented in the order we completed them in: Field Test, LCA, Financial Analysis, and Impact Calculator. Each preceding deliverable informed the proceeding deliverable to complete our full analysis of the tradeoffs between SUPGBs and RRBs. Each of the other deliverable reports are organized into the following sections:

- **Objective**: Summary of the goal of each deliverable.
- **Background**: Description of the motivation for the deliverable.
- **Methods**: Detailed steps taken to complete each deliverable, including all data sources and assumptions used to complete the analysis.
- **Results**: Report of the findings or outcome of the analysis based on the methodology performed.
- **Discussion**: Explanation of the meaning, importance, and relevance of the results of our analysis in relation to the objective and overall goal of our project.

Following all of the deliverables sections, is the Recommendations and the Conclusion section which includes our overall analysis, conclusions, and recommendations informed by the cumulative results of our project's deliverables.

V. Field Test

Objective
Field-test the RRB at UCSB to help WSP understand the feasibility of implementing RRBs in place of SUPGBs to line recycling receptacles in commercial campus recycling programs (Objective #1).

Background
One of the barriers to analyzing the feasibility of the RRB as a liner for recycling receptacles at Company X's corporate campus was the lack of information regarding the janitorial process and actual use of the bag at Company X or a comparable institution. While we were able to contact the RRB supplier and manufacturer—Zorch International and Factory Direct Promos respectively—to receive information about the manufacturing of the RRB, they were unable to provide data or customer reviews about bag use. As stated previously, there are no other RRBs on the market and the RRBs analyzed in our project are not yet a part of mainstream recycling programs; therefore, there is a lack of information on the durability, use, and janitorial implications of the bag. However, this information was critical to the completion of our LCA and financial analysis, as well as our recommendation to WSP regarding the feasibility of implementing the RRBs in Company X's campus janitorial services.

For our LCA sensitivity analysis and financial analysis, we needed detailed information on Company X's janitorial processes. We lacked information about Company X's use of SUPGBs in their current recycling program, specifically how many times recycling receptacles were emptied each week. Company X's campus was operating under minimal use prior to and during this project while the facility conducted renovations and faced COVID-19 restrictions. Given that most employees were working remotely and janitorial crews were operating at low capacity, Company X was unable to provide information on SUPGB use and janitorial procedures within their recycling program at this location.

Therefore, to collect the necessary qualitative and quantitative information for our analysis of the use of RRBs versus SUPGBs in campus recycling programs, we implemented a field test of the RRB. Field tests are a common method used to test a new product or idea to gather information and feedback and evaluate its effectiveness before implementation (Detweiler, 2019). We collaborated with the University of California, Santa Barbara (UCSB) to implement and evaluate RRBs and evaluate their previous recycling process with SUPGBs in comparison to the recycling process with RRBs.

Data and Information Collected

Our first task was to find information on the lifespan of the RRB. While a tag on the inside of the RRB stated it could be used a *minimum* of 125 times, there was no accessible research, field tests, or data to support this statement. For the LCA, it was necessary to have an accurate use or lifetime estimate to generate a robust quantification of the environmental impact of the RRB. We also needed information on how often janitorial teams replaced SUPGBs from receptacles to deduce the amount of SUPGB waste generated within a year and accurately quantify the reference flow in our LCA. For our financial analysis, we needed this same data, as well as how much time went into training the janitorial team to use the RRBs, how much time it took facilities teams to service receptacles with each bag option, and how much time it took to clean the RRBs to accurately quantify the annual cost of using SUPGBs compared to RRBs. This data would allow us to factor in the financial costs of all bags used within a calendar year and equate monetary values to the janitorial work time required to use SUPGBs and implement and use RRBs.

In addition to collecting pertinent data for our other analyses, we conducted the field test to understand the feasibility of implementing RRBs in campus recycling programs, including bag durability, the facility team's experience using the RRBs, as well as on-site operations and logistics needed to effectively implement RRBs. The field test offered an opportunity to collect qualitative responses and reactions from facilities staff, janitorial management, and waste management personnel to provide a better understanding of the tradeoffs associated with switching from SUPGBs to RRBs. Overall, this allowed us to make a more informed recommendation regarding the use of RRBs at Company X's corporate campus, as well as relay improvement suggestions to WSP.

Methods

Choosing the Field Test Location

Our field test was conducted at the UCSB campus in The Bren School of Environmental Science & Management (Bren) building. Although conducting this field test on Company X's campus would have provided the most accurate information regarding RRB use specific to Company X's recycling program due to COVID-19 restrictions, this was not plausible during the duration of this project. At the time, Company X's campus was under minimal use, with most employees working remotely as a safety precaution (A. Ortega, personal communication, June 25, 2021). This meant that on-campus janitorial teams were operating at low capacity with minimal waste generation and disposal.

We chose the Bren building because it was easily accessible; the building has centralized and highly-frequented waste and recycling collection bins similar to Company X, it was fully operational at time of implementation and was predicted to remain so, the current program used SUPGBs to line recycling receptacles, and the RRBs fit the building's 19 gallon recycling containers. Additionally, the Bren janitorial team showed interest in testing RRBs at this location, as RRBs could also help them eliminate SUPGBs from their recycling process. The only large difference between Company X's campus and the Bren building was the building users. Because the building is home to the Bren School of Environmental Science & Management, the recycling bins are frequented by students, staff, and faculty that we assume are more conscious of their recycling practices than the average person. Given the time constraints of this project, this was the overall easiest, most affordable, and observable option for our field test.

Interviews: Before Field Test Implementation

Prior to implementing the bags, our team met with Bren building staff to discuss the current recycling program and determine field test procedures. We interviewed Sage Davis (Bren Building Supervisor), Matthew O'Carroll (Refuse, Recycling & Water Efficiency Manager), Byron Sandoval (Sr. Superintendent, Custodial Services), and Fabian Salas (Bren Building Custodial Supervisor) to gather information about UCSB's and the Bren School's current recycling practices, determine a location for the field test, and create a field test protocol. Overall, these interviews allowed us to gather information about the janitorial teams' experience with SUPGBs before implementing RRBs, and we made a collaborative decision on how we could feasibly implement the RRBs at the Bren building and effectively collect RRB use data from the janitorial team.

Field Test Protocol

We instructed the Bren building janitorial team to follow the following protocol throughout the field test to inform accurate results. Janitors placed one RRB in each of the three recycling containers (slim jims) tested—the second, third, and fourth floor kitchen bins. The team implemented a total of six RRBs: they assigned two RRBs to each bin for the duration of the field test; with one bag in use while the other served as a back-up and was stored in the building's custodial closets. Janitorial team members checked each bin daily (Monday through Friday), excluding holidays. If a RRB was not full, janitors did not service it. If a RRB was full, janitors dumped recyclables from the RRB into a SUPGB-lined large 32 gallon transporting receptacle, which, once full, was transported to the recycling dumpster outside of the Bren Building (To read more about the Bren building recycling program, see Appendix, Field Test)**.** Janitors then checked the RRBs for any contamination from food or liquids, as well as other damages. If janitors found RRBs were contaminated, they cleaned the bag in the janitorial closet sinks in whatever method they deemed fit. Janitors used back-up bags in place of any RRB that needed more time to clean and/or dry from the cleaning process or if a RRB was damaged. If the RRB was damaged to the point that it was determined unusable, janitors removed the RRB, saved it for future examination by our group, and replaced it with the back-up RRB. If the RRB was not contaminated or damaged, janitors placed the bag back into the recycling container.

Each recycling receptacle was accompanied by a laminated checklist, placed on a wall or surface next to it (Appendix, Field Test). Janitors filled out the checklist with an erasable marker each time the RRB was used, cleaned, and or a new bag was needed. We defined these actions as follows:

- **Used**: Anytime an RRB was physically removed from the recycling bin and emptied
- **Cleaned**: Anytime an RRB was cleaned in any way, whether it was wiped down or sprayed with water and dried
- **New Bag Needed**: Anytime a RRB was damaged

Janitors wrote the date and checked off the appropriate action each time the RRBs were used, cleaned, or a new bag was needed. To collect information about the janitorial team's experience, we sent a Google Form questionnaire to Fabian Salas each week the campus was in operation, including during the period of December 2021 to January 2022, when the campus was operating at a lower capacity due to a surge in COVID-19 (excluding holidays). At the end of every week, Fabian Salas reported the checklist results for each of the three recycling locations and six RRBs to our team through this questionnaire and answered a series of questions about their experience with the RRBs. To further clarify questionnaire results or gather additional information, we followed-up with Fabian Salas through emails and meetings. With these procedures in place, the janitorial staff implemented six RRBs on the morning of November 17th in the 2nd, 3rd, and 4th floor centralized kitchen locations at the Bren building.

Data collected from the weekly questionnaires and checklists was organized in Google Sheets/Excel. Tab 1 shows results from the initial interviews, Tab 2 shows both quantitative and qualitative results from the weekly questionnaires and interviews during and after bag implementation, Tab 3 shows results from the checklists filled out by janitorial staff per emptying, cleaning, and/or discarding of RRBs, Tab 4-8 shows the same data as in Tab 3 in a calendar format for a user-friendly visualization of monthly RRB use and care.

Results

We ran the field test at the Bren building in the 3 kitchen locations from November 17th, 2021 through February 28th, 2022. Table 1 shows the initial interview results before the RRBs were implemented at the Bren building by the janitorial staff.

Table 1. Initial Interview Results - UCSB

Question	**Answer**
What is the overall recycling process at the Bren building?	SUPGB are left in the bin until they are no longer usable ie. the bag is ripped or is highly contaminated. SUPGBs with recyclables are emptied into larger 32 gallon containers, transporting receptacles that are also lined with SUPGBs. When each transporting receptacle is full, it is transported to the recycling dumpster outside of the Bren building. The janitors remove the SUPGB with recyclables from the transporting receptacle, tie it shut and throw it into the recycling receptacle.
Why do you line with SUPGB vs. leaving bins unlined?	Pros of SUPGB: SUPGBs have ties at the top to easily seal and lift the bags, making it easier for janitorial staff to empty the bins. Cons of SUPGB: SUPGBs create extra labor for the recycling hauler. Marborg has a new standard that SUPGBs can not be in the commingled recycling stream. Marborg employees rip the SUPGB before the recyclables arrive at the resource center.
What are the issues with leaving recycling bins unlined?	Leaving bags unlined makes it difficult for the janitorial staff to safely empty the recyclables into the dumpster. It is unsafe for staff to lift the bins into the 4' tall dumpster to dump. However, if bins are lined with bags the staff can pick up the bag with 2 hands from the top and safely dispose of them. Also, leaving bins unlined results in contamination by food and beverages, and it is challenging for janitorial staff to clean the bins themselves.
How often are bins emptied?	Recycling bins inside the Bren building are checked daily, but usually only emptied once per week.
Do you empty recycling bins only when they are full?	Yes.
Do you have any concerns about the RRB?	We are concerned that they make our job harder and take more time. Cleaning these bags might be difficult.

Table 2 shows the results from the checklists filled out by janitorial members each time they interacted with one of the RRBs. The "date" column shows the date the corresponding RRB was interacted with and the "bag location" column shows which bag was interacted with. The "emptied, cleaned, and need new bag" columns show if the janitorial team emptied, cleaned, or found a damaged bag that needed to be replaced by checking the respective box. Unchecked boxes indicate that the interaction did not occur.

Table 2. Checklist Results - UCSB - November 29th - February 28th

Date	Bag Location	Emptied	Cleaned	Need New Bag
11/29/2021	3rd floor kitchen	X	X	
11/29/2021	2nd floor kitchen	X	X	
12/3/2021	3rd floor Kitchen	X	X	X
12/3/2021	4th floor Kitchen	X	X	
12/10/2021	2nd floor kitchen	X	X	
12/17/2021	4th floor Kitchen	X	X	
12/21/2021	3rd floor Kitchen	X	X	
1/21/2022	3rd Floor Kitchen	X		
1/21/2022	2nd floor kitchen	X	X	
1/21/2022	4th floor Kitchen	X		
1/28/2022	4th floor kitchen	X		
1/31/2022	2nd floor kitchen	X		
2/4/2022	2nd floor kitchen	X	X	
2/4/2022	3rd Floor Kitchen	X		
2/11/2022	4th floor kitchen	X		
2/10/2022	3rd floor kitchen	X	X	
2/11/2022	2nd floor kitchen	X		
2/18/2022	2nd floor kitchen	X	X	
2/18/2022	3rd floor kitchen	X		
2/22/2022	4th floor kitchen	X		
2/25/2022	3rd floor kitchen	X		
2/25/2022	4th floor kitchen	X		
2/25/2022	2nd floor kitchen	X		
2/28/2022	4th floor kitchen	X		

Table 3 shows the qualitative questionnaire and interview results about the janitorial team's experience and the RRB's feasibility as a replacement for SUPGBs.

Table 3. Janitorial Experience and RRB Feasibility Results - UCSB - November 29th - February 28th

Question	Summarized Answer
What do you like about the RRBs?	The RRBs usually fit the slim jim and do not have to be tied into place, which is easier and more efficient than SUPGBs. SUPGBs have to be tied into place, which takes time and is difficult because the janitor's gloves get caught during the tying process. The RRB is beneficial because the elastic band at the top of the bag slips over the container easily and quickly. The RRBs are more durable than SUPGBs. If the SUPGBs slip or rip open, it takes more time for janitors to dispose of recycling because they have to put the recyclables in a new bag and clean up any mess left behind. The RRBs take less time to work with than SUPGBs. It takes more time to restock SUPGBs on janitorial carts, pull a bag from a roll of SUPGBs, open the bag, fit the bag over the bin, and tie the bag to fit the bin correctly. When we remove the bag, it also takes time to undo the tie or cut the side of the bag to remove it from the bin. Other benefits of RRBs: - Easy to clean - Lightweight and easy to carry - Sturdiness makes them easy to place into slim jim bins and stand up while drying - Waterproof, leakproof - Easy to empty - Foldable and easy to store The janitors believe that people recycling in the bins with RRBs are more inclined to recycle properly, and the visual signal of the RRB reduced the amount of contaminated recyclables. As a result, there was less contamination occurring in the three recycling bins than before the field test.

Table 3. (continued)

What do you dislike about the RRBs?	- Woven material allows for water leakage while cleaning - They can get stained when food gets in in the bag - The bag is about one inch too small to fit the width of the slim jim bins perfectly - The shape of the bags doesn't work with round containers - The handles on the bags should be on the opposite sides they are currently on for better weight distribution when janitors pull them out of the slim jim bins
Did the RRB increase the time and workload for the janitorial staff? If so, did this time increase interfere with completing their other work?	No increase in workload
Describe the cleanliness of the RRBs. Was food/liquid/contamination an issue with the RRBs?	The 3rd floor RRB was stained due to food contamination and a janitor was not able to remove the stain. Janitors reported minor liquid and food contamination across all bags, but not every week.
Did any of the RRBs get damaged? If so, were any replaced? If so, please describe the situation and damage.	No. None of the bags were damaged by liquid or any other contamination.
Did any RRBs leak liquid or contaminants?	While there was no leakage of liquid contaminants from any of the RRBs, one of the RRBs leaked during the cleaning process. The RRB was filled with water about ¼ of the way full and left to soak to try to remove a stain. Water leaked during this time and is most likely due to the woven nature of the PP.

Table 3. (continued)

How were the RRBs cleaned (i.e. hosed down, wiped down, etc.) Did you use any cleaning products? How did you dry them?	Each RRB was cleaned with the same cleaning process. First, janitors lightly sprayed each bag with a mixture of water and Buckeye Terminator disinfectant with a hose located in each custodial closet within the Bren building (“Buckeye Terminator,” n.d.). If any stains were found inside the bag, a soft cleaning brush was used to lightly scrub the stain away if possible. Second, bags were lightly rinsed with water using the hose. Third, the bag was left to dry in the custodial closet. In some cases, the bag was hand-dried with a towel. The janitors hoped to dry the bags by turning them inside-out to let the wet, inside portion dry faster, but the bags were too sturdy to do so.
Do you prefer RRBs or SUPGBs in your recycling program?	We prefer the RRBs, especially if we can get different sizes for our different bins.
Do you think the RRB could last longer than 125 uses?	Yes. The bag is very durable and, if cared for properly, could last many years.
How has COVID-19 impacted campus recycling programs?	The campus switched to remote instruction and work from January 3rd - 28th, which reduced waste generation on campus and, therefore, RRB usage.

Table 4 shows the quantitative questionnaire and interview results about the Bren building recycling process, janitorial wages and working days, details about the size and cost of SUPGBs normally in use, and the time it took to train janitors to use the RRBs, empty SUPGBs, empty RRBs, and clean and dry RRBs. This table also shows contamination charges incurred by UCSB or the Bren building by the waste hauler; however, we were unable to acquire this information.

Table 4. Questionnaire and Interview Quantitative Results - UCSB - November 29th - February 28th

Question	**Answer**
How many days per year do you conduct waste management services?	247 days/year They do not work weekends They have 14 holidays
What size are the SUPGBs you currently use?	40 gallons
What is the cost per SUPGB?	$0.1411
What is the starting wage for janitors?	$21.65
How much time did you spend training your janitorial team on how to use the RRB in your recycling system?	30 minutes
How long does it take to empty a SUPGB usually used in your recycling services?	120 seconds/2 minutes
How long does it take to empty the RRBS that are being tested in your recycling services?	90 seconds/1.5 minutes
How long does it take to clean a RRB?	240 seconds/4 minutes
Has UCSB or Bren received any contamination charges?	Unknown

Discussion & Analysis

The results of the field test provided us with data and information necessary for our LCA and financial analysis and allowed us to make informed assumptions for Company X's recycling program. We aimed to find an estimate for the minimum use amount or lifetime of the RRB and how often the janitorial team emptied containers for both SUPGBs and RRBs. While we were able to collect data on how often bags were emptied, we were unable to collect a minimum lifetime estimate for the RRB. This was due to the time constraints of our project—November, 2021 through March, 2022—with the RRBs only emptied one or fewer times per week, as shown in Table 1 and Table 2, as well as the fact the campus was operating under a lower-than-normal capacity from December 20th, 2021 to January 28th, 2022 due to school holidays and closures as a result of a surge in COVID-19.

All bags were still in use by the end of the field test. As shown in Table 2, the 2nd floor, 3rd floor, and 4th floor RRBs were each individually emptied a total of 8 times and cleaned 4, 5, and 2 times respectively. This shows the bags were only emptied, on average, once per week taking into account the lower-than-normal capacity from December 20th, 2021 to January 28th, 2022.

Throughout the field test, the janitors only had to rotate one RRB with a back-up bag, as shown in Table 2. This occurred while a janitor was deep soaking the primary bag with water to remove a stain and noticed water leakage from the inside of the bag to the outside of the bag during this process. Janitors placed the back-up bag in the 3rd floor bin while they investigated the leakage. At first, they thought the leakage might have been due to damage caused by recyclables or contaminants, but this leakage was actually due to the large amount of water sitting within the bag while it was soaking and the woven nature of the polypropylene material. Once the bag was fully cleaned and dried, the janitorial team placed it back in the 3rd floor recycling bin to test its functionality. After monitoring the bag, the janitors found the RRB was still functional, keeping all liquid and food contaminants from reaching the bin itself. As shown in Table 3, none of the bags leaked any contaminants into any of the bins throughout the field test.

While the RRBs do not leak contaminants, this one instance of leakage during cleaning suggests that heavy cleaning or soaking (where the RRB holds a lot of water for an extended period of time) could cause damage to RRBs in the long term, which could potentially lead to leakage of contaminants from the inside of the bag to the recycling bin. To keep this from occurring and to ensure the longevity of the RRBs, the janitorial team switched to a lighter cleaning process and used a brush to help remove any stains from the bag, as shown in Table 3. While the janitors did not need to rotate the bags with their back-ups after each cleaning due to the small scale and quick cleaning/drying time for the RRBs, janitors hypothesized that rotating the bags might increase the longevity of the RRBs because no one bag would be in constant use.

These results show that the RRBs are functional as a liner for recycling bins and have a similar functionality to SUPGBs; however, there are a few tradeoffs, which can be seen in Table 3 and Table 4. The janitors reported benefits from using the RRBs, including that they were more durable, easier to place into and remove from recycling bins, required less time to work with, and reduced the amount of plastic waste generated. While it takes time to clean and dry the RRBs, the janitors did not find this to be a burden and believed that this process took less time than restocking, organizing, and replacing SUPGBs. Janitors also reported drawbacks of the RRBs, including that they leaked when soaked, stained on the inside of the fabric, did not fit all container shapes and sizes, and had unideal handle placements. These drawbacks provide important insight into potential bag improvements, such as changing the bag material to withstand all leakage and stains, adjusting the handle placements, and increasing the range of RRB sizes and shapes. Overall, the janitorial team reported they would choose RRBs over SUPGBs, as seen in Table 3, and the benefits associated with the RRB outweighed the drawbacks. This suggests the RRB could be a feasible and favorable substitution for SUPGBs in other campus recycling programs.

The visual appearance of the RRBs may have contributed to a reduction in contamination and subsequent wear on the bags. After implementing the RRBs, the janitors noticed a reduction in the amount of contamination, specifically food and liquid contaminants, co-mingling with recyclables. The janitors hypothesized that people recycling in the bins lined with RRBs were more inclined to recycle properly due to the visual signal of the bag. As a result, there was less contamination occurring in the three recycling bins than before the field test. While we cannot confirm this finding, research shows that visual cues can influence proper recycling behavior and decrease contamination (Felske, 2020). While we did not test this potential visual cueing during this field test because it was outside of the scope of our project, it may influence the longevity of the RRB and should be investigated through future projects.

VI. Life-Cycle Assessment (LCA)

Objective

Conduct a Life-Cycle Assessment (LCA) to identify the bag option—SUPBGs or RRBs—with the lowest environmental impact (Objective #2).

Background

Goal of the study

The principal goal of this LCA was to evaluate and compare the environmental impacts of High Density Polyethylene (HDPE) SUPGBs and Woven Polypropylene (PP) RRBs. The purpose of this comparison was to evaluate the environmental tradeoffs of each bag type and analyze how reusability influences the environmental impact of bags used to line recycling receptacles.

While reusable grocery bags have been widely accepted and analyzed as an alternative solution to single-use grocery bags, reusable bags have yet to be adopted or studied as an alternative for SUPGBs used to line recycling bins. LCA has been used to motivate data-driven decision making regarding which grocery carrier bag is the most environmentally sustainable option (Ahamed et al., 2021; Civancik-Uslu et al., 2019). This study mimics the strategy used to analyze the environmental implications of grocery carrier bags by applying LCA to make a comparative assessment of PP RRBs and HDPE SUPGBs used to line recycling receptacles. Although LCA has been applied to analyze garbage bags made from different materials that could be used in recycling programs, a reusable bag has never been included in such analysis (Saibuatrong et al., 2017). Therefore, this study is the first environmental analysis comparing a SUPGB to a RRB for the purpose of lining recycling receptacles.

We performed this LCA for WSP's Sustainability, Energy and Climate Change division. WSP will use the results of this study to evaluate the environmental footprint of RRBs in comparison to HDPE SUPGBs and to inform their clients of the environmental impact of each bag type. If the LCA results indicate use of RRBs produces a lower environmental impact than SUPGBs, it is possible WSP will use the results of this study to motivate their clients to implement RRBs in their corporate campus recycling programs.

Scope of the study

We defined the goal of this LCA as the identification and analysis of the cradle to grave environmental impacts of SUPGBs and RRBs to line recycling containers. We analyzed the following bag types:

- High Density Polyethylene (HDPE) Single Use Plastic Garbage Bags (SUPGBs)
- Woven Polypropylene (PP) Reusable Recycling Bags (RRBs)

The characteristics of each bag are detailed in Table 5. We carried out the environmental analysis following the LCA methodology in accordance with ISO 14040 standards (*Env. Management - LCA*, 2006). To complete this analysis, we used GaBi Professional software version 9.0.0.42 to model the life cycle of SUPGBs and RRBs to line recycling containers, generate life cycle inventory data, and estimate the related environmental burdens of each bag. After modeling, we conducted several scenario analyses to project how changes in the frequency of RRB use affects the total environmental impact of a RRB. Our scenario analyses vary the number of times recycling bins are serviced annually, which results in a different number of SUPGBs and RRBs used. We also conducted a sensitivity analysis of the minimum lifespan of the RRB to evaluate how changes in minimum lifespan affect the environmental impacts of a RRB.

Table 5. Characteristics of the analyzed bags

High density Polyethylene (HDPE) Single Use Garbage Bags (SUPGBs) (1 use)	
Weight (g)	27
Dimensions (in)	48H x 40W
Volume (gal)	40
Thickness (μm)	12
Reuse	Single Use
Composition	0% recycled
Source	Store Sample (Staples, n.d.)

Table 5. (continued)

Woven Polypropylene (PP) Reusable Recycling Bags (RRBS) (125 uses)	
Weight (g)	233.25
Dimensions (in)	33H x 21W
Volume (gal)	23
Thickness (µm)	Unknown
Reuse	Reusable
Composition	20% - 40% pre-consumer recycled content
Source	Zorch, Factory Direct Promos

Methods

Functional Unit and Reference Flow

To begin process modeling, we defined the functional unit as “containing and protecting 40 gallons of recyclable materials for disposal once a day for one year”. For Scenario 1, we defined the functional unit as “containing and protecting 40 gallons of recyclable materials for disposal once a day for 249 days.” We assumed the number of days in the functional unit to be equivalent to the number of days janitorial staff would service recycling receptacles, meaning when a RRB was reused or a SUPGB used and disposed of. We chose to use 249 days because it accounted for the calendar year, excluding weekends and federal holidays.

We defined the reference flow as the amount of bag material needed to accommodate the functional unit. Table 6 shows the reference flows obtained by calculating the number of bags needed for 249 disposals of recyclables. To determine the reference flows of each bag, we took into account the transportation capacity of the bags (in terms of volume in gallons) and the number of reuses. Then, to calculate the number of bags required during a year (in which 249 disposals occur), we considered the number of reuses per each bag. The results were presented for 125 uses for the RRB as specified by the manufacturer and one use for the SUPGB.

Table 6. Reference Flows based on Scenario 1 corresponding to the defined functional unit (FU)

Material	**Volume (gal)**	**Used Volume**	**Number of bags per 40-gal recycling bin**	**Number of uses per bag**	**Number of bags per functional unit (249 uses in a year)**	**Mass of bag material needed per FU (g)**	**Mass of nylon needed per FU (g)**	**Mass of elastic needed per FU (g)**
HDPE SUPGB	40.00	40.00	1.00	1.00	249.00	27.00	N/A	N/A
PP RRB	23.00	23.00	1.74	125.00	1.99	366.42	24.66	14.57

Table 7 defines the scenarios analyzed as a part of this study. The three scenarios analyze the different number of uses per bag in a year, representing the varied frequency at which recycling receptacles could be serviced at a facility. We defined the scenarios as follows; Scenario 1: 249 uses in a year (disposal once a day on weekdays; excluding weekends and federal holidays), Scenario 2: 365 uses in a year (disposal once a day every day, no exceptions), and Scenario 3: 52 uses in a year (disposal once a week) also seen on Table 7. We then compared these scenarios to each other to analyze how the frequency a janitorial team services recycling receptacles influences the environmental impact of bag use for lining recycling bins.

Table 7. Scenarios analyzed in this study

Scenario	**Scenario Description**	**Number of HDPE SUPGBs used per manufacturer recommendation**	**Number of PP RRBs used per manufacturer recommendation**
1	249 days of use (excludes weekends and federal holidays)	249	1.99
2	365 days of use (one use per calendar day)	365	2.92
3	52 days of use (one use per calendar week)	52	0.42

Impact Categories

We used the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) for the environmental impact assessment portion of this study (US EPA, 2015). The impact categories used in this study are the standard impact categories analyzed for plastic product LCA's; however, because this is the first study of its kind, the impact categories chosen were not based on previous literature. We instead aimed to establish a baseline for analyzing the environmental impacts of reusable and single use garbage bags used to line recycling receptacles.

The following environmental impact categories (EICs) were used in the study:

- Acidification Potential
- Eutrophication Potential
- Global Warming Air, Excluding Biogenic Carbon
- Global Warming Air, Including Biogenic Carbon
- Ozone Depletion Air
- Resource & Fossil Fuel Use

The following indicators were also included in the analysis:

- Primary Energy Consumption
- Water Consumption

Hypothesis and Limitations

- The most recent data available to us in the GaBi Professional Database was from 2012.
- Both the SUPGB and RRB producers were located in China; however, Global (GLO) or European (EU-27) data was used in both analyses because country specific data for China was unavailable. Country specific data is extremely costly and purchasing China specific data was unattainable given the budget constraints of our project.
- We assumed SUPGBs and RRBs were filled at 100% capacity for each use.
- A GLO truck with 17.3 tons of maximum load was used for all trucking transportation processes. We assumed all trucks returned loaded with other products, thus the return trip was not included in the transportation assessment.
- We assumed both SUPGB and RRB bag manufacturing and assembly occur at a single facility; therefore, there was no transportation between steps. We assumed this for the RRB because the manufacturer was unable to provide process level data for production and assembly.
- No data was available for the distance between the manufacturing facilities and the shipping freight, storage warehouses, or landfill facilities because we did not have access to the exact locations of the manufacturer, distributor, or landfill.
- The strict Hours of Service (HOS) regulations set by the Federal Motor Carrier Safety Administration (FMCSA) state that a truck driver can drive for a maximum of 11 hours in a 24-hour period which approximately equals 500 miles of travel per day or 805 km (Beckmann, n.d.). This approximate distance was used for all transportation processes.

- No environmental data on the production of woven PP material was available in the GaBi database. Similar to a 2019 study of woven PP bags, the production of woven PP was assimilated to PP film in this analysis (Civancik-Uslu et al., 2019). However, it is understood that PP film production requires less energy and water inputs than woven PP production (Civancik-Uslu et al., 2019); therefore, this hypothesis undoubtedly impacts the results to benefit the RRB.
- The manufacturer specified 20-40% of the RRB was made from recycled content. However, the manufacturer and distributor were unable to provide us with the source or type of recycled content, pre-consumer versus post-consumer (M. Callahan, personal communication, June 10, 2021). Based on the lack of data, it was assumed the recycled material contribution to PP production came from runaround scrap within the manufacturing facility. To account for runaround scrap recycling—scrap materials generated at the manufacturing facility by the RRB production process that are reintroduced into the system—the percentage of material loss during the PP sheeting process was reduced to 0%, meaning the grams of PP material needed to produce one RRB was assumed to equal the weight of the final product and no material was lost in the process.
- We added the elastic band as weight in the assembly step because no textile data was available for elastic production in the GaBi database.

System Boundaries

We used a cradle-to-grave approach for both products, and identified the system boundaries as the total life cycle of the bags, including extraction of raw materials, transportation, production, distribution to consumers, and end-of-life disposal. We also used the "cut-off approach" because the second life of the bag material was unknown in open-loop recycling (i.e. recycling a product to create a new product), for end-of-life (EoL) allocation (Baumann & Tillman, 2014). We used the following unit processes for the HDPE SUPGB model: HDPE plastic film production, transportation, freight shipping, and landfill disposal. For the RRB model, we included the following unit processes: PP plastic film production, nylon plastic extrusion, bag assembly, transportation, freight shipping, and landfill disposal. Finally, we used the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) for the environmental impact assessment of both bags (US EPA, 2015).

Inventory Analysis

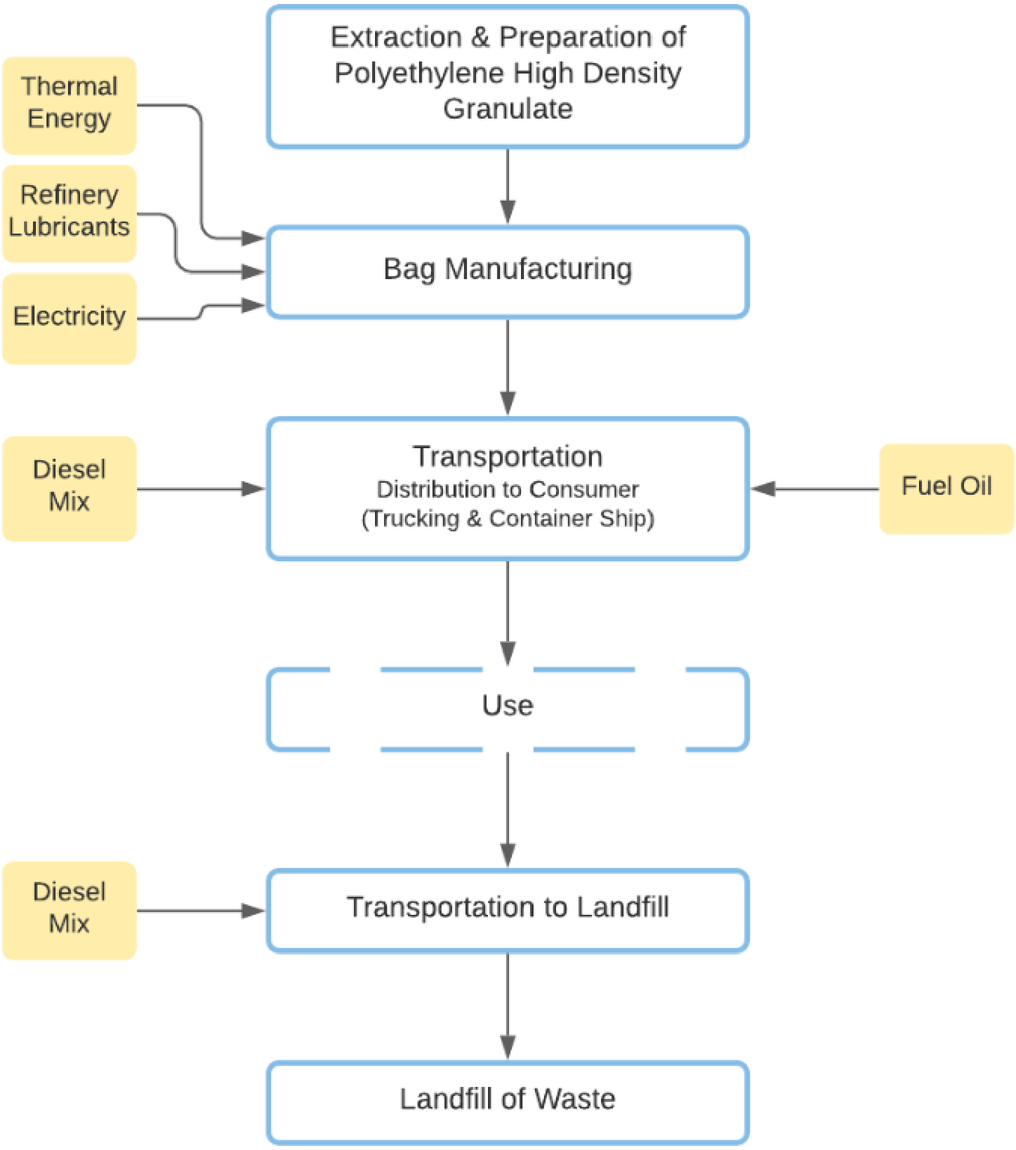

Figure 1. HDPE SUPGB System Diagram

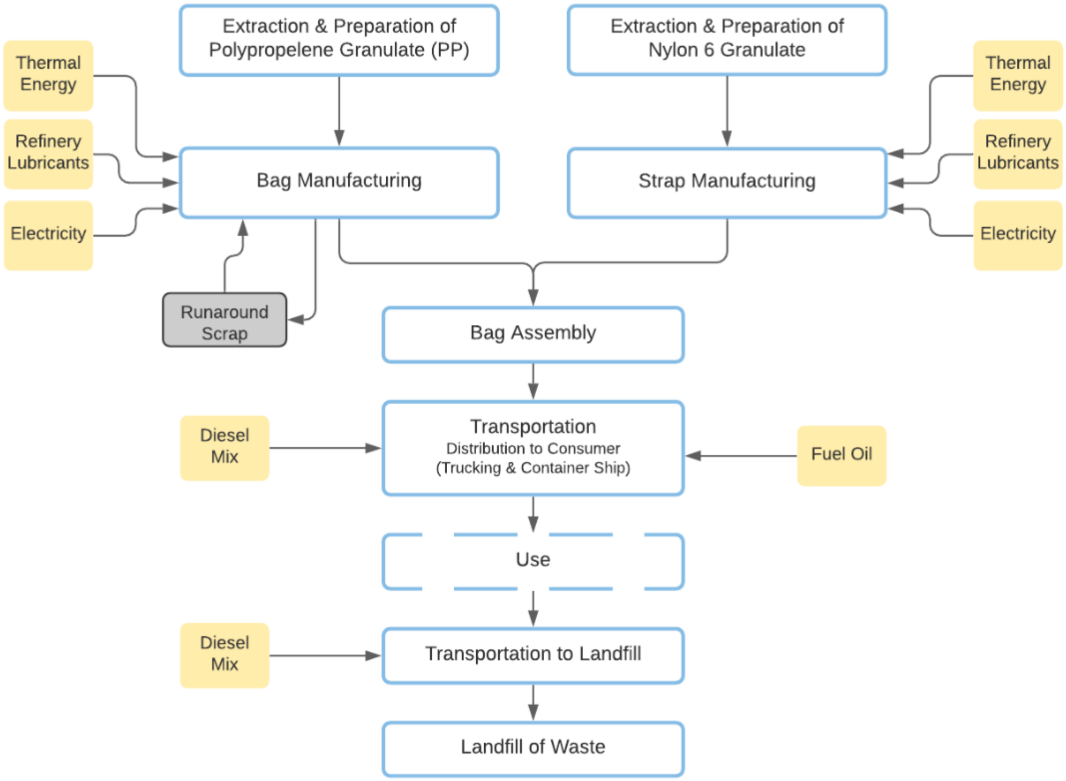

Figure 2. PP RRB System Diagram

Results

Impact Assessment

As stated previously, we used the following TRACI 2.1 EICs to obtain results for the environmental impact analysis of SUPGBs and RRBs: acidification potential; eutrophication potential; global warming air, excluding biogenic carbon; global warming air, including biogenic carbon; ozone depletion; and resource & fossil fuel use. The global warming impact is the largest environmental impact of both SUPGBs and RRBs and is an important consideration for WSP's clients; therefore, we discuss the global warming impact results in depth. We also considered primary energy consumption and water consumption as indicators. We analyzed blue water consumption in depth because blue water refers to potable water resources; therefore, it is an important consideration for the environmental impact assessment of both bags. Table 8 shows a comparison between the five major EICs for Scenario 1, where both bags were used 249 times in a year. The "per FU" row refers to the total impact measured by the functional unit. The "per # bags/year" row measures the impact by the number of bags needed in a year when recyclables were disposed of 249 times. The results per functional unit measure the cradle-to-grave impact of one SUPGB versus one RRB; whereas the results per number of bags per year measure the impact of the number of SUPGBs and RRBs needed to empty receptacles 249 times, assuming SUPGBs are used once and RRBs are reused until their end of life of 125 uses.

Based on the reference flow calculations shown in Table 6, we used 249 SUPGBs and 2 RRBs to fulfill the parameters for Scenario 1, disposing of recyclables 249 times per year.

As seen in Table 8, the results per functional unit indicate the SUPGB has a lower environmental impact across all five impact categories; however, the results shown per number of bags per year indicate the RRB has a significantly lower environmental impact in all categories. This shows the RRB's reusability affects its overall environmental impact and indicates that RRBs reused until their end of life stage at the minimum lifespan estimate can produce a lower environmental impact than SUPGBs. For example, the global warming excluding biogenic carbon category indicates use of 249 SUPGBs produces approximately 21.50 kg of CO_2, while in contrast use of 2 RRBs produces 2.85 kg of CO_2. Therefore, use of RRBs in place of SUPGBs reduces the global warming impact by 18.7 kg of CO_2, or 85%, considering recycling bins are emptied 249 times per year.

Table 8. TRACI 2.1 EIC Results - Scenario 1 (249 Uses per Year)

	Acidification [kg SO2-Equiv.]	**Eutrophication [kg N-Equiv.]**	**Global Warming Air, excl. biogenic carbon [kg CO2-Equiv.]**	**Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]**	**Ozone Depletion Air [kg CFC 11-Equiv.]**	**Resources, Fossil fuels [MJ surplus energy]**
SUPGB						
per FU	3.94 E-4	1.88 E-5	0.09	0.09	2.35 E-12	0.29
per # bags/year	0.10	4.68 E-3	**21.50**	22.70	5.85 E-10	71.90
RRB						
per FU	6.19 E-3	6.77 E-4	1.43	1.50	3.42 E-11	4.09
per # bags/year	0.01	1.35 E-3	**2.85**	2.99	6.80 E-11	8.14

Table 9 shows the Scenario 1 results for primary energy consumption throughout the life cycle of both bags. Consistent with the TRACI EIC Results in Table 8, when SUPGBs and RRBs are compared on a bag-to-bag functional unit basis, SUPGB production requires a drastically lower amount of energy. However, when compared on the basis of the number of bags used in a year, the overall energy consumption of the RRB was significantly lower than the SUPGB for both renewable and nonrenewable resources. The primary energy demand for renewable and nonrenewable resources for 249 SUPGBs and 2 RRBs was 612.54 MJ and

69.41 MJ, respectively. Therefore, use of RRBs in place of SUPGBs reduces the primary energy demand by 543.10 MJ or 89%, given that recycling receptacles are emptied 249 times per year.

Table 9. Energy Consumption Results - Scenario 1 (249 Uses per Year)

	Primary energy demand from renewable and nonrenewable resources (gross cal. value) [MJ]	Primary energy from nonrenewable resources (gross cal. value) [MJ]	Primary energy from renewable resources (gross cal. value) [MJ]
SUPGB			
per FU	2.46	2.42	0.04
per # bags/year	**612.54**	602.58	10.23
RRB			
per FU	34.88	34.40	0.48
per # bags/year	**69.41**	68.46	0.95

Table 10 shows the Scenario 1 results for water use throughout the life cycle of both bags. Similar to the previous results, the results per functional unit and results per number of bags per year indicated the water consumption of RRBs was significantly lower than for SUPGBs in all water use categories. Therefore, with proper reuse of RRBs until their end of life of 125 uses, RRBs produce a lower water impact than SUPGBs. Again, we chose to analyze the blue water consumption metric because blue water consumption impacts potable water availability. For example, the blue water consumption for 249 SUPGBs was 35.86 kg in comparison to 9.95 kg for 2 RRBs, meaning that the use of RRBs in place of SUPGBs decreases the blue water consumption by 25.91 kg or 72%.

Table 10. Water Use Results - Scenario 1 (249 Uses per Year)

	Blue water consumption [kg]	Blue water use [kg]	Total freshwater consumption (including rainwater) [kg]	Total freshwater use [kg]
SUPGB				
per FU	0.14	6.71	0.29	6.88
per # bags/year	**35.86**	1670.79	72.21	1713.12
RRB				
per FU	4.90	101.00	7.11	103.00
per # bags/year	**9.95**	200.99	14.15	204.97

Table 11 shows a comparison between the five major EICs for Scenario 2. Based on the reference flow calculations shown in Table 6, 365 SUPGBs and 3 RRBs were used to fulfill the parameters for Scenario 2, disposing of recyclables 365 times per year. Similarly to Scenario 1, when comparing on the functional unit basis, the SUPGB resulted in a lower environmental impact across all five categories. However, the results for the number of bags per year showed the RRB had significantly less impact across the board. global warming excluding biogenic carbon shows that use of 365 SUPGBs would produce 31.57 kg of CO_2 in contrast to 21.5 kg of CO_2 produced in Scenario 1 (Table 8) and use of approximately 3 RRBs produced 4.18 kg of CO_2 in comparison to 2.85 kg of CO_2 produced in Scenario 1 (Table 8). In comparison to Scenario 1, Scenario 2 increases the global warming impact of RRBs by 10.1 kg of CO_2, an approximate 68% increase, and the global warming impact of SUPGBs by 1.4 kg of CO_2, an approximate 67% increase. In Scenario 2, use of RRBs in place of SUPGBs reduces the global warming impact of recycling programs by 87% or 27.4 kg of CO_2.

Table 11. TRACI 2.1 EIC Results - Scenario 2 (365 Uses per Year)

	Acidification [kg SO2-Equiv.]	**Eutrophication [kg N-Equiv.]**	**Global Warming Air, excl. biogenic carbon [kg CO2-Equiv.]**	**Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]**	**Ozone Depletion Air [kg CFC 11-Equiv.]**	**Resources, Fossil fuels [MJ surplus energy]**
SUPGB						
per FU	3.94 E-4	1.88 E-5	8.65 E-2	9.12 E-2	2.35 E-12	0.29
per # bags/year	0.14	6.86 E-3	**31.57**	33.29	8.58 E-10	105.49
RRB						
per FU	6.19 E-3	6.77 E-4	1.43	1.50	3.42 E-11	4.09
per # bags/year	1.81 E-2	1.98 E-3	**4.18**	4.38	9.99 E-11	11.94

Table 12 shows the Scenario 2 results for primary energy consumption throughout the life cycle of both bags. Consistent with the TRACI EIC results in Table 11, when SUPGBs and RRBs were compared on a bag-to-bag functional unit basis, SUPGB production required a lower amount of energy. When compared on the basis of the number of bags used in a year, the overall energy consumption of the RRB was significantly lower than the SUPGB for both renewable and nonrenewable resources. The primary energy demand for renewable and nonrenewable resources for 365 SUPGBs was 897.90 MJ in Scenario 2 compared to 612.54

MJ in Scenario 1 (Table 9), and the energy demand for 3 RRBs was 101.85 MJ in Scenario 2 compared to 69.41 MJ in Scenario 1 (Table 9). In comparison to Scenario 1, Scenario 2 increases the energy demand of RRBs by 32.50 MJ, a 47% increase, and the energy demand of SUPGBs by 285.40 MJ, a 47% percent increase. In Scenario 2, use of RRBs in place of SUPGBs reduces the primary energy demand by 796 MJ, an 89% percent decrease.

Table 12. Energy Consumption Results - Scenario 2 (365 Uses per Year)

	Primary energy demand from renewable and nonrenewable resources (gross cal. value) [MJ]	**Primary energy from nonrenewable resources (gross cal. value) [MJ]**	**Primary energy from renewable resources (gross cal. value) [MJ]**
SUPGB			
per FU	2.46	2.42	0.041
per # bags/year	**897.90**	883.30	15.00
RRB			
per FU	34.88	34.40	0.48
per # bags/year	**101.85**	100.46	1.39

Table 13 shows the Scenario 2 results for water use throughout the life cycle of both bags. Consistent with the water use results for Scenario 1, the results per functional unit and results per number of bags per year indicated the water consumption of the RRB was significantly lower than the SUPGB in all water use categories. Therefore, with proper reuse of RRBs until their end of life of 125 uses, RRBs produce a lower water impact than SUPGBs, assuming bags are used 365 times per year. The blue water consumption for 365 SUPGBs used in a year was 52.56 kg in comparison to 14.31 kg for 3 RRBs. As discussed above, the use of RRBs in place of SUPGBs decreases the blue water impact of recycling programs by 38.26 kg or 92%.

Table 13. Water Use Results - Scenario 2 (365 uses per Year)

	Blue water consumption [kg]	**Blue water use [kg]**	**Total freshwater consumption (including rainwater) [kg]**	**Total freshwater use [kg]**
SUPGB				
per FU	0.14	6.71	0.29	6.88
per # bags/year	**52.56**	2449.15	105.85	2511.20
RRB				
per FU	4.90	101.00	7.11	103.00
per # bags/year	**14.31**	294.92	20.76	300.76

Table 14 shows a comparison between the five major EICs for Scenario 3. Based on the reference flow calculations shown in Table 6, 52 SUPGBs and 0.42 RRB were used to fulfill the parameters for Scenario 3, disposing of recyclables 52 times per year.[4] Consistent with Scenario 1 and 2, when comparing on the functional unit basis, the SUPGB resulted in a lower environmental impact across all five categories. However, the results for the number of bags per year showed the RRB had significantly less impact across the board. Global warming excluding biogenic carbon shows that use of 52 SUPGBs would produce 4.50 kg of CO_2 in contrast to 21.50 kg of CO_2 produced in Scenario 1 (Table 4) and use of approximately 1 RRB produced 0.60 kg of CO_2 in comparison to 2.80 kg of CO_2 produced in Scenario 1 (Table 4). In comparison to Scenario 1, Scenario 3 decreases the global warming impact of RRBs by 2.2 kg of CO_2 and decreases the global warming impact of SUPGBs by 17 kg of CO_2. In Scenario 3, use of RRBs in place of SUPGBs reduces the global warming impact of recycling programs by 3.90 kg of CO_2, or 87%.

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[4] We acknowledge that using 0.42 bags is impractical. In reality, the bag user would always be using 1 whole bag. However, based on the FU calculations, the impacts of using a RRB 52 times a year would equate to using less than half a bag.

Table 14. TRACI 2.1 EIC Results - Scenario 3 (52 Uses per Year)

	Acidification [kg SO2-Equiv.]	**Eutrophication [kg N-Equiv.]**	**Global Warming Air, excl. biogenic carbon [kg CO2-Equiv.]**	**Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]**	**Ozone Depletion Air [kg CFC 11-Equiv.]**	**Resources, Fossil fuels [MJ surplus energy]**
SUPGB						
per FU	3.94 E-4	1.88 E-5	0.09	0.09	2.35 E-12	0.29
per # bags/year	0.02	9.77 E-4	**4.50**	4.74	1.22 E-10	15.03
RRB						
per FU	6.19 E-3	6.77 E-4	1.43	1.50	3.42 E-11	4.09
per # bags/year	2.60 E-3	2.84 E-4	**0.60**	0.63	1.44 E-11	1.72

Table 15 shows the Scenario 3 results for primary energy consumption throughout the life cycle for both bags. Consistent with the TRACI EIC results in Table 14, when SUPGBs and RRBs were compared on a bag-to-bag functional unit basis, SUPGB production required a drastically lower amount of energy. However, when compared on the basis of the number of bags used in a year, the overall energy consumption of the RRB was significantly lower than the SUPGB for both renewable and nonrenewable resources. The primary energy demand for renewable and nonrenewable resources for 52 SUPGBs was 127.92 MJ in Scenario 3 compared to 612.54 MJ in Scenario 1 (Table 6), and the energy demand for 1 RRB was 14.65 MJ in Scenario 3 compared to 69.41 MJ in Scenario 1 (Table 6). In comparison to Scenario 1, Scenario 3 decreases the energy demand of RRBs by 54.80 MJ and decreases the energy demand of SUPGBs by 484.58 MJ. In Scenario 3, use of RRBs in place of SUPGBs reduces the primary energy demand of recycling programs by 113.32 MJ or 88%.

Table 15. Energy Consumption Results - Scenario 3 (52 Uses per Year)

	Primary energy demand from renewable and nonrenewable resources (gross cal. value) [MJ]	Primary energy from nonrenewable resources (gross cal. value) [MJ]	Primary energy from renewable resources (gross cal. value) [MJ]
SUPGB			
per FU	2.46	2.42	0.04
per # bags/year	**127.92**	125.84	2.14
RRB			
per FU	34.88	34.40	0.48
per # bags/year	**14.65**	14.45	0.20

Table 16 shows the Scenario 3 results for water use throughout the life cycle of both bags. Following the trend shown in Scenario 1 and 2, the results per functional unit and results per number of bags per year indicated the water consumption of the RRB continued to be lower than the SUPGB in all water use categories. With the proper reuse of RRBs until their end of life of 125 uses, and used once a week for a year, RRBs can produce a lower water impact than SUPGBs, assuming bags are used 52 times per year. The blue water consumption for 52 SUPGBs used in a year was 7.49 kg in comparison to 2.06 kg for a RRB. Therefore, use of RRBs in place of SUPGBs reduces blue water consumption by 5.43 kg, or 72%, in Scenario 3.

Table 16. Water Use Results - Scenario 3 (52 Uses per Year)

	Blue water consumption [kg]	Blue water use [kg]	Total freshwater consumption (including rainwater) [kg]	Total freshwater use [kg]
SUPGB				
per FU	0.14	6.71	0.29	6.88
per # bags/year	**7.49**	348.92	15.08	357.76
RRB				
per FU	4.90	101.00	7.11	103.00
per # bags/year	**2.06**	42.42	2.99	43.26

Sensitivity Analysis

Sensitivity analysis allows us to assess how a model is influenced in response to changes in uncertainty factors. A key factor in comparing SUPGBs and RRBs was assessing how reusability of the RRB affects its environmental impact. A major assumption of this model was the manufacturer-provided lifespan of the RRB (125 uses); therefore, we conducted a sensitivity analysis to assess how increasing the expected number of reuses of the RRB would influence the environmental impact. We intended to collect a new estimated minimum lifespan through our field test; however, none of the RRBs reached their end of life stage before the end of the field test. Therefore, we assumed the manufacturer lifespan was a conservative estimate and RRBs are likely viable beyond 125 uses. Although no concrete data was available on alternative lifespan estimates for the RRB, we know of at least one bag that has been tested in at-home recycling programs and has been in use for more than five years with weekly emptying (5 years x 52 weeks = 260 uses), giving preliminary evidence the RRB could be viable beyond 250 uses (S. Katz, personal communication, June 2, 2021). In conjunction with this LCA, we field-tested the RRB at UCSB, where janitorial staff confirmed the RRB is durable and they assumed it would be viable well beyond 125 uses; supporting our suspicion that the manufacturer's 125-use lifespan was a conservative, low range estimate. Based on this, we chose to assess the sensitivity of our model using a mid-range estimate of a 250 use lifespan and high estimate of a 500 use lifespan.

Scenario 1 was used as the baseline for the sensitivity analysis and the lifespan of the RRB was increased to test the sensitivity of the comparison. Table 17 shows the results in "per number of bags/ year" units for five major EIC categories across the three lifespans assessed: 125 (manufacturer-recommended), 250, and 500 uses. Increasing the lifespan of the RRB decreased the environmental impact of the RRB in all five TRACI impact categories (Table 17). As seen in Table 8, under Scenario 1 the global warming excluding biogenic carbon impact of use of 249 SUPGBs is approximately 21.50 kg CO_2. As stated previously, assuming a 125-use lifespan for the RRB, use of RRBs in place of SUPGBs reduces the global warming impact by 18.70 kg of CO_2 (Table 8, Table 17). If the expected RRB lifespan is doubled to 250 uses, use of RRBs reduces the global warming impact by 1.43 kg of CO_2 from the manufacturer's expected lifespan of 125 uses. If the expected RRB lifespan is doubled again to 500 uses, use of RRBs reduces the global warming impact by 0.71 kg of CO_2. Doubling RRB lifespan leads to a 50% decrease in global warming impact from the manufacturer's expected lifespan of 125 uses.

Table 17. Comparison of TRACI 2.1 EIC Results Based on Three Different RRB Lifespans - Scenario 1 (249 Uses per Year)

Lifespan of RRB	**Acidification [kg SO2-Equiv.]**	**Eutrophication [kg N-Equiv.]**	**Global Warming Air, excl. biogenic carbon [kg CO2-Equiv.]**	**Global Warming Air, incl. biogenic carbon [kg CO2-Equiv.]**	**Ozone Depletion Air [kg CFC 11-Equiv.]**	**Resources, Fossil fuels [MJ surplus energy]**
125 Uses (manufacturer recommended)	0.01	1.35 E-3	**2.85**	2.99	6.81 E-11	8.14
250 Uses	6.17 E-3	6.70 E-4	**1.42**	1.49	3.41 E-11	4.07
500 Uses	3.08 E-3	3.40 E-4	**0.71**	0.75	1.70 E-11	2.04

Table 18 shows the results in “per number of bags/ year” units for primary energy consumption across the three lifespans assessed: 125 (manufacturer-recommended), 250, and 500 uses. Consistent with the results in Table 14, increasing the lifespan of the RRB decreases the primary energy consumption. As seen in Table 9, under Scenario 1 the primary energy demand for renewable and nonrenewable resources for 249 SUPGBs is approximately 612.54 MJ. As discussed previously, assuming the manufacturer's estimated lifespan of 125 uses, use of RRBs in place of SUPGBs reduces the primary energy demand for renewable and nonrenewable resources by 89% (Table 9). If the expected lifespan of 125 is doubled to 250 uses, the energy demand of the RRB is reduced by 34.67 MJ and if the expected lifespan is doubled again to 500 uses, the energy demand of the RRB is reduced by 52.03 MJ. Similar to the global warming impact, doubling the RRB lifespan leads to a 50% decrease in primary energy demand from the manufacturer's expected lifespan.

Table 18. Comparison of Energy Consumption Results Based on Three Different RRB Lifespans - Scenario 1 (249 Uses per Year)

Lifespan of RRB	Primary energy demand from renewable and nonrenewable resources (gross cal. value) [MJ]	Primary energy from nonrenewable resources (gross cal. value) [MJ]	Primary energy from renewable resources (gross cal. value) [MJ]
125 Uses (manufacturer recommended)	**69.41**	68.46	0.95
250 Uses	**34.74**	34.27	0.47
500 Uses	**17.37**	17.13	0.24

Table 19 shows the results in "per number of bags/ year" units for water use across the three lifespans assessed: 125 (manufacturer recommended), 250 and 500 uses. Consistent with the results in Table 17 and Table 18, increasing the lifespan of the RRB decreases the water impact. As seen in Table 10, under Scenario 1 the blue water consumption for 249 SUPGBs is approximately 612.54 kg. As discussed previously, assuming the manufacturer's estimated lifespan of 125 uses, use of RRBs in place of SUPGBs reduces the blue water consumption by 25.91 kg, a 72 % reduction (Table 19). If the expected lifespan is doubled to 250 uses, the blue water consumption of the RRB is reduced by 5.07 kg from the manufacturer's expected lifespan and if the expected lifespan is doubled again to 500 uses, the water consumption of the RRB is reduced by 7.51 kg. Both lifespan adjustments decrease the water consumption impact by 50%.

Table 19. Comparison of Water Use Results Based on Three Different RRB Lifespans - Scenario 1 (249 Uses per Year)

Lifespan of RRB	Blue water consumption [kg]	Blue water use [kg]	Total freshwater consumption (including rainwater) [kg]	Total freshwater use [kg]
125 Uses (manufacturer recommended)	**9.95**	200.99	14.15	204.97
250 Uses	**4.88**	100.60	7.08	102.59
500 Uses	**2.44**	50.30	3.54	51.29

Discussion & Analysis

The results of the LCA indicate the RRB has a lower environmental impact across all TRACI EICs in comparison to SUPGBs; most importantly in the global warming impact, primary energy consumption, and water consumption categories, as these had the highest environmental impact. The global warming impact of recycling programs is important for companies to consider and reduce because GHG emissions are the most significant contributing factor to climate change. The results of this study show RRBs, under all scenarios and life spans analyzed, reduce the amount of GHGs companies contribute to the environment.

Another EIC of interest is resource and fossil fuel use. Reduction in fossil fuel use is an important global consideration that is particularly of interest to companies working to reduce their Scope 1, 2, and/or 3 emissions. The results indicate the RRB reduces resource and fossil fuel use compared to SUPGBs in all scenarios, which can reduce a company's overall GHG impact. However, both the SUPGB and RRB are manufactured with electricity from China's electricity grid, which is heavily reliant on coal (64% coal, 28% renewables, and 5% nuclear), contributing to the high GHG emissions for both the RRB and SUPGB. While companies that choose RRBs over SUPGBs contribute less GHGs, if China reached its goal of 80% renewable energy by 2060, the RRB production process could contribute even less GHGs (Yin, 2021).

Other important EICs to consider include acidification and eutrophication. While these EICs have low environmental impacts, they can produce harmful effects locally. Assessing the impacts of acidification and eutrophication are important local considerations in regions where raw material extraction occurs. The acidification and eutrophication of local water can cause many issues, including reducing the integrity of food webs and ecosystem services, such as recreation, sportfishing, and commercial fisheries ("Eutrophication and Hypoxia," n.d.; "Top Fossil Fuel," 2019). The results show the RRB has a smaller acidification and eutrophication impact than the SUPGB in all scenarios analyzed, which would reduce local and global environmental impacts of bag use on local watersheds.

Additionally, while ozone depletion is no longer a big concern in the United States, countries such as China still face issues regarding pollution from industrial practices causing ozone depletion. Ozone depletion causes UV radiation levels to increase at Earth's surface, especially in polluted regions, which is damaging to terrestrial and aquatic ecosystems, as well as human health ("Ozone Layer Depletion," n.d.). The RRB results show the impact of ozone depletion is smaller in all scenarios analyzed compared to the SUPGB. Prioritizing production of goods that have overall less environmental impact in this category could be beneficial in the long run as China's economy and population continue to grow. These considerations give us insight that even small changes in certain EICs can benefit the countries and local communities where RRB materials are extracted and the RRB is manufactured.

Our results show that the RRB production consumes less water across its life cycle compared to the SUPGB across all scenarios. However, it is important to note that this analysis of water use does not take into consideration water used for cleaning of the RRB; therefore, the total water use for the RRB including cleaning would be higher than our results. However, we assume the overall water impact for the RRB will not be higher than the water impact for the SUPGB even if water use for cleaning were to be incorporated. Regardless, the water impact of these bags is important to consider because blue water—fresh surface water and groundwater—is a scarce resource in high demand for products and communities (Boccaletti et al., 2009). Since the SUPGB and RRB are manufactured in China, both bags' water requirements would impact China's water resources. According to WRI's Aqueduct Water Risk Atlas, China's resources are dwindling quickly. Many regions across China are currently experiencing very high and worsening water stress—when there is not enough water to meet the demands of people and the environment—due to high levels of demand and low water supply (Wang, & Zhong, 2017). Given that RRBs use less water than SUPGBs across their lifecycle, primarily in their production and manufacturing life cycle steps, this alternative can reduce a company's contribution to water stress in China.

One of the limitations to our analysis was the lack of concrete data on the recycled material content of the RRB. The RRB manufacturer reported 20-40% of the woven PP material was recycled content but was unable to provide data or evidence supporting whether or not the material was post-consumer recycled content (M. Callahan, personal communication, June 10, 2021). Therefore, we assumed the "recycled" material was runaround scrap produced and collected at the RRB manufacturing facility and there was no post-consumer recycled material included in the production of the RRB. Runaround scrap refers to PP scrap material that, instead of entering the waste stream, re-enters the bag manufacturing process. Although use of runaround scrap reduces landfill waste, this process does not produce truly recycled—post-consumer—content. To incorporate runaround scrap into the model, we reduced material loss in the manufacturing step of the RRB to 0%.

If any or all of the reported recycled content in the RRB was post-consumer recycled content, we assume this would further reduce the environmental impact of the RRB. The production of virgin PP was the main driver of water and energy consumption in the RRB life-cycle; therefore, we assume substitution of post-consumer PP would significantly reduce both water and energy impacts. However, we hypothesize if post-consumer recycled material was included in the model, the impacts associated with the recycling process, production of post-consumer recycled PP material, and transportation of recycled material would introduce additional impacts to consider and analyze.

As stated in the assumptions section, we were unable to access LCI inventory data for the production of woven PP material. At the time of this analysis, LCI data for woven PP did not exist in any public LCA database or software. Based on the literature, we substituted the production of PP film for the production of woven PP in this analysis. This assumption favors the RRB, as PP film production is less energy and water intensive than woven PP production (Civancik-Uslu et al., 2019). However, SUPGB impacts are more than five times higher on average in all TRACI EIC's and primary energy use categories; therefore, we assume the effects of substituting film production for weaving did not influence the overall conclusion that the RRB is less environmentally impactful than SUPGBs.

A major assumption we made for this analysis surrounded the inclusion of the elastic band in the RRB. Elastic is a textile and the production of elastic should be included as a unit process in this analysis; however, the GaBi database we had access to did not have textile data for elastics. The elastic band comprised 3.6% of the total weight of the RRB; therefore, using the 1% cut-off criteria for material mass, the weight of the elastic was included in the RRB model despite the lack of elastic textile data. Therefore, the weight of the elastic, 14.57 grams, was added to the assembly step in the RRB model. We expect this influenced the results to again favor the RRB, since LCI data for the elastic band was not truly integrated into the model and assessed by TRACI.

Further analysis of the individual processes in the RRB life cycle demonstrated the three highest contributors to water use and consumption were the nylon granulate process used to make the nylon handles, the PP granulate process used to make the PP material, and the water demand of the global electricity grid mix. Due to the fact the granulate processes we used in this study were aggregate processes found in the GaBi database, further research is required to understand what aspect of the raw material extraction process contributes most significantly to the high-water demand and if adjustments to raw material extraction could be made to lessen the demand.

The main limitations of our analysis were the lack of data from the RRB manufacturer and supplier and the data limitations in the software available given the budgetary limits of this project. Both the data quality and software could be improved in future analyses to generate a more accurate assessment of the environmental impacts of RRBs in comparison to SUPGBs. Our LCA could be made more robust with concrete life cycle inventory data for the raw material sourcing, China specific manufacturing, and transportation of the RRB to replace the aggregate inventory data used in this assessment. Further, concerte information on the source of the recycled content in the RRB would eliminate the assumptions made regarding runaround scrap. However, this analysis is a robust initial comparison of the environmental impacts associated with single-use and reusable bags used to line recycling receptacles.

VII. Financial Analysis

Objective

Create a financial model to identify the monthly, annual, and multi-year costs of lining recycling receptacles with SUPGBs versus RRBs (Objective #3).

Background

The goal of the financial analysis was to provide detailed information on the financial tradeoffs between RRBs and SUPGBs to help WSP and Company X better assess the feasibility of using a RRB to line recycling receptacles. Without a cost comparison of SUPGB versus RRB lining systems, Company X did not understand which bag option would result in cost savings. Cost savings often motivate companies to implement environmental improvements; therefore, information on what bag option reduces costs could motivate Company X to implement the more environmentally sustainable bin lining system (*5 Ways Managers Can Use Finance to Make Better Decisions* | *HBS Online*, 2020). To help WSP and Company X properly evaluate the financial tradeoffs, we created a financial model that analyzes and compares the costs of implementing each bag type on Company X's corporate campus and provides information on which bag option results in cost savings.

Our financial analysis was created as an Excel-based model that calculates the monthly and annual costs of using SUPGBs and RRBs to line recycling receptacles. The model was run with pertinent data for Company X's corporate campus to produce detailed financial comparisons—cost differences between bag options, the total cost for each bag option, the initial investment cost of the RRB, and the monthly variable and intermittent costs for both bag options. The model also quantified the annual monetary value of the environmental impact of each bag option using Company X's internal cost of carbon. Internal carbon pricing is a mechanism used by companies to put a value on their greenhouse gas emissions. The model used known inputs from Company X's campus, results from the LCA, and assumptions based on our field test results to conduct the cost calculations. The cost comparisons generated by the financial model for Company X were estimates of the actual costs due to the lack of data WSP and Company X were able to provide about their recycling program. However, updated data could be inputted into this model to generate more accurate results.

The price per unit of the RRB was pertinent data for the inputs used in our model. At the time of this project, Waste Management (WM) was the only direct-to-consumer retailer of RRBs; however, the WM RRB (19 gal) was not the correct size to fit the receptacles at Company X's campus (40 gal). It was not plausible within the timeline of this project to design a bag to fit Company X's receptacles, so we did not have a direct quote on the price for a 40 gallon RRB. Therefore, we extrapolated a price per gallon estimate for the RRB by dividing the

WM price by its size, 19 gallons (*Commercial Reusable Recycling Bag,* 2022). If Company X is to further consider implementation of the RRBs, WSP could work with the manufacturer and distributor of RRBs— Factory Direct Promos and Zorch International respectively— to obtain a more accurate quote on a price for RRBs. Use of this price as an input in the model would generate more accurate cost estimates.

We also provided a blank copy of the model to allow other companies to input their unique data and visualize the cost comparisons of use of SUPGBs versus RRBs. The blank model provides companies with results from the LCA and our field test; however, companies could adjust the inputs to fit their unique information if further environmental analysis is conducted in the future or the RRBs are field tested in other locations. Furthermore, if a campus has multiple bin sizes, the model could be run twice to account for this. After building the financial model, the calculations and results from this analysis were then used as the basis for the Shiny App Impact Calculator.

Design

The design of our financial model was a multi-tab spreadsheet-based model created in Microsoft Excel. The spreadsheet had five tabs: (1) Inputs, (2) SUPGB Costs, (3) RRB Costs, (4) Cost Savings, and (5) Monetary Value of the Environmental Impact. The cost comparison was conducted over a 12-month period. Tab 1, the inputs tab, included data from Company X about their recycling program, results from the LCA, and results from the field test. Tab 2 and 3 calculated the monetary value of the variable costs, intermittent costs, capital costs, total monthly costs, and total annual cost for the SUPGB and RRB respectively. Tab 4 quantified the annual cost difference, showing which bag results in cost savings. Finally, Tab 5 generated a monetary value of the environmental impact using Company X’s internal cost of carbon.

Methods & Assumptions

To create our financial model, we created a list of inputs, determined the relevant capital, variable, and intermittent costs, and created the necessary functions to calculate the costs in the spreadsheet model.

First, we created a list of pertinent inputs necessary to calculate the costs associated with each bag. The inputs were acquired from Company X, the results of the field test, results of the LCA, and the reusable bag itself. UCSB’s campus recycling program mimics those of Company X; therefore, we assumed data collected from our field test as a proxy for data we could not collect directly from Company X. We used these inputs to quantify the total costs associated with SUPGB and RRB bin lining systems, including the relevant variable costs, intermittent costs, and capital costs associated with the recycling program.

We then determined the capital costs relevant to lining recycling receptacles with single-use or reusable bags. The capital costs included the fixed, one-time expenses incurred if RRBs were implemented in Company X's recycling program. At the time of this project, Company X was lining recycling receptacles with SUPGBs; therefore, we assumed there were no capital costs with the SUPGB system because this was the business-as-usual scenario. Capital costs included the initial purchase of the RRBs, cost to train janitorial staff on RRB procedures, cost of cleaning supplies purchased, and cost of new equipment purchased. We assumed Company X would purchase two RRBs per recycling receptacle based on the results of our field test. The janitorial staff at UCSB confirmed that having two bags per bin was necessary, so they would have a replacement bag when the primary bags were removed for cleaning or needed replacement due to damage. To quantify the price per RRB, we used the cost available for the RRB sold on the Waste Management Website and divided this by the number of gallons to quantify a per gallon cost for the RRB, as described in the Background section (*Commercial Reusable Recycling Bag,* 2022). The function for the initial purchasing cost of RRBs was calculated as the product of the number of recycling receptacles at Company X's campus, receptacle size in gallons, and price of RRB per gallon multiplied by two. We assumed Company X would not need to invest in new equipment to transport recyclables or cleaning supplies; however, there are cells within the capital costs section of this model for such inputs if future research deems this is necessary. This assumption was based on our observations of the field test and understanding of equipment used at Company X's campus. We accounted for the cost to train the janitorial staff by calculating the product of the janitor's hourly wage, the hours spent to train the janitorial staff on implementing the RRB system, and the number of janitorial employees on-site. We assumed the training time from the field test as an estimate of training time for Company X's campus. Although this gave a monetary quantification of the time cost to the janitorial staff, we assumed RRB implementation training will occur during regular working hours; therefore, this would not be an added cost incurred by Company X. The sum of the capital costs showed the initial investment cost for Company X to switch to the RRB system.

We then determined the relevant intermittent costs that would be incurred by Company X for lining recycling receptacles. We assumed SUPGBs would have no intermittent costs since they were disposed of after each use. Intermittent costs included the replacement costs for the RRBs, cleaning supplies purchased to clean the RRB, and contamination charges incurred from contaminated recycling. Based on the results of our field test, we assumed the additional cleaning supplies needed to clean the RRBs would not significantly impact the janitorial budget allotted for cleaning supplies. Based on the results of the field test, we assumed the intermittent cleaning cost for Company X to clean RRBs would be zero. However, a row was left in the model for cleaning costs if future RRB use and cleaning gives evidence of substantial costs for cleaning products. Contamination costs incurred from contaminated recycling were another intermittent cost (M. O'Carroll, personal communication, October 2021). We assumed this cost was intermittent since the contamination per month could vary based on disposal. The contamination cost row was the average monthly charge added to Company X's bill from their recycling collector. At this time we do not have data on contamination charges incurred by Company X. However, a space was left in the financial analysis for contamination charges because this could be pertinent to other companies or to Company X in the future.

The RRB bag lining system would incur intermittent replacement costs for the RRBs themselves. The replacement cost for RRB was calculated by finding the product of the cost per RRB per gallon, the number of recycling receptacles at Company X's campus, the size of the receptacle in gallons, and the replacement rate of the RRB multiplied by two, to replace both bags initially purchased for each bin. The replacement rate of the RRB was quantified using the minimum number of uses of the RRB (125 uses). For the purposes of this analysis, we defined 'use' as the RRB being lifted from the recycling receptacle and emptied into exterior or collection bins. Since two bags would be in rotation at Company X's campus, Company X would need to purchase a set of two bags per bin after 250 uses (125 uses x 2 bags). Therefore, given daily use—RRBs being emptied every day of the five-day work week—RRBs would need replacement every fifty weeks (250 uses/5 days = 50 weeks), meaning replacement would occur in month twelve of the first year. We assumed holidays would have a negligible impact on the cost comparison; therefore, we excluded holidays from our financial analysis.

We then determined the variable costs relevant to recycling bin lining at Company X's campus. We assumed Company X was currently purchasing SUPGBs to line recycling receptacles monthly. Therefore, the cost of purchasing SUPGBs was quantified by calculating the product of the cost per SUPGB, the number of recycling receptacles, and the turnover rate—the frequency the bins are emptied and the SUPGB is replaced. To maintain an apples to apples comparison of bag types, we used the direct to consumer price per SUPGB available on the Staples website, instead of the bulk purchasing cost per bag provided by Company X (Staples, n.d.). Recycling receptacles were emptied daily at Company X, so the turnover rate was 30 SUPGBs per month. With the RRB system, the cost of purchasing RRBs was not a variable cost because the bags would not need replacement at monthly intervals. The janitorial cost for emptying recycling receptacles in both systems was a variable cost. Our field test gave us estimates for the average time to empty recycling receptacles using the SUPGB bin lining system and RRB bin lining system. We assumed these time estimates were comparable to the time it would take janitorial staff at Company X's corporate campus to empty receptacles. Therefore, we quantified the janitorial time cost for emptying recycling bins with the SUPGB system by calculating the product of the number of recycling receptacles, the hourly wage for the janitorial staff, and the estimated time to empty a recycling receptacle with a SUPGB. Again, we assumed the janitorial wage as described above. We assumed emptying the bag is part of the janitor's daily routine, so this would not be an additional cost to the janitor's salaries. For the RRB system, we assumed water use and cleaner use for cleaning the bags would vary by month depending on recycling contamination. Although Company X would incur costs for both water and cleaner used to clean the RRBs, we assumed the added consumption of water and cleaner would not substantially increase Company X's total water and cleaning costs, so these metrics were assumed to be zero.

Following the cost breakdowns in Tabs 2 and 3 for the SUPGB and RRB systems respectively, we quantified the annual difference in cost by subtracting the annual total cost values for SUPGB and RRB to determine which bag was the more cost-effective option for Company X in Tab 4.

Finally, in Tab 5 we quantified the monetary value of the environmental impact of each bag option. We used the results from our LCA for the TRACI 2.1 impact category for total life-cycle GHG emissions excluding biogenic carbon for both the RRB and SUPGB, the number of SUPGBs and RRBs used by Company X in a year assuming recycling receptacles were emptied daily, and Company X's internal cost of carbon—a monetary value for each ton of carbon emissions associated with the company—to quantify the monetary value of the environmental impact of annual purchasing of recycling bin liners. This generated the internal cost of carbon for use of the RRBs versus SUPGBs over a one year period under Scenario 1.

Results

The results of our financial model run with data for Company X are displayed in the tables below. The results were based on the Scenario 1 assumptions that recycling receptacles are serviced daily, meaning every day of the 5-day work week and the RRB was viable for 125 uses, the minimum number of uses on the RRB tag. Table 20 displays the monthly costs of the SUPGB system; Table 21 shows the capital investment cost of the RRB system; Table 22 displays the monthly costs of the RRB system; Table 23 shows a side-by-side comparison of SUPGB versus RRB costs; Table 24 displays the annual costs of both the SUPGB and RRB systems and the cost savings; and Table 25 shows the monetary value of the environmental impact of purchasing each type of bag for one year.

Table 20 displays the monthly costs of the SUPGB system. Our analysis assumed SUPGBs were the business-as-usual scenario for Company X; therefore, use of SUPGBs would incur no capital costs. The variable costs for SUPGBs are consistent each month because recycling receptacles are serviced daily (Scenario 1), meaning a consistent number of SUPGBs are assumed to be purchased per month. The model for SUPGB costs did not include costs associated with cleaning as these costs are only associated with RRB use. We also assumed the contamination charges incurred with the use of SUPGBs was zero due to a lack of data. Data regarding contamination charges incurred by Company X due to the use of SUPGBs contaminating recyclables would make the monthly cost assessment more robust. The total monthly cost for Company X to line recycling receptacles with SUPGBs was $5,918.94. SUPGB costs included the cost of purchasing bags ($1,862.40) and janitorial time cost for emptying bins ($3,649.14) (Table 20). SUPGB monthly costs did not vary; therefore, the costs displayed below would be incurred every month of the calendar year. Additionally, the monthly costs could be expanded beyond the one year period to compare costs across a multi-year period.

Table 20. SUPGB Monthly Costs - Company X

Variable Costs	
Cost of Purchasing SUPGBs	$2,269.80
Janitorial Cost (Emptying Bins)	$3,649.14
Janitorial Cost (Cleaning Bags)	0
Cleaner Cost for Cleaning Bags	0
Intermittent Costs	
Replacement Bags	0
Cleaning Supplies	0
Contamination Charges	0
Total Monthly Costs	**$5,918.94**

Table 21 shows the initial capital investment costs of the RRB system. We assumed capital investment costs would occur before the calendar year begins in “Month 0”. We assumed Company X would not need to purchase additional equipment or cleaning supplies based on our field test results and lack of Company X specific janitorial information; therefore, the capital costs only included the initial purchasing cost of the RRBs ($15,618.02) and the cost to train the janitorial staff ($9.50) to implement the RRB system. The total capital investment cost for Company X to implement the RRB system is $15,627.52 (Table 21).

Table 21. RRB Capital Investment Costs - Company X

Capital Investment Costs	
RRB's Initial Purchasing Cost	$15,618.02
Cost to Train Janitorial Staff	$9.50
Cost of New Equipment	0
Cost of Cleaning Supplies	0
Total Capital Investment Cost	**$15,627.52**

Table 22 displays the monthly variable costs for the RRB system. Because the RRB was assumed to be reused 125 times, the cost of purchasing RRBs was not a variable cost incurred by Company X as the bags would not need to be replaced monthly. The cost for purchasing RRBs was included as an intermittent cost. The intermittent costs for the RRB system, not shown, were zero until Month 12 when the RRBs reached their 125 minimum use lifespan[5]. Therefore, in Month 12 Company X would incur an additional $15,618.02 cost for purchasing two new RRBs per recycling receptacle (See Table 21 for RRB Purchasing Cost). We lacked data from our field test to confirm the cost of cleaning supplies for the RRB, so we assumed the cost of cleaning supplies would be zero. Therefore, the janitorial time cost for emptying bins with the RRBs and cleaning the RRBs were the only costs that varied monthly for Company X. The total monthly variable costs for the RRB system at Company X are $2,769.57 with the janitorial time cost of emptying bins with the RRB ($2,764.50) and the janitorial time cost for cleaning the RRBs ($5.07) (Table 22).

Table 22. RRB Monthly Costs

Variable Costs	
Cost of Purchasing RRBs	0
Janitorial Cost (Emptying Bins)	$2,764.50
Janitorial Cost (Cleaning Bags)	$5.07
Cleaner Cost for Cleaning Bags	0
Total Monthly Costs	**$2,769.57**

Table 23 displays a side-by-side comparison of all costs incurred by both bag lining systems. On the RRB side, it is important to note that the intermittent cost for bag replacement only

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[5] Assuming each receptacle has 2 RRBs, there were a combined 250 uses per bin (2 x 125 = 250), and assuming bins were emptied 5x per week, the 250 uses would extend over a 50 week period (250/5 = 50). Therefore, RRBs would need to be replaced in the 50th week of the calendar year, which is in Month 12.

occurs one time in Month 12 of the analysis; therefore, this cost is excluded from the RRB monthly cost calculation and only added into the annual cost calculation one time. The annual cost for the SUPGB system was calculated by taking the sum of the monthly variable costs (Table 20) over a calendar year. The annual cost of the RRB system was calculated by taking the sum of the capital investment cost of the RRB system (Table 21), the monthly variable costs of the RRB system (Table 22) over a calendar year, and the one time intermittent cost for replacing the RRBs incurred in Month 12 of the analysis (Table 23).

Table 23. SUPGB versus RRB Cost Comparison

SUPGB System Costs		**RRB System Costs**	
Capital Investment Costs		**Capital Investment Costs**	
Initial Purchasing Cost	0	RRB's Initial Purchasing Cost	$15,618.02
Cost to Train Janitorial Staff	0	Cost to Train Janitorial Staff	$9.50
Cost of New Equipment	0	Cost of New Equipment	0
Cost of Cleaning Supplies	0	Cost of Cleaning Supplies	0
Total Capital Costs	**$0**	**Total Capital Costs**	**$15,627.52**
Variable Costs		**Variable Costs**	
Cost of Purchasing SUPGBs	$2,269.80	Cost of Purchasing RRBs	0
Janitorial Cost (Emptying Bins)	$3,649.14	Janitorial Cost (Emptying Bins)	$2,764.50
Janitorial Cost (Cleaning Bags)	0	Janitorial Cost (Cleaning Bags)	$5.07
Cleaner Cost for Cleaning Bags	0	Cleaner Cost for Cleaning Bags	0
Intermittent Costs		**Intermittent Costs**	
Replacement Bags	0	Replacement Bags*	$15,618.02*
Cleaning Supplies	0	Cleaning Supplies	0
Contamination Charges	0	Contamination Charges	0
Total Month Costs	**$5,918.94**	**Total Monthly Costs**	**$2,769.57**
Total Annual Cost	**$71,027.28**	**Total Annual Cost**	**$64,480.37**

Table 24 displays the annual costs for each bin lining system and the annual cost savings. Our model showed implementing RRBs at Company X's corporate campus would result in annual cost savings in the first year. The RRB system reduced Company X's annual costs by

$7,546.91. The total annual cost for the SUPGB system and RRB system were $71,027.28 and $64,480.37 respectively (Table 24).

Table 24. Annual Cost Comparison - Company X

	SUPGB System	RRB System
Total Annual Cost	$71,027.28	$64,480.37
Annual Cost Savings	–	**$7,546.91**

Table 25 shows the monetary comparison of the environmental impact. Our model calculated the monetary value of the annual environmental impact of each bin lining system using the greenhouse gas (GHG) emissions for each bag from our LCA and Company X's internal cost of carbon and applied these metrics to the number of each bag used annually. The annual GHG emissions for producing the number of SUPGBs used by Company X in one year was 3.43E-02 tons of CO2 equivalents, and the annual GHG emissions for producing the number of RRBs used by Company X in one year was 6.31E-03 tons of CO2 equivalents. The monetary value of the SUPGB system and RRB system were $100 and $18 respectively, meaning RRBs reduced the internal cost of carbon for bag purchasing bags to line recycling receptacles by $82 (Table 25).

Table 25. Monetary Comparison of the Annual Environmental Impact - Company X

	SUPGB System	RRB System
GHG Emissions (tons)	3.43 E-02	6.31 E-03
Internal Cost of GHG Emissions	$100	$18
Annual Savings	–	**$82**

Discussion & Analysis

Our financial model provided an estimate of Company X's operating expenses for the use of either SUPGBs or RRBs in their campus recycling program and compared the annual costs between the bin lining options. The results assumed Company X serviced recycling receptacles every day of the five-day work week. Several factors in the creation of the model and the collection of inputs specific to Company X led to the results not being fully reflective of the true operating expenses for each bag option; however, the model and data are robust enough to conclude that implementation of the RRB system would save Company X money in the first year.

Our model was based on the assumption that a RRB would be viable for 125 uses, as stated on the bag's tag as the minimum expected lifespan. However, this number is not supported by data or case study results; therefore, if the RRB is viable beyond 125 uses, the results presented above would not accurately represent the costs of the RRB system for Company X. The RRB has previously been tested in one in-home recycling system and has lasted five years with emptying once per week (S. Katz, personal communication, June 2, 2021). This provides us with preliminary evidence that the RRB may be viable for upwards of 250 uses; therefore, the results of the financial analysis would further favor the RRB and reflect larger cost savings. Continued use of the RRB in our field test and future field testing of the RRB is necessary to generate a more concrete estimate of the actual lifespan of the RRB and make this analysis more robust.

Our model includes assumed inputs for Company X due to a lack of data. As discussed previously, the price per gallon for the RRB was not acquired directly from the bag distributor (See Background Section). The price per gallon used in our model was extrapolated from a direct-to-consumer price for one bag, and not the distributor's cost per bag or cost of ordering RRBs in bulk. We assume a direct quote from the bag manufacturer would lower the price per gallon of purchasing the RRB. Therefore, we assume the results for the cost of purchasing RRBs is an overestimation of the true cost and use of a more accurate bag cost in the model would further favor the RRB and reflect larger cost savings. Future collaboration with the RRB manufacturer and distributor to receive a direct quote on the price per RRB for Company X's bin size would improve our models' estimate of the RRB costs.

Our model also includes assumptions of the inputs for contamination charges, equipment and cleaning supplies, water usage, and janitorial time costs due to a lack of Company X specific data. We set contamination charges incurred by Company X for contaminated recyclables to zero which produced results that favored the RRB; however, we assume Company X is incurring some amount of contamination charges so we expect the true benefit of switching to the RRB to be even larger. Additionally, we assumed that the capital costs for equipment and cleaning supplies for the RRB would be zero; however, we did not have specific information on Company X's janitorial equipment or cleaning supplies. Therefore, the capital costs for the RRB could be higher if Company X needs to purchase additional supplies to implement the RRB. We also assumed the water usage cost for cleaning the RRBs to be zero, underestimating the cost of the RRB system. This assumption was made due to our inability to measure water usage for cleaning the bags in the field test or access UCSB's water bill to understand their monthly water charges and if RRB use increased monthly charges. Future analyses with the capability to measure water usage for cleaning could incorporate this into the model to give a more robust quantification of RRB costs. We also lacked Company X specific data on the janitorial time to service recycling receptacles. Although we assumed time data from our field test would be comparable to the time for Company X's janitorial program, the timing of processes could differ at Company X's campus which would change the results of the model. Field testing RRBs at Company X's campus would give WSP and Company X more robust data for the janitorial labor time and a more accurate picture of additional equipment or cleaning supplies that would be required, making this financial analysis more robust.

The inclusion of janitorial time cost in the model adds costs that would not be directly incurred by Company X because the janitorial staff would be expected to empty recyclables as part of their general responsibilities included in their hourly wage or salary. The inclusion of janitorial processes provided an estimate of the monetary value of the time value of janitorial labor; however, this inclusion of these costs means the model did not produce exact values for the costs of both systems. If Company X wanted to visualize the direct costs incurred from each bag option, the janitorial costs could be excluded from the model.

Further, our model includes the estimated monetary value of the environmental impact associated with SUPGBs and RRBs used in Scenario 1. In 2020, Company X expanded their internal cost of carbon to cover some Scope 3 emissions, including company travel emissions and implemented procurement procedures to reduce Scope 3 supply chain emissions. If Company X were to expand their internal cost of carbon to additional Scope 3 emissions, such as those of their on-campus recycling services, SUPGBs and RRBs would contribute to their costs. Currently, SUPGBs and RRBs are outside of the scope of Company X's internal carbon costs and may be unrealistic for them to consider, given the larger carbon impacts of other parts of their organization. However, we calculated the internal cost of carbon associated with Company X's use of SUPGBs and potential use of RRB in the case that this value fits into the scope of emissions covered by their internal cost of carbon in the future. Regardless, the GHG emissions associated with bin lining for recycling is small in the larger scope of Company X's emissions; therefore, the monetary quantification of the internal cost of carbon would not likely impact Company X's purchasing decisions. We understand Company X is unique in having a robust carbon reduction strategy; therefore, this aspect of the model may not be applicable to WSP's other corporate clients now or in the future.

Finally, in addition to the model run with Company X specific data we also ran a model with data from our field test at UCSB. We were able to collect robust data for UCSB as we were able to implement the bags on UCSB's campus and meet with waste management and facilities staff. The model run with UCSB's data also resulted in annual cost savings. This analysis is proof of concept that our financial model is a robust framework to assess the financial implications of SUPGBs and RRBs and compare costs over time.

VIII. Shiny App Impact Calculator

Objective

Create a Shiny App Impact Calculator using the results of the financial analysis and LCA to allow WSP's clients to compare the financial cost, as well as the greenhouse gas and waste impact, of SUPGBs and RRBs (Objective #4).

Background

As a complement to the financial analysis, we created a financial and environmental impact calculator. Our calculator tool provides a user-friendly interface which allows users to input their company's unique parameters to obtain an estimate of the financial and environmental costs associated with SUPGB versus RRB bin lining systems. We drew inspiration for this calculator from the OZZI System Savings Calculator, which allows users to input values and obtain financial and environmental cost estimates for replacing single-use meal to-go containers with reusable alternatives ("OZZI System Savings Calculator," n.d.). At the time of this project, a user-facing calculator for our purposes was not publicly available.

Our calculator was created using the R package, "Shiny", which allows developers to easily code interactive web applications, called "Shiny Apps", within the environment of the statistical software R. Shiny Apps are helpful for professionals looking to communicate information to a targeted audience through an interactive website. (Gavras & Baumann, 2019) Our app will allow WSP to communicate the financial and environmental costs of using SUPGBs versus RRBs to line recycling receptacles in campus recycling to their clients, primarily Company X.

Methods

Inputs, Calculations, and Outputs

Our impact calculator is a simplified version of the financial analysis, and it synthesizes data from key calculations in the financial model and results from the LCA. We chose which calculations to include based on data that would be readily available to WSP and their clients. Our calculator works by allowing users to enter five unique input values for their company's facilities: (1) number of recycling receptacles, (2) size of receptacles (gal), (3) how often the receptacles are serviced per week (1-7), (4) price per unit of SUPGB ($/bag), and (5) contamination charges per month.

Using these five user inputs, the calculator makes 13 backend calculations (derived from the financial analysis) to arrive at the estimated materials required and cost outputs for each bin lining system. For detailed information on the assumptions that we made for these calculations, refer to the "Methods & Assumptions" section under Financial Analysis. These 13 calculations include:

1. Multiplying the number of receptacles by the service frequency and the number of weeks per year (52) to obtain the total number of SUPGBs the company uses per year
2. Multiplying the contamination charges per month by the number of months per year (12) to obtain total contamination charges per year
3. Multiplying the total number of SUPGBs the company uses per year by the price per unit of SUPGB plus the yearly contaminations charges to obtain the total cost of the SUPGB lining system
4. Multiplying the size of the receptacles by 1.00631579 (cost per gallon of the RRBs)[6] to obtain the price per unit of RRB (*Commercial Reusable Recycling Bag,* 2022)
5. Multiplying the number of receptacles by two because we are assuming two bags will be needed per receptacle for replacement purposes when one is dirty to obtain the total number of RRBs needed per year
6. Multiplying the total number of RRBs needed by the price per unit of RRB to obtain the total cost of the RRB lining system
7. Subtracting the total cost of the SUPGB by the total cost of the RRB lining systems to obtain the cost difference of switching from SUPGBs to RRBs
8. Multiplying the size of the receptacles by the total number of SUPGBs the company uses per year and 0.675[7] and then dividing that number by 1000 to obtain the waste generated by the SUPGB lining system per year in kilograms
9. Multiplying the size of the receptacles by the total number of RRBs needed per year and 12.2763158[8] and then dividing that number by 1000 to obtain waste generated by the RRB lining system per year in kilograms
10. Multiplying the number of SUPGBs used per year by the size of the receptacles and 0.0021625 (kg CO2e per gallon of SUPGB from LCA) and dividing by 1000 to obtain the GHG emissions associated with the SUPGB lining system in metric tons CO2e
11. Multiplying the initial number of RRBs by 0.03575 (kg CO2e per gallon of RRB from LCA) and divide by 1000 to obtain the GHG emissions associated with the RRB lining system in metric tons CO2e
12. Subtracting the waste generated in kilograms of the SUPGBs system from the RRB system to obtain an estimate of waste reduction achieved by switching from a SUPGB to a RRB lining system in kilograms
13. Subtracting the GHG emissions in tons of CO2e per gallon of the SUPGBs system from the RRB system to obtain an estimate of GHG emissions reductions achieved by switching from a SUPGB to a RRB lining system in tons of CO2e

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[6] There is only one size of RRB that is currently produced; therefore, to obtain cost estimates for Company X, we divided the price of the RRB ($19.12) by its size (19 gallons) to estimate a cost per gallon price (~$1.00).

[7] A 40 gallon HDPE bag (SUPGB used by Company X) weighs 27g (Table 5); therefore, we are estimating the average SUPGB weight is 0.675g per gallon.

[8] A 19 gallon RRB weighs 233.25g (Table 5); therefore, we are estimating the average RRB weight is 12.2763158g per gallon.

Coding Design

The Shiny app was made using the `fluidPage(), navbarPage(), tabPanel(), and fluidRow()` functions for structure. The app has three tabs in the navigation bar; the first is a "How To Use" tab in which we describe the inputs needed to calculate estimates, describe the associated assumptions in the calculator's backend calculations, and go in detail on how to use the calculator. The second tab is "Annual Savings". In this tab, the user can input their company's unique values to obtain estimated cost outputs of their current recycling program using SUPGBs compared to the recycling program using RRBs. The final tab is "Recycling Recommendations" where we detail our recommendations for how to properly implement RRBs and good recycling practices to maximize the lifespan of RRBs in the campus recycling program. The server calculations were all made reactive to enable the app to use output values as inputs for later calculations. For detailed methods on how to create a Shiny app, refer to R Studio's website for a tutorial ("Learn Shiny," 2020).

Company X Inputs

To obtain financial and environmental cost estimates for each bag lining system for Company X's corporate campus, the values in Table 26 were used as inputs to the calculator.

Table 26. Calculator inputs using information & assumptions for Company X.

Parameter	Inputs
Number of Recycling Receptacles	194
Size of Receptacles (gal)	40
How Often the Receptacles are Serviced Per Week (1-7)	5
Price per Unit of SUPGB ($/bag)	0.39
Contamination Chargers per Month	0

Results

Our calculator ran effectively with data from Company X. (See "Financial Analysis" section for detailed information on the data and assumptions made). Table 27 shows annual estimates of the program using SUPGBs: estimated number of SUPGBs used, contamination charges (if applicable), estimated costs of their current recycling program with SUPGBs, waste generated by a SUPGB system, and the GHG emissions associated with this system in metric tons of CO2e.

Table 27. Calculator outputs of annual estimates of Company X's recycling program with SUPGBs.

Parameters	Outputs
SUPGBs Required	50,440
Contamination Charges	$0
Cost of SUPGB System	$19,671.60
Waste Generated by SUPGB System (kg)	1361.88
GHG Emissions Associated with a SUPGB System per Year (metric tons CO2e)	4.36

Table 28 shows annual estimates of the program with RRBs: the price per RRB, the number of RRBs the user's company would have to purchase, contamination charges, the estimated cost of the program with RRBs, waste generated by a RRB system, and the GHG emissions associated with this system in metric tons of CO2e.

Table 28. Calculator outputs of annual estimates of Company X's recycling program with RRBs.

Parameters	Outputs
Price per Unit of RRB ($/bag)	$40.25
RRBs Required	388
Contamination Charges	$0[9]
Cost of RRB System	$15,618.02
Waste Generated by RRB System (kg)	190.53
GHG Emissions Associated with a RRB System in the First Year (metric tons CO2e)	0.55

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[9] This number remains static regardless of user inputs. This is because we are assuming the company is not incurring SUPGB contamination charges if using RRBs.

Finally, Table 29 shows the annual estimates of the cost difference of switching from a SUPGB to a RRB lining system, waste reduction in kilograms, and the GHG emissions difference from switching from a SUPGB to a RRB recycling system in metric tons CO2e.

Table 29. Calculator outputs of annual financial & environmental tradeoffs from switching to RRBs from SUPGBs.

Parameters	Outputs
Cost Difference	$4,053
Waste Reduction (kg)	1,171.35
GHG Emissions Difference (metric tons CO2e)	3.81[10]

Discussion & Analysis

Our financial and environmental impact calculator provides an accessible, user-friendly tool for companies considering RRBs as an alternative to SUPGBs as bin liners in campus recycling programs. It outputs preliminary cost estimates of switching to RRBs from SUPGBs, as well as waste reduction and GHG emission savings. However, due to design limitations within Shiny, we had to make choices as to which calculations were the most robust to include in this simple calculator. These decisions were made considering data availability to WSP and their clients. Data used for this impact calculator as inputs are items a company can easily find in purchasing records and waste management billing records. This calculator is intended to be less detailed than the financial model developed in Excel, which includes more inputs and cost parameters. Extrapolating the methods used to create the financial model into the impact calculator allows a broader audience to obtain cost estimates on switching to RRBs from SUPGBs.

The estimated costs that our calculator outputs are not designed to be precise, due to the simple nature of Shiny apps and the limited user-inputs we chose to include, but the outputs could provide a crucial first step in decision-making for companies considering RRBs as an alternative to using SUPGBs in their recycling programs. For example, if Company X was using this calculator, their inputs would output cost estimates that would give them a preliminary result that a RRB lining system would be less costly and more environmentally friendly than a SUPGB lining system. The purpose of the calculator is to show users these financial and environmental estimates and communicate that implementation of RRBs could be a viable solution to help them reach their sustainability goals of zero-waste.

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[10] For reference, a typical passenger vehicle emits about **4.6 metric tons of carbon dioxide per year** (US EPA, 2022).

This calculator could be made more robust by incorporating more accurate data, as is true for most of our deliverables. Additionally, allowing the price per unit of RRB ($/bag) to be a user input rather than a number used within calculation 4 (see *Inputs, Calculations, and Outputs* subsection), would allow flexibility for companies who are interested in adopting a RRB different from the one sold on the WM website. Furthermore, we are referencing a certain brand of HDPE SUPGB in our analysis, and the specific weight of this product has been ingrained within calculation 8 (see *Inputs, Calculations, and Outputs* subsection) to output waste reduction (Staples website, 2022). This is another limitation that could be improved by changing the SUPGB weight calculation in the source code (refer to footnote 6). However, to stay within the scope of this project and because WM's RRB is the only one available for sale at this time, we chose to integrate the price per RRB within the backend calculations and reference the SUPGB Company X uses in their campus recycling program. Lastly, if a LCA with more robust data was conducted for these bags, the numbers used for kilograms of CO2e per gallon could be updated within the source code for more accurate results.

IX. Discussion

Reusable Bags are Feasible, Environmentally Beneficial & Financially Viable

The results of our deliverables allowed us to assess the environmental and financial tradeoffs between SUPGBs and RRBs used to line recycling receptacles, and we concluded that RRBs are a feasible, environmentally beneficial, and financially viable alternative to SUPGBs. The field test helped us understand the feasibility of implementing RRBs in place of SUPGBs in campus recycling, and showed RRBs are a feasible alternative and well-liked by the janitorial team.The LCA results showed RRBs have a lower environmental impact across all impacts categories analyzed, while the financial model showed RRBs would slightly reduce the costs associated with Company X's recycling program. More broadly, wide adoption of RRBs could reduce the impact of SUPGB contamination on the recycling industry and in the natural environment.

The results of the field test showed RRBs are functional and a feasible substitute for SUPGBs in campus recycling. The Bren janitorial team preferred using RRBs to SUPGBs because they thought RRBs were easier to use and did not add any additional burden to their operations. However, we understand our field test was conducted on a small scale and does not fully reflect Company X's or other large corporate campuses' recycling programs. On a larger scale, efficiency measures, such as bag rotation, would need to be implemented to make the RRB an effective alternative to SUPGBs. Additionally, implementing larger sized RRBs than the 19 gallon RRBs used for our field test could require a more extensive cleaning process and additional resources, potentially influencing the janitors' response and receptiveness to the RRB. Companies interested in purchasing different sized RRBs will need to work directly with the RRB distributor, Zorch International, to design bag sizes to meet the needs of their recycling program.

The LCA allowed us to determine that RRBs have a lower environmental impact than SUPGBs in all TRACI categories, most importantly in global warming impact, primary energy consumption, and water use. GHG emissions are the central contributing factor to climate change and the key environmental impact reported by large corporations, such as Company X. Therefore, the reduction in GHG emissions from using RRBs would bolster Company X's carbon reduction strategy and reduce the climate impact of their recycling program. Although the RRB had a lower primary energy consumption than SUPGBs, if the bags were produced with a larger fraction of renewable energy compared to fossil fuel energy sources, this would further reduce the energy impact of the RRB. Additionally, our sensitivity analysis showed increasing the expected lifespan of the RRB reduces its environmental impact in all categories; therefore, it is important for Company X and other potential RRB users to prioritize reuse and maintaining bag viability for long periods of time to maximize their environmental benefits.

The results of our financial model—assuming RRBs are viable for the manufacturer's expected lifespan of 125 uses—showed use of RRBs would reduce Company X's annual costs. Although RRBs reduce annual costs by X, this cost reduction would have a negligible impact on Company X's total campus operating budget; therefore, the decision to switch to RRBs should not be based on financial implications. However, WSP's other clients may be motivated to switch to RRBs if a financial analysis shows RRBs result in cost savings for their recycling program. Although financial implications may not serve as the basis for decision making, cost savings are important for WSP to highlight when pitching RRBs to clients. In our model, we used a direct to-consumer price for both SUPGBs and RRBs to try to maintain an apples to apples comparison of both bag options as bulk purchasing of RRBs is not currently available; however, we understand that Company X and WSP's other corporate clients purchase SUPGBs in bulk. We understand the lack of bulk purchasing considerations limits the accuracy of our financial results and purchasing bags in bulk would lower the cost of both SUPGBs and RRBs. As discussed previously, at the time of our project, RRBs were not widely used or distributed and were only available for sale on the Waste Management website, which is not a reflection of the true cost of the RRB. However, if these bags become more widely used, we assume RRB manufacturing will scale in response and RRBs will become cheaper. Additionally, our Shiny app can be easily updated to incorporate more accurate data specific to Company X or any company and is therefore useful in providing preliminary cost estimates to consider when making a decision to switch to RRBs.

More broadly, the results of our project contribute to reducing the environmental externalities of SUPGB pollution and contamination experienced by recycling facilities. If RRBs are to become adopted by Company X and WSP's other corporate clients, use of RRBs in place of SUPGBs would significantly reduce the amount of SUPGB waste ending up in recycling facilities and landfills. Therefore, RRBs have the potential to reduce ecotoxicity and ecosystem degradation caused by SUPGB disposal in landfills and the negative externalities of SUPGB contamination in recycling facilities, such as work stoppages, employee risk, and decreased value of recycled material.

Further Considerations

Our project was successful in accomplishing our objectives and determined the RRB is a beneficial and viable solution to reducing the environmental impacts posed by use of SUPGBs to line recycling receptacles; however, several considerations beyond the scope of our project are important to discuss including alternative recycling bin lining solutions not covered within this analysis and social and corporate responsibility considerations associated with the purchase of RRBs

Many companies may analyze other alternatives to SUPGBs before considering RRBs, including lining bins with paper bags or leaving bins unlined. Leaving bins unlined poses challenges to janitorial teams as this results in contamination of the receptacle itself, creating a sanitation issue. Paper bags that are accepted by commercial recycling facilities do not have a moisture barrier; therefore, if recyclables are contaminated with food or liquid the bags deteriorate, leading to bin contamination and complicating the process of emptying recycling receptacles for janitorial teams. Alternatively, paper leaf bags—paper bags sealed with a moisture barrier to resist breaking down—could be a viable solution to resist contamination but are much more expensive than SUPGBs and are not accepted by commercial recycling facilities (S. Katz, personal communication, February 16, 2022). Therefore, use of paper leaf bags would continue to propagate contamination of commercial recycling facility operations.

Another important consideration for Company X and many of WSP's other clients is improving and upkeeping corporate social responsibility (CSR) initiatives. Prior to investing in RRBs, it would be in Company X or other companies' best interest to investigate the working conditions at the factory where the RRB is manufactured. Sourcing supplies from manufacturing facilities that violate human rights and harbor poor working conditions would pose a business risk to large corporations, making them a target for human rights groups and undermining CSR efforts. Since it is difficult to receive transparent information on the working conditions at these facilities, buying supplies made in U.S. factories is always the safest option. We assume implementation of RRBs could be publically highlighted as a corporate environmental improvement in ESG or CSR reporting; therefore, understanding the social and equity implications of RRB production is crucial to avoid public criticism or backlash. Additionally, associating with factories that have well regulated working conditions can increase a company's transparency and accountability. However, it was beyond the scope of this project to collect information and assess the conditions at factories where RRBs are made; therefore, future investigation into the social and equity components of RRB manufacturing is crucial.

X. Recommendation & Conclusion

Company X Should Implement RRBs

After careful consideration of our project's results, we recommend Company X invests in and implements RRBs to line recycling receptacles at their corporate campuses. Use of RRBs in place of SUPGBs would reduce the GHG emissions and amount of landfilled waste produced by Company X's recycling program, potentially helping them become UL certified. As stated previously, RRBs would not significantly impact Company X's campus operating income in a manner that should prevent Company X from pursuing this environmental improvement due to financial concerns, and implementing RRBs could lead to annual cost savings. Although the RRB is shown to produce cost savings for Company X, these savings are arguably negligible for a corporation of this size.

Furthermore, to maximize the environmental benefits of switching to RRBs, we recommend Company X take into account our best practice guidance for use of the RRB, including training janitorial staff in proper cleaning and handling methods. We also recommend implementing effective signage around recycling receptacles to encourage proper recycling practices to minimize contamination and maximize the lifespan of the RRBs.

Next Steps & Future Work

If Company X chooses to move forward with implementing RRBs they will need to work with the RRB distributor, Zorch International, to design RRBs specific to the recycling receptacles on their corporate campus. Once an appropriate RRB is designed, Company X should obtain a price quote from the manufacturer and input the new RRB cost into our financial model to produce a more accurate estimate of the costs associated with switching their bin lining system to RRBs. Additionally, prior to bulk ordering RRBs, we recommend Company X field tests a sample of the newly designed RRBs at their corporate campus to gather janitorial input on RRB feasibility pertinent to their unique campus recycling program. Further, WSP can use the results of our project to incentivize other corporate clients to consider implementing the RRB, and the Shiny App is a viable method for other clients to assess the environmental and financial tradeoffs between SUPGBs and RRBs.

Finally, the conclusions drawn from our project could be further expanded beyond our objectives and initial scope in the future. WSP could potentially collaborate with Zorch

International to improve RRB production to further mitigate the environmental impacts by drawing on the environmental hot spots of RRB production identified in our LCA. WSP could look into developing different RRB shapes and sizes with Zorch to make the RRB a more easily accessible solution for their corporate clients. Use of RRBs could then be easily expanded from use as liners for recycling collection bins to liners for other receptacles used by janitorial teams, such as receptacles used to transport recyclables, further eliminating SUPGB use in recycling programs. Additionally, if future field testing and RRB use deems the bag is durable enough to withstand high levels of contamination, this RRB or a modified version of a reusable bag could be used to line garbage receptacles as well. Therefore, our project could have a broad impact on reducing SUPGB waste and the subsequent recycling contamination produced by corporations.

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XII. Appendix

A. Acronyms
  - SUPGB - Single-use plastic garbage bag
  - RRB - Reusable recycling bag
  - PP - Polypropylene
  - HDPE - High Density Polyethylene

B. Field Test
  - UCSB Bren School Building's Recycling Program
    - Recycling bins are located at all central kitchen locations at the Bren building. Janitors place SUPGBs within recycling bins as liners. Janitors check each bin daily and remove the SUPGB with recyclables if the bag is full or contaminated. If the SUPGB is not full or contaminated, the SUPGB is left in the bin until it becomes full or contaminated. SUPGBs with recyclables are emptied into a large 32-gallon transporting receptacle lined with a SUPGB. When each transporting receptacle is full, it is transported to the recycling dumpster outside of the Bren Building. Janitors use a metal rod to prop open the recycling dumper lid, so they do not strain their arms holding the lid open. Once the lid is held open, the janitors remove the SUPGB with recyclables within SUPGBs from the transporting receptacle, tie it shut and toss it into the recycling receptacle. Janitors can request a step to use to more easily reach the inside of the recycling dumpster.
    - Removing the SUPGB bag liner is dependent on the waste composition inside the bag- if the waste is not wet or contaminated with non-recyclable materials then the bags are left in. Marborg does not want liners in the comingled recycling stream so the waste hauler (Marborg employee) physically tears the bags (from intermediate bins) before the recycling enters the resource center.
    - Photos:

Image of RRB installed in sim jim bin with the checklist on the wall behind it.

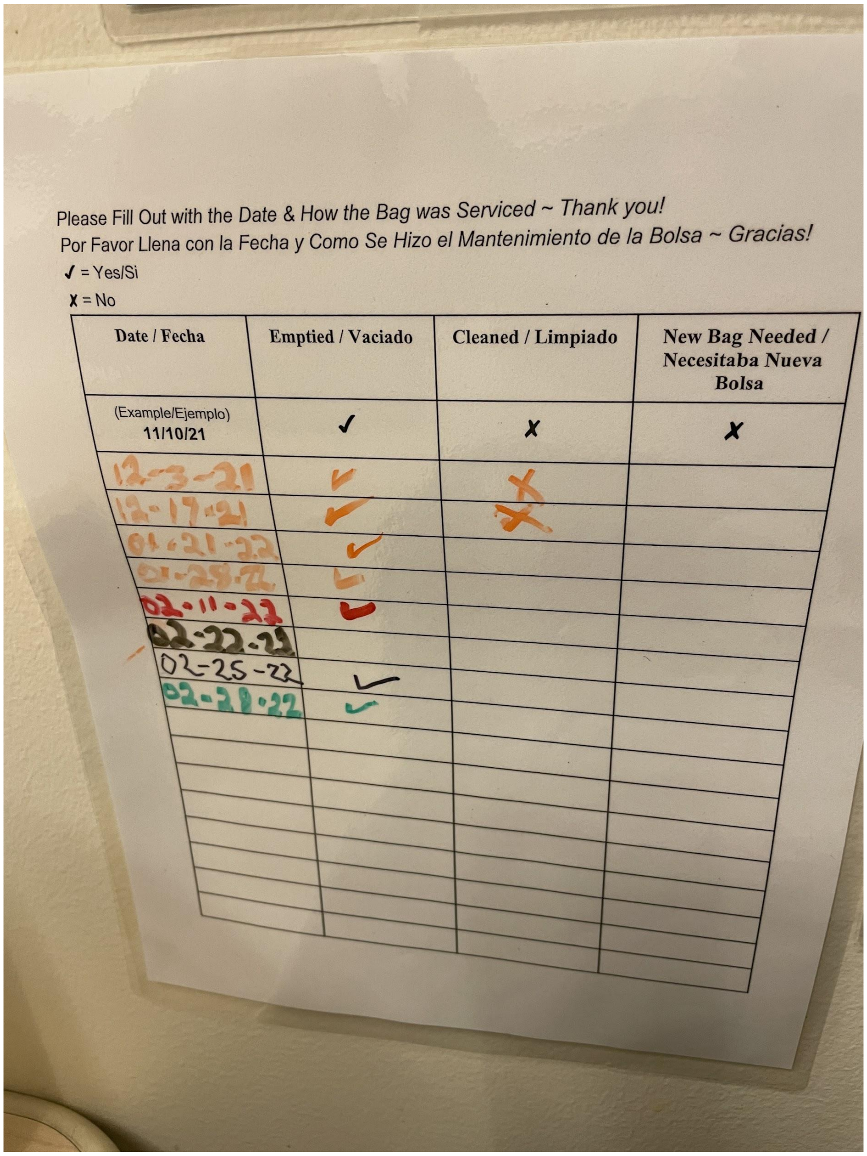
Image of centralized transport bin with wheels. Recyclables from smaller bins get collected and transported to the dumpster outside using this bin.

Image of cleaning fluid used to clean the RRBs being diluted by janitorial staff.

Image of Fabian Salas opening the recycling dumpster with a metal rod. This rod helps janitorial staff open and support the recycling dumpster's lid without straining their arms.

Image of Fabian Salas pulling the bag of collected recyclables out of the transporting bin and dumping it in the recycling dumpster outside.

- Checklist



Please Fill Out with the Date & How the Bag was Serviced ~ *Thank you!*

Por Favor Llena con la Fecha y *Como Se Hizo el Mantenimiento de la Bolsa ~ Gracias!*

✓ = Yes/Sí

✗ = No

Date / Fecha	**Emptied / Vaciado**	**Cleaned / Limpiado**	**New Bag Needed / Necesitaba Nueva Bolsa**
(Example/Ejemplo) 11/10/21	✓	✗	✗
12-3-21	✓	✗	
12-17-21	✓	✗	
01-21-22	✓		
01-28-22	✓		
02-11-22	✓		
02-22-21			
02-25-22	✓		
02-28-22	✓		

Image of the checklist used by the janitorial staff for the field test portion of this project.

C. LCA

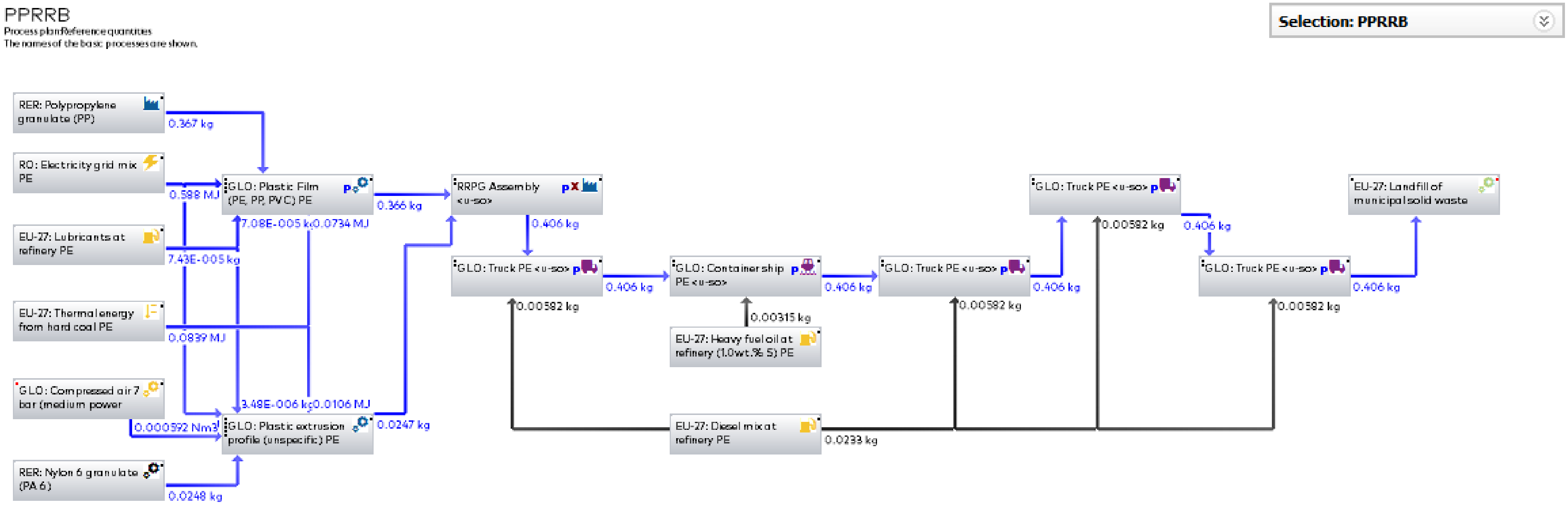


Image of the completed GaBi LCA model created to analyze the RRB.

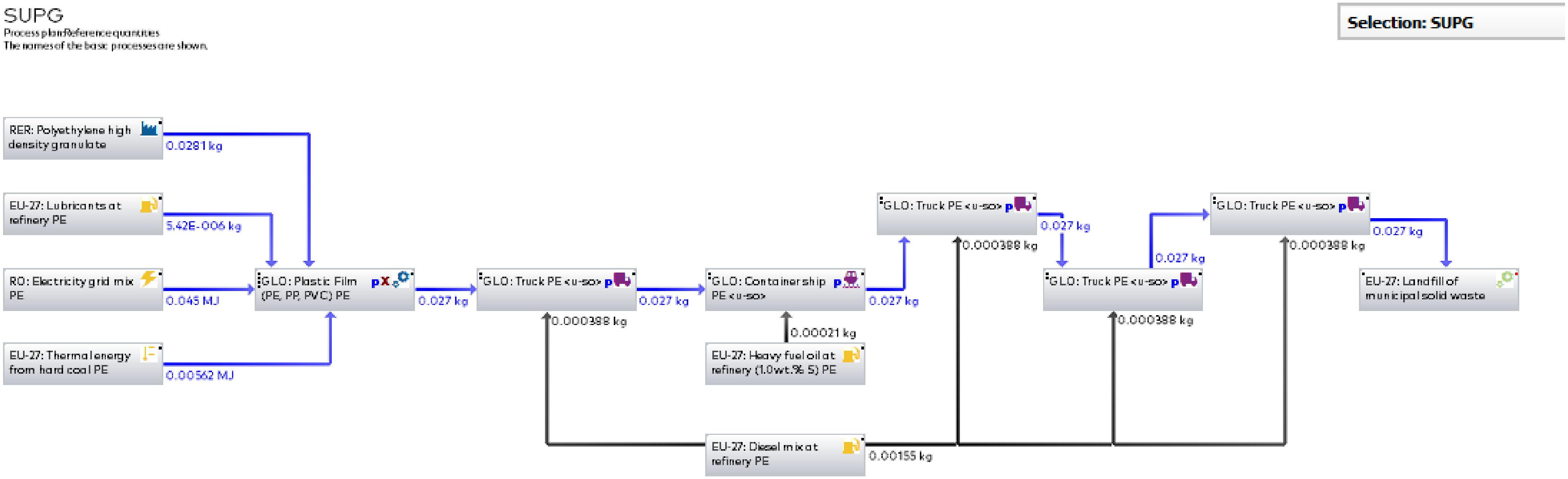


Image of the completed GaBi LCA model created to analyze the SUPGB.

D. Shiny App

  - Link to Impact Calculator
  - Shiny app source code:

```
library(shiny)
library(shinythemes)
library(scales)

ui <- fluidPage(theme = shinytheme("cerulean"),
                navbarPage("Single-Use Bag vs. Reusable Recycling Bag:
Impact Calculator",
                           tabPanel("How To Use", img(src =
"Bag_Ladies_Logo.png", height = 150, width = 130, style = "display:
block; margin-left: auto; margin-right: auto;"),
                                    mainPanel(align = "center",
h4(strong("What Is The Single-Use Bag vs. Reusable Recycling Bag: Impact
Calculator?")),
                                              "This calculator tool
allows you to input parameters about a company's commercial recycling
operation to obtain an estimate of the financial and environmental costs
associated with lining recycling bins with two different bag types:
single-use plastic bags and reusable recycling bags. The goal of this
calculator is to provide companies with the tradeoffs between each bag
type within their recycling operations to encourage them to pursue the
most environmentally- and cost-friendly option. To learn more about the
motivation for this calculator, please review our project report
here."),
                                    mainPanel(align = "center",
h4(strong("How To Use The Calculator")),
                                              "To use this calculator,
go to the Annual Costs tab at the bar at the top of the page. Once
there, follow the instructions throughout the page. First, type your
inputs into the boxes under "Input Your Recycling Process Values Here".
Second, If you do not know or have a value for any of the boxes, type
either an estimate or a 0 in the box. Finally, the calculator will
output values for the estimated environmental and financial costs of
your recycling operations with single-use bags and reusable recycling
bags, as well as the financial & environmental tradeoffs between these
two scenarios."),
                                    mainPanel(align = "center",
h4(strong("Calculator Assumptions")),
                                              "List assumptions here")),
                           tabPanel("Annual Cost",
```

```
                                    fluidRow(
                                        column(4,
                                               h4("Input Your Values"),
                                               numericInput("recep",
label = "Number of Recycling Receptacles:", value = 0),
                                               numericInput("recep_gal",
label = "Size of Receptacles (gal):", value = 0),
                                               numericInput("freq",
label = "How Often the Receptacles Are Serviced per Week (1-7):", value
= 0),
                                               numericInput("price",
label = "Price per Unit of Single-Use Bag ($/bag):", value = 0),

numericInput("contam_mth", label = "Contamination Charges per Month
($):", value = 0)),
                                        column(8,
                                               h4("Annual Cost of
Recycling Program with Single-Use Bags"),
                                               strong("Single-Use Bags
Required:"), textOutput("num_SUPGB_out"),
                                               strong("Contamination
Charges:"), textOutput("contam_yr_out"),
                                               strong("Cost of
Single-Use Bag System:"), textOutput("tot_cost_SUPGB_out"),
                                               strong("Waste Generated
by Single-Use Bag System (kg):"), textOutput("waste_SUPGB_out"),
                                               strong("GHG Emissions
Associated with Single-Use Bag System (metric tons CO2e)"),
textOutput("ghg_SUPGB")),
                                        column(8,
                                               h4("Annual Cost of
Recycling Program with Reusable Bags"),
                                               strong("Price per Unit of
Reusable Bag ($/bag):"), textOutput("price_RRB_out"),
                                               strong("Reusable Bags
Required:"), textOutput("initial_RRB_out"),
                                               strong("Contamination
Charges:"), textOutput("contam_yr_RRB_out"),
                                               strong("Cost of Reusable
Bag System:"), textOutput("tot_cost_RRB_out"),
                                               strong("Waste Generated
by Reusable Bag System (kg):"), textOutput("waste_RRB_out"),
                                               strong("GHG Emissions
```

```
Associated with Reusable Bag System (metric tons CO2e"),
textOutput("ghg_RRB")),
                                        column(8,
                                               h4(strong("Annual
Financial & Environmental Tradeoffs for Your Recycling Program")),
                                               strong("Cost Difference
Between the Single-Use and Reusable Bag System:"),
textOutput("tot_annual_sav_out"),
                                               strong("Waste Reduction
Between the Single-Use and Reusable Bag System (kg):"),
textOutput("waste_sav"),
                                               strong("GHG Emissions
Difference Between the Single-Use and Reusable Bag System (metric tons
CO2e):"), textOutput("ghg_sav")))),



                           tabPanel("Recycling Recommendations", img(src
= "", height = 150, width = 130, style = "float:right;"),
                                    sidebarLayout(
                                        mainPanel(""),
                                        mainPanel(""))
                                    )
                           )
                )


server <- function(input, output) {

  # 1
     num_SUPGB <- reactive({
         RC <- input$recep
         FQ <- input$freq
         RC * FQ * 52
         })

     output$num_SUPGB_out <- renderText({
         paste(num_SUPGB())
         })

  # 2
     contam_yr <- reactive({
         CM <- input$contam_mth
```

```
       CM * 12
       })

   output$contam_yr_out <- renderText({
       paste("$", round(contam_yr(), 2))
       })

   contam_yr_RRB <- reactive({
     0
   })

   output$contam_yr_RRB_out <- renderText({
     paste("$", round(contam_yr_RRB(), 2))
   })

# 3
   tot_cost_SUPGB <- reactive({
       PR <- input$price
       RC <- input$recep
       FQ <- input$freq
       CM <- input$contam_mth
       CY <- CM * 12
       NS <- RC * FQ * 52
       (NS * PR) + CY
       })

   output$tot_cost_SUPGB_out <- renderText({
       paste("$", tot_cost_SUPGB())
       })

# 4
   price_RRB <- reactive({
       RG <- input$recep_gal
       RG * 1.00631579
       })

   output$price_RRB_out <- renderText({
       paste("$", price_RRB())
       })

# 5
   initial_RRB <- reactive({
       RC2 <- input$recep
```

```
        RC2 * 2
        })

    output$initial_RRB_out <- renderText({
        paste(initial_RRB())
        })

# 6
    tot_cost_RRB <- reactive({
        RC3 <- input$recep * 2
        RGP <- input$recep_gal * 1.00631579
        RC3 * RGP
        })

    output$tot_cost_RRB_out <- renderText({
        paste("$", tot_cost_RRB())
        })

# 7
    output$tot_annual_sav_out <- renderText({
        paste("$", round(tot_cost_SUPGB() - tot_cost_RRB(), 2))
        })

# 8
    waste_SUPGB <- reactive({
      NS <- input$recep * input$freq * 52
      SG <- input$recep_gal * NS
      WS <- 0.675
      CF <- 1000
      (SG * WS)/ CF

    })

    output$waste_SUPGB_out <- renderText({
        paste(waste_SUPGB())
    })

# 9
    waste_RRB <- reactive({
      NR <- input$recep * 2
      RG <- input$recep_gal * NR
      WS2 <- 12.2763158
      CF2 <- 1000
```

```
      (RG * WS2)/ CF2
    })

    output$waste_RRB_out <- renderText({
      paste(waste_RRB())
    })

 # 10
    tons_ghg_SUPGB <- reactive({
      RGP2 <- input$recep_gal
      RC4 <- input$recep
      FQ <- input$freq
      NS <- RC4 * FQ * 52
      (NS * RGP2 * 0.0021625) / 1000
    })

    output$ghg_SUPGB <- renderText({
      paste(tons_ghg_SUPGB())
    })

 # 11
    tons_ghg_RRB <- reactive({
      RGP2 <- input$recep_gal
      RC5 <- input$recep
      FQ <- input$freq
      NR <- RC5 * 2
      (NR * RGP2 * 0.03575) / 1000
    })

    output$ghg_RRB <- renderText({
      paste(tons_ghg_RRB())
    })


 # 12
    output$waste_sav <- renderText({
      paste(waste_SUPGB() - waste_RRB())
    })

 # 13
    output$ghg_sav <- renderText({
      paste(tons_ghg_SUPGB() - tons_ghg_RRB())
    })
```

```
     }

# Run the application
shinyApp(ui = ui, server = server)
```