An Integrated Environmental and Economic Assessment for the Disposal of Food Waste from Grocery Retail Stores towards Resource Recovery

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Abstract

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Food waste gives rise to many environmental problems. A large amount of food waste is produced by grocery retail stores. It is therefore important to apply efficient food waste treatment technologies with minimal environmental impact and investigate the optimal approach for food waste collection, transportation, and treatment. In the present study, a life cycle impact assessment (LCIA) was conducted to analyze different food waste disposal scenarios, including incineration, landfilling, composting, anaerobic digestion, and bioconversion. The impacts of the five scenarios on the environmental, economic and social aspects were assessed. The results suggested that the landfilling scenario has the lowest net cost for the treatment of food waste, followed by the incineration scenario. The bioconversion treatment cost has the most significant positive effect on the net cost of the bioconversion scenario, and both the price and yield of compost have a significant negative effect on the net cost. The rankings of the five scenarios are the same under both weight determination methods, with the bioconversion scenario performing the best, followed by the composting scenario. The results of this study can help improve the disposal of food waste in grocery retail stores in the framework of sustainability and the circular economy.

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

With the advancement of human technology, global food production has increased dramatically, while the food waste problem has become increasingly significant. According to a study by the Food and Agriculture Organization (FAO), approximately 1.3 billion tons of food for human consumption is wasted globally each year, which is almost a third of the total (FAO, 2013). The data reported by the FAO (2011) on the amount of food waste show that the average food waste generated by each person is 95–115 kg/year in North America and Europe. By contrast, this amount decreases significantly to 6–11 kg/year in Southeast/South Asia and Sub-Saharan Africa. Food waste can result in many economic, social, health, and environmental problems. These problems include the waste of water for food production, the loss of soil nutrients due to non-composting, and the climate problems caused by greenhouse gases (GHGs) from landfills (Chen and Yuan, 2009). Canada's food waste problem has worsened in recent years, with the percentage of total production lost and wasted increasing to 58% and economic losses increasing to $49 billion (Van Bemmel and Parizeau, 2020). Therefore, minimizing food waste is an urgent need, and it is necessary to apply efficient food waste treatment technologies with minimal environmental burdens.

Grocery retail stores are a major source of edible food waste with high economic losses. As a result, retail-oriented sustainable and ecological food waste management strategies are required (Huang et al., 2016). Grocery retail stores may play a direct role in determining the optimal techniques for food waste collection, transportation, and treatment, opening up new business prospects for food waste repurposing in a circular economy (Secondi et al., 2015; Tian et al., 2023). As grocery retail stores are at the far end of the supply chain, the environmental effects of shipping, packaging, and other operations are already significant before the food even reaches shops. This concentrates sizable amounts of garbage in a small number of physical areas, making it easier to collect waste for later treatment and to gather information on the types and amounts of waste. It was estimated that 6 million tons of solid food waste was generated from grocery retail stores and consumers in Canada alone in 2007 (Abdulla et al., 2013). These loss estimates do not include waste generated from manufacturing and processing processes. Grocery retail stores become an important target in the examination of food wastes and establishment of waste disposal measures, which can help minimize the negative environmental impacts of wastes while ensuring economic efficiency (Brancoli et al., 2017).

Currently, various methods of food waste management such as landfilling, composting, conversion to animal feeds, and incineration are used worldwide (An et al., 2012; Bilal and Iqbal, 2019; S. Li et al., 2013). These waste management approaches are associated with environmental impacts of varying intensity (e.g., air quality, GHG emissions, surface water groundwater pollution, soil contamination, human health, biodiversity issues, and vegetation destruction). Food waste usually has high moisture and rich nutrient contents, making it a good breeding environment for various microorganisms and highly susceptible to infectious diseases and bacterial contamination, thereby affecting human health and the environment (Ng et al., 2020). During disposal, food waste directly or indirectly emits large amounts of GHGs, such as methane and carbon dioxide, along with other harmful gases. GHGs contribute to global warming and climate change, which are detrimental to both people and organisms (Karthikeyan et al., 2017; Wang et al., 2022). The production of other toxic and flammable gases can also lead to the degradation of air quality, destruction of biodiversity and vegetation, fire, and explosion hazards, and so on. Therefore, the comprehensive assessment and comparison of food waste disposal options are crucial for determining the appropriate waste management strategies.

There have been some previous studies regarding food waste management by grocery retail stores. Huang et al. (2021) reported that grocery retail stores that disclose their activities in accordance with the food waste hierarchy place a greater emphasis on minimizing food waste and distributing excess food for human use than on energy recovery and recycling through incineration. According to Moult et al. (2018), grocery retail stores generate different GHG emissions using different food waste disposal alternatives with landfills producing the highest emissions, and the use of food wastes as animal feeds and anaerobic digestion can help reduce fish and bread wastes. The environmental performance of food waste disposal solutions is typically assessed using life cycle assessment (LCA) (Bartocci et al., 2020; Brancoli et al., 2017; Tong et al., 2018). One of the advantages of LCA is that it allows for the identification and quantification of the potential environmental impacts of various waste management solutions (Buttol et al., 2007). At the same time, the environmental performance of various waste treatment systems can be evaluated to support sustainable waste management and to provide direction for developing environmentally sound strategies. Albizzati et al. (2021) studied combined socioeconomic impacts when they assessed the environmental impacts of different options for converting food waste to high-value products and found that animal feed production options had lower climate impacts and socioeconomic costs than other alternatives. In addition, the multi-criteria decision analysis (MCDA) is often used as an effective tool to help decision makers in waste recycling and environmental impact assessment (Deshpande et al., 2020; Vlachokostas et al., 2021). For example, a study that evaluated various potential agrifood waste feedstocks for biopolymer production using MCDA found that low-cost and underutilized food processing wastes were the most promising feedstocks (Bolaji et al., 2021). Although these previous findings are encouraging, the comprehensive assessment and analysis for the disposal and use of food waste from grocery retail stores are still lacking.

To address this challenge, the present study aims to develop a new framework for assessing the environmental impacts of different technologies for the disposal of food waste from grocery retail stores. Different disposal scenarios were considered, and cost-benefit and sensitivity analyses were also performed. The optimal disposal scenario was determined using the MCDA method. The results can help determine the food waste management strategy based on the environmental, social, and economic performances of different options.

Chapter 2. Literature review

2.1. Alternatives and technologies for food waste management

2.1.1. Generation and properties of food waste

Food waste is a universal problem with far-reaching implications for both the environment and global food security. One of the main factors contributing to food waste is at the household level, where consumer behavior and choices play a key role. According to a study by Parfitt et al. (2010), households tend to discard large quantities of food as a result of over-purchasing, misinterpretation of shelf life and improper storage. This not only has an impact on the economy, as consumers waste money on uneaten food, but also on the environment, increasing the overall carbon footprint associated with food production. In addition, retail and restaurants are major generators of food waste. A report by Buzby et al. (2011) estimates that in the United States, about 31% of the available food supply at the retail and consumer levels goes uneaten. Reasons for this waste include overstocking, cosmetic defects leading to rejection of products, and disposal of unsold cooked food. In addition, agricultural production practices contribute to food waste in both developed and developing countries. Post-harvest losses, including crop damage, inadequate storage facilities and inefficient transportation, result in a large proportion of the harvest never reaching the consumer (Gustavsson et al., 2011). Addressing food waste at different sources is essential for developing effective mitigation strategies. Measures that promote consumer awareness, education and behavioral change can reduce household food waste. For example, campaigns that emphasize proper storage techniques, smarter shopping habits and creative use of leftovers can positively influence consumer behavior. On the commercial side, partnerships between retailers and food banks or charitable organizations can help redirect leftover but still edible food to those in need, thereby reducing overall waste. In addition, technological advances in agriculture, such as improved storage and transportation infrastructure, can minimize post-harvest losses. Government policies that incentivize food donations, provide tax incentives to food-related businesses involved in waste reduction efforts and enforce stricter expiration-date labelling requirements can also help to curb overall food waste throughout the supply chain.

Understanding the characteristics of food waste is essential for determining appropriate management strategies and maximizing its potential benefits. Food waste is predominantly organic and includes fruits, vegetables, grains, meat and dairy products. Although food waste is discarded, its nutrient content is still valuable. Different types of food waste have different nutrient profiles, with fruits and vegetables often rich in vitamins and minerals. In addition, the high water content of food waste poses a challenge for transportation and disposal. However, this characteristic also provides an opportunity to utilize food waste in processes such as anaerobic digestion, as the water content helps microorganisms break down organic matter. While managing food waste through composting and anaerobic digestion has clear environmental benefits, it is important to recognize that inappropriate disposal methods can have harmful effects. Therefore, a sustainable approach to managing food waste is not only economically and environmentally sound, but also essential to mitigating its negative impact on climate change.

2.1.2. Treatment and disposal methods

The most common method of disposing of food waste is by co-mingling it with plastics, non-recyclable and inert metals, and other municipal waste for landfill. For instance, in Australia, an average of 1.6 million tonnes of food waste is generated each year, with approximately 91% ending up in landfills, constituting a significant environmental pollution factor (Randell et al., 2014). Currently, in the US, over 97% of food waste is estimated to be buried in landfills, and similarly, Canada relies primarily on landfills for food waste disposal (Levis et al., 2010). Methane is generated during the landfilling of food waste (as shown in Figure 2.1), and landfill gases, if not collected or not fully collected, can lead to greenhouse gas emissions (Scheutz and Kjeldsen, 2019). For example, these gases account for 20% of the national methane emissions in Canada. Landfill leachate from food waste can also contribute to ground and surface water contamination if not treated effectively and promptly (Shewa et al., 2020). In addition to the main impacts mentioned above, toxic and explosive gases contained in food waste landfill gas, along with bacteria and odors from landfills, can have environmental impacts, posing potential hazards such as fire, air quality, health hazards, and vegetation damage (Iacovidou et al., 2012). Food waste landfills, however, do offer benefits such as not requiring the separation of food waste from mixed waste, the ability of new landfills to collect and convert emitted landfill gas into energy, and economic cost advantages.

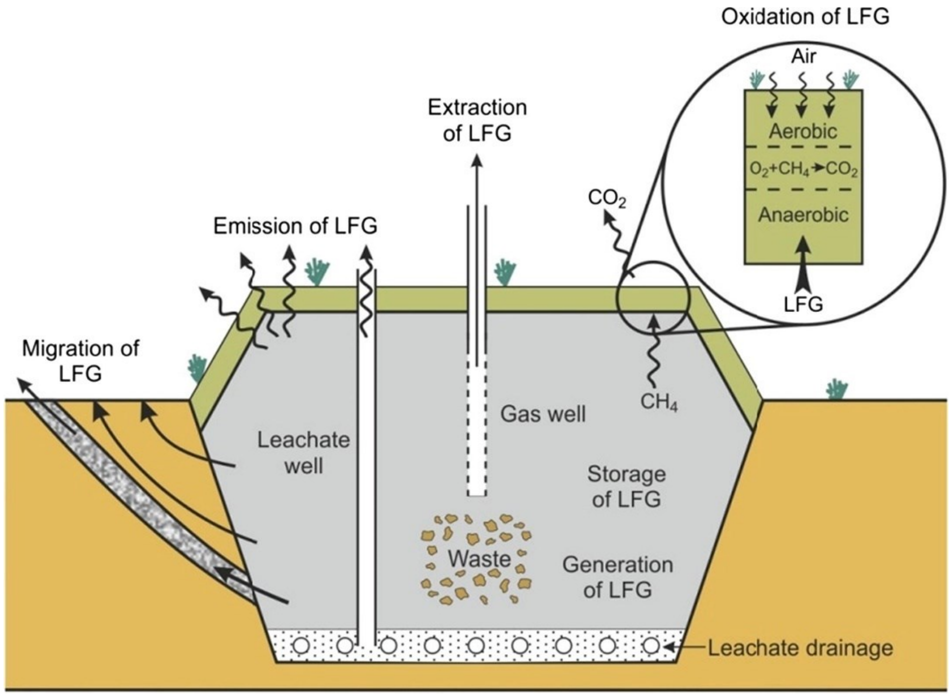

Figure 2.1 Methane production from food waste landfills (Scheutz and Kjeldsen, 2019).

Many countries, including the United States and Singapore, use incineration to dispose of food waste, a method that effectively reduces landfill space requirements and waste volumes (Khoo et al., 2010). Incineration is not often applied in developing countries, such as Brazil and Ukraine, mainly due to its higher capital, operation, and maintenance costs compared to other food waste disposal methods (Yates and Gutberlet, 2011). It also requires expensive instrumentation and highly technical operations to control gas emission residues. Although incineration can significantly reduce the volume of waste and generate heat, the high water content in food waste affects its practical application in incineration. The incineration process can lead to three potential sources of environmental exposure: atmospheric emissions, ash and slag, and through wastewater. Gases released from incineration are emitted into the air, contributing to the formation of smog and acid rain, along with the release of substantial amounts of toxic organic pollutants, such as dioxins. Exposure to particulate matter from incineration can be detrimental to health in both the short and long term. Short-term exposure affects heart and lung function, while long-term exposure increases the risk of death from diseases such as cardiovascular disease and lung cancer. With technological advancements, the environmental impact of exhaust emissions can be minimized by installing suitable filters. Data from the U.S., U.K., and Germany indicate that this method can reduce dioxin emissions by more than 99% and heavy metals by 90% (de Titto and Savino, 2019). Incineration ash and wastewater can also impact the environment if not properly arranged and managed.

Composting, the process of converting various components of food waste into stable humus, is a biochemical process, and the resulting product can be used as organic fertilizer or soil conditioner (Lashermes et al., 2012). Composting serves as an alternative waste treatment method to divert food waste from landfills, reducing greenhouse gas and air pollution emissions, mitigating groundwater contamination, and generating useful products (He et al., 2011). Food waste composting is considered an effective method, especially in developing countries, due to its economic efficiency and simple operation and management. In India, for example, there are over 70 composting facilities processing mixed municipal solid waste, recovering 5.9% of total food waste and generating approximately 4.3 million tonnes of compost annually (Thi et al., 2015). Composting is a dynamic and variable process involving changes in various microorganisms and complex metabolic processes using different composting materials. While the principles of composting remain largely the same, numerous factors, including moisture content, temperature, aeration rate, pH level, nutrient content, and particle size, can significantly impact the final product and environmental burden as the decomposition process evolves (Kumar et al., 2010). For instance, pH level affects ammonia emission and microbial growth, temperature influences pathogen reduction, and moisture content alters the physicochemical properties of the raw material. All these factors interact and correlate with each other (Z. Li et al., 2013). Food waste composting also poses several environmental challenges, such as the production of offensive odors and attraction of pests, potential health issues due to microorganisms leading to allergies and infections, environmental pollution from the generation of methane, nitrous oxide, and ammonia, as well as potential concerns related to heavy metals, inorganic salts, and ammonia-nitrogen (Awasthi et al., 2020).

Considering the high-moisture and energy-rich characteristics of food waste, anaerobic digestion is regarded as a more suitable and cost-effective technology for waste treatment and renewable energy production (Romero-Güiza et al., 2016). Anaerobic digestion technology utilizes anaerobic microorganisms to convert food waste, comprising various organic waste types and biomass, into biogas, consisting of 60-70% methane, 30-40% carbon dioxide, and traces of other gases. This biogas serves as a highly efficient energy source, with the remaining residue suitable for land applications (Sheets et al., 2015). Given its substantial volume, high energy content, and widespread availability, food waste holds significant potential as a substrate for anaerobic digestion (Paritosh et al., 2017). Anaerobic digestion stands out as a promising method for food waste treatment compared to traditional approaches such as landfill and incineration. However, its global application has been limited due to various social, economic, and technical challenges. In the United States, for instance, less than 2% of food waste undergoes anaerobic digestion treatment, a fraction significantly lower than that treated through composting or landfill methods (Xu et al., 2018). Despite being a mature technology widely employed for sewage sludge, animal manure, and high-strength wastewater treatment, anaerobic digestion encounters specific challenges when applied to food waste, including volatile fatty acid accumulation, process instability, low buffer capacity, foaming, transportation issues, and high operating costs (Zhang et al., 2020). Anaerobic digestion demonstrates a lower environmental impact concerning greenhouse gas emissions, ecotoxicity, and ozone depletion compared to traditional methods like landfill and incineration. However, it places a higher burden on the environment in terms of terrestrial acidification, particulate matter formation, and marine eutrophication (Slorach et al., 2019). During the food waste treatment using anaerobic digestion technology, the main contributors to environmental impact include volatilization of digestate, release of nitrate to water, ammonia to air from digestate use, and methane escape (Whiting and Azapagic, 2014).

Food waste pyrolysis is a technology that capitalizes on the thermal instability of organic matter in waste, distilling it by heating it in anaerobic or anoxic conditions. This process induces thermal cracking of organic matter, resulting in the formation of various new gases (methane, carbon monoxide, carbon dioxide, hydrogen), liquids (organic acids, bio-oil), and solids (biochar, slag) after condensation (Wang et al., 2021). Among these products, bio-oil serves as an alternative liquid fuel, pyrolysis gases can be used as fuel for internal combustion engines, and biochar finds applications not only as a carbon material for environmental remediation, energy storage, and catalysis but also as an alternative solid fuel (Park et al., 2021). The conversion of food waste by pyrolysis into products with the advantages of high efficiency, environmental friendliness, and a wide range of applications aligns well with the principles of the circular economy (Su et al., 2021). However, challenges arise due to the high moisture content and low calorific value of food waste, necessitating the absorption of a significant amount of heat in the pyrolysis process, especially during the pre-pyrolysis drying stage. This increased demand for external heating energy results in higher operating costs. Additionally, the coexistence of water vapor and combustible pyrolysis gases leads to low calorific value in products. The complexity of food waste composition introduces uncertainty and instability into the pyrolysis process, and environmental impacts such as greenhouse gas emissions, acidification, and eutrophication can be associated with the pyrolysis process (Ning et al., 2013).

2.1.3. Conversion of food waste to value-added products

As shown in Figure 2.2, Food waste can be converted into a variety of high-value products, including activated carbon adsorbent, antioxidants, bioactives, bioethanol, biobutanol, biodiesel, biogas, bioelectricity, biopolymers, bionic composites, chitosan, corrosion inhibitors, DHA, industrial enzymes, films, high fructose syrup, lecithin acid, mushroom cultivation, nutraceuticals, organic acids, pigments, single-cell protein, sugars, vermicompost, wax esters, and xanthan gum (Sindhu et al., 2019).

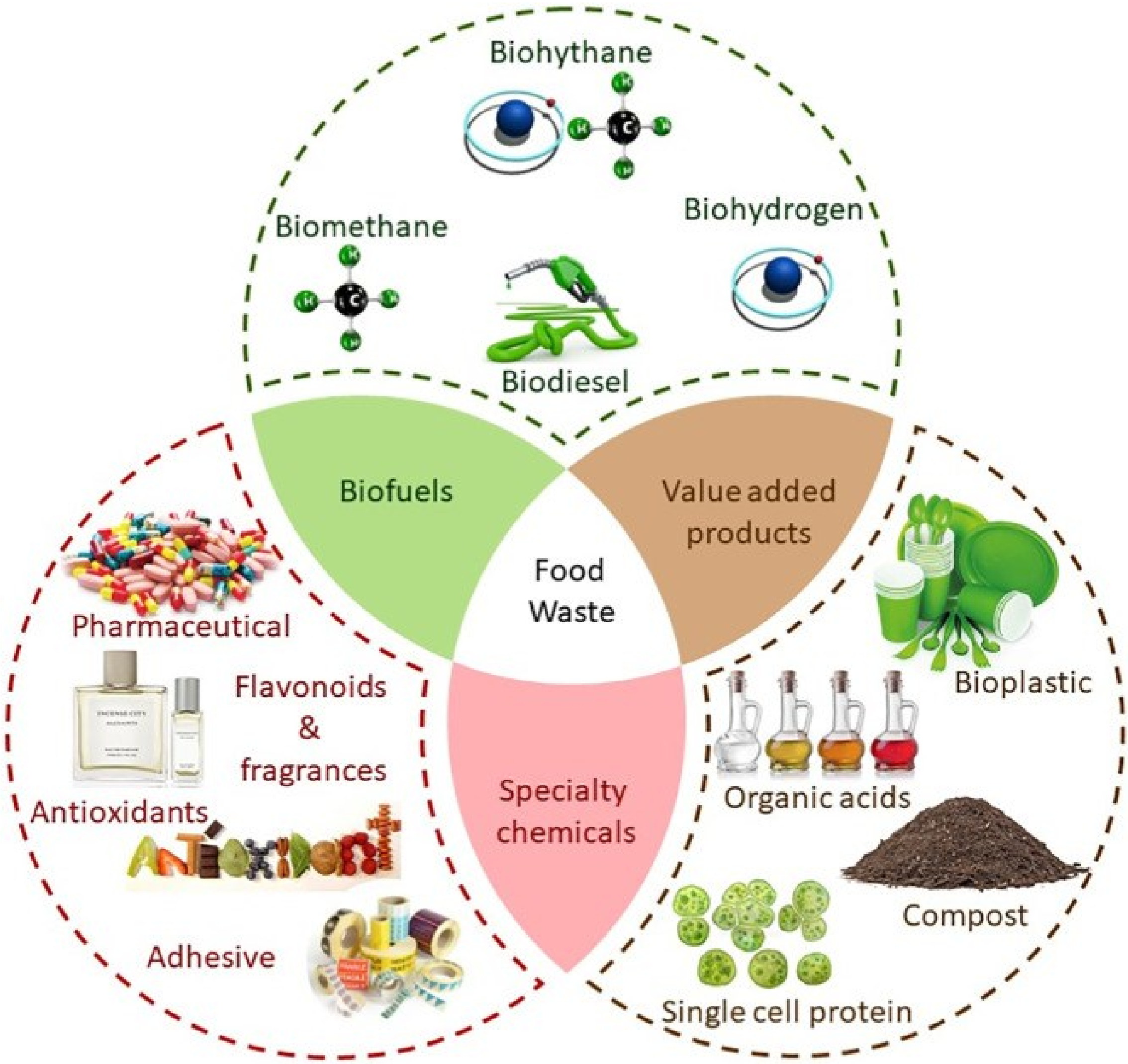

Figure 2.2 High-value products from food waste (Yukesh Kannah et al., 2020).

Given that food waste is rich in starch, fiber, protein, lipids, and inorganic salts, it can be repurposed into animal feed using various methods, including microbial organisms. In countries with a high demand for animal feed, such as Korea and Japan, 81% and 33% of the total production of food waste is respectively utilized for animal feeding, as the use of food waste in animal feed is actively encouraged (Thi et al., 2015). However, the mixing of meat, bones, and offal from various animals in food waste poses a significant challenge, as accurate sorting becomes impractical. This presents a notable risk when using food waste as feed, raising concerns about animal food safety. To address this issue, several countries, including the US, Canada, and the EU, have established feed regulations. Due to the complex composition and diverse origins of food waste, feed ingredients have the potential to introduce biological safety hazards such as pathogens, heavy metals, homologous problems, and organic contaminants (Westendorf, 2000). The environmental impacts of using food waste as animal feed are comparable to those of composting and anaerobic digestion, but they are relatively low (Salemdeeb et al., 2017).

Ethanol has been hailed as a "cleaner" biofuel due to its net zero CO_2 emissions during combustion, making it an environmentally beneficial component in fuel blends aimed at reducing greenhouse gas emissions in automobiles. Despite having a lower energy density compared to methane, ethanol's H_2 and energy equivalent are 68 percent lower than those of fossil fuels (Vohra et al., 2014). When produced and burned, ethanol emits 12 percent fewer greenhouse gases than gasoline, leading to its utilization in gasoline blends ranging from 10 to 85% (v/v) (Hill et al., 2006). In the ethanol sector, fermentation-produced ethanol accounts for over 90% of the total. However, the use of food-based components like sugarcane and corn in ethanol production makes bioethanol fuel more expensive than fossil fuels (Karmee, 2016). Consequently, ethanol fermentation from food waste emerges as a viable solution for waste management and disposal. Food waste, with its readily convertible fermentable sugars in an environmentally acceptable manner and a low pH, presents attractive features. However, challenges such as heterogeneous composition and varying moisture content, depending on the sources, need to be addressed (Pham et al., 2015). One prevalent type of food waste is bakery trash, including waste cake, constituting 8% to 17% of total food waste in countries like China and Singapore. Typically discarded by bakeries, households, and supermarkets, waste cake is primarily composed of carbohydrates, which can be hydrolyzed into monomers and utilized as a feedstock for ethanol production (Han et al., 2019). The ethanol manufacturing process from food waste involves three main steps: (1) hydrolysis (saccharification) converts the raw material to glucose, (2) fermentations convert glucose to ethanol and carbon dioxide, and (3) ethanol separation and purification by distillation. Numerous research efforts have been undertaken to address challenges associated with ethanol production from food waste, including optimizing fermentation process parameters and addressing contaminants during fermentation (Anwar Saeed et al., 2018).

Antioxidants are substances that prevent molecules from oxidizing and becoming free radicals. Consequently, these chemicals are used as preservatives in foods and cosmetics, as well as oxidation inhibitors in fuels. Moreover, antioxidants lower the risk of certain diseases in humans.

Synthetic antioxidants may pose health risks, prompting people to consume more natural antioxidants, which offer higher health benefits. Various food industry wastes, such as peels and seeds, can be utilized to produce antioxidants (Barba et al., 2016). Olive fruits and potato peel waste serve as good sources for antioxidants. The production of antioxidants from olive pomace has numerous ecological and environmental advantages.

Compounds that influence living organisms are known as bioactive substances. As antibacterial, antidiabetic, antihypertensive, anticoagulant, or anticancer medicines, these substances offer potential health benefits. Processing waste from fish and shellfish is a good source of bioactive substances. Several bioactive peptides, proteins, and amino acids are derived from fish waste and marine processing waste. Marine processing wastes contain a substantial number of different proteins that can be used to make various bioactive substances. Peptides obtained from the sea serve as promising nutraceuticals. This approach is economically viable since waste streams are used in the manufacturing process (Harnedy and FitzGerald, 2012).

An increase in fossil fuel consumption, coupled with their depletion, results in an energy crisis. Consequently, alternative energy strategies are sought. The use of food waste as a source for bioethanol production is suitable. The simultaneous hydrolysis and fermentation of unprocessed food waste into ethanol, using thermophilic anaerobic bacteria, is a safe and environmentally friendly procedure that avoids the use of dangerous chemicals and extreme conditions (Dhiman et al., 2017). Biobutanol is a biofuel that can be used in internal combustion engines. It is non-polar, and experiments have shown that it may be used in gasoline-compatible engines with no modifications. One of the key constraints limiting butanol synthesis is the expense of the substrate, but it is feasible to manufacture butanol from industrial starchy food waste (Ujor et al., 2014). Biogas is a renewable gas consisting of methane, carbon dioxide, moisture, hydrogen sulphide, and siloxanes. It is produced from the anaerobic digestion of various wastes. Food waste is a significant problem, and anaerobic conversion to biogas is a viable solution. Several research and development projects are underway worldwide to address this problem. Biodiesel is composed of mono-alkyl esters of long-chain fatty acids, and one of its primary drawbacks is the high cost of manufacture. This can be avoided by utilizing non-edible oils from food waste as a biodiesel manufacturing source.

Compared to petroleum-based polymers, one of the keys limiting issues for biopolymer production is the high manufacturing cost, primarily supplied by the carbon source. Therefore, using food waste as a carbon source, such as sugars and fatty acids, appears to be a potential method. Waste vegetable oils can be used to make epoxy resin mixes and composites as an alternative source, potentially providing a low-cost material that does not compete with food crops. Chitosan is produced chemically when chitin is de-acetylated. Chitosan is a nontoxic, biodegradable, and biocompatible polymer used in various sectors, including food, agriculture, and medicine. Arthropods and fungi both include chitin as a structural component. Shrimp shell waste may be used to make chitosan, offering both profitability and cost-effectiveness. The cost of materials and the quality of the end product are two important constraints in chitosan manufacture. Utilizing shrimp shell waste for chitosan production is a cost-effective option (Gómez-Ríos et al., 2017).

Amylases are enzymes that break down starch into smaller sugar units, such as glucose, maltose, and malt triose. It is one of the most significant industrial enzymes, with applications in paper, textiles, food, detergent, and the generation of fuel ethanol. Commercial carbon and nitrogen sources are frequently employed in amylase production. Agricultural residues, as well as food waste, can be used as an alternative, cost-effective source for amylase production (Hasan et al., 2017). The successive activity of cellulases results in complete cellulose hydrolysis. Cellulases are involved in biomass hydrolysis and are used in various industries, including biofuel, paper and pulp, textiles, detergents, food, and feed. Agricultural and food waste residues, such as corn cobs, carrot peelings, wheat bran, composites, wheat straw, orange peelings, pineapple peelings, and rice husk, could be used to make cellulases without the need for additional nutrients. Proteases are enzymes that catalyze protein hydrolysis and are used in the pharmaceutical, food, and detergent industries. Bread scraps are an excellent substrate for solid-state fermentation. The use of this waste for value addition appears promising in terms of both economic and environmental benefits (Melikoglu et al., 2015). Pectinases are enzymes that hydrolyze pectin and have a wide range of applications in the food industry, including fruit juice clarity and tea and coffee fermentation. Other applications include pectic oligosaccharide synthesis, plant DNA extraction, and fiber degumming. It is critical to establish cost-effective production strategies to meet rising demand. Several agro-industrial residues, as well as fruit and vegetable wastes, are excellent pectinase substrates.

Nutraceuticals are nutritional medications with health-promoting properties. Shrimp processing enterprises generate a large amount of shrimp waste each year, which can be used to make the nutraceutical astaxanthin. The quality of the nutraceutical is determined by the extraction methods used, the nutrient content, and its effectiveness as a dietary supplement. Astaxanthin has a wide range of uses, including antioxidant, cardioprotective, anti-hypertensive, and anti-tumorigenic properties. Astaxanthin can be extracted using various chemical methods, as well as environmentally friendly methods such as microbial fermentation and enzymatic extraction. Using shrimp waste to produce astaxanthin aids in waste management (Prameela et al., 2017).

Acetic acid is a carboxylic acid extensively generated by anaerobic bacteria fermenting substrates. Waste cheese whey can be used to produce acetic acid and whey protein (Pal and Nayak, 2016). Fumaric acid is used in food, medicine, and the production of resins and mordants, and demand is growing year after year. The petrochemical pathway is used to create the majority of fumaric acid. The biological path to fumaric acid synthesis will be both cost-effective and environmentally beneficial. Different types of food waste biomass can be utilized to make fumaric acid. Citric acid is used extensively in the food, beverage, and pharmaceutical sectors. It is commonly used as a flavor enhancer and acidifying agent. As the demand for citric acid grows, researchers are looking for new, cost-effective substrates for its manufacture. Fruit waste is typically used as animal feed or dumped in the soil. Because these wastes are high in carbs and other nutrients, they can be used as a low-cost substrate for the synthesis of citric acid. Propionic acid is a preservative and food additive that is frequently used. Currently, the majority of propionic acid is produced via an expensive petrochemical process. A viable alternative will be microbial production of this molecule using inexpensive and readily available waste biomass, such as apple pomace (Piwowarek et al., 2016).

The current surge in interest in the use of coloring agents has resulted in a rise in cancer rates. Consequently, the importance of safe and natural coloring chemicals has grown in recent decades, as has their demand. Pigment manufacturing using microorganisms is a safe technique, but most of the currently known strategies are not economically viable due to the high cost of fermentation substrates. Pigments made from agro-industrial leftovers are a sustainable and cost-effective pigment production approach (Panesar et al., 2015).

Xanthan gum is a significant microbial exopolysaccharide generated by a variety of microorganisms that use glucose or sucrose as their only carbon source. It is the first industrially manufactured microbial biopolymer. It has uses in various industries, including pharmaceuticals, food, and oil. It is frequently used as a thickener, stabilizer, and thickening agent in the food industry. The use of pure glucose or sucrose as a carbon source for xanthan gum manufacturing makes the method economically unviable, adding to xanthan gum's high cost. Using inexpensive substrate for production appears to lower fermentation costs. Food waste hydrolysis is a low-cost strategy for xanthan gum production and an effective food waste management strategy (Li et al., 2016).

The production of chemicals from food waste, such as glucoamylase, polyphenols, bio-succinate, alcohol, etc., is a new technology with advantages such as low-cost raw materials. However, challenges include the difficulty of separating food waste components, high processing and operating costs, and certain environmental impacts (Elkhalifa et al., 2019). Biotechnology integrated treatment methods, involving the use of biotechnology for resource treatment of food waste, include wet anaerobic biological treatment processes and automatic oxygen control methods of composting technology. This method maximizes waste resource utilization, especially for food waste with high organic content (Wong et al., 2020). One example of utilizing food waste is the production of biodiesel and other valuable products from the larvae of the black soldier fly (Li et al., 2019). Moreover, various special treatments can be applied to finely sorted food waste to produce a wealth of valuable products. Food waste serves as an abundant source of organic carbon, enabling the production of a diverse array of chemicals and high-value compounds. Despite the advantages and disadvantages associated with converting food waste into value-added products, there is a current lack of suitable equipment for efficient conversion. This technological challenge primarily arises due to the diverse nature of food waste. However, there exists significant potential for an environmentally friendly, green approach to producing value-added goods from food waste. To achieve proper management of food waste, available technologies and techniques need to be fine-tuned. Consequently, extensive research in this field is crucial to making the process commercially viable.

2.1.4. Research gaps

Research on environmental and economic assessment of food waste disposal strategies in retail food outlets has progressed, but significant research gaps remain, particularly in the exploration of environmental and economic factors. While some studies have delved into the environmental impacts of disposal methods, more detailed life cycle assessment analyses that consider the entire life cycle, including upstream and downstream impacts of disposal strategies, are needed to fully understand their environmental footprint (Brancoli et al., 2017; Moult et al., 2018). Moreover, economic research remains insufficient and limited attention has been paid to the long-term financial impacts of specific disposal methods used by grocery retailers. There is a research gap in terms of a comprehensive study of the cost-effectiveness, return on investment and potential economic benefits or drawbacks of different disposal strategies, which is essential to guide retailers in making economically viable and sustainable choices (Cicatiello et al., 2016). In addition, the lack of research that incorporates economic and environmental criteria into the MCDA framework hinders the development of holistic decision-making tools that consider both sustainability and economic viability. Addressing these gaps is imperative to deepen the understanding of the synergies and trade-offs between environmental and economic aspects of food waste management in the Canadian food retail industry.

Chapter 3. Methodology

3.1. Life cycle assessment

LCA can provide a significant contribution to the examination of waste management through providing environmentally friendly alternatives or better management alternatives along the entire supply chain in a circular economy framework. The LCA method has frequently been used to evaluate food waste management operations in recent years (Notarnicola et al., 2017). It can be used to compare the environmental impact of different waste management options on the environment. In this study, the analysis was performed using the SimaPro9 software developed by PRé Sustainability, based in the Netherlands.

3.1.1. Goal and scope definition

The purpose of this study is to assess five scenarios to determine the potential environmental impacts connected with the handling of food waste produced by a grocery retail store. All disposal scenarios (incineration [scenario 1] and landfilling [scenario 2]) and the alternative scenarios for the recycling/recovery of the organic fraction (composting [scenario 3], anaerobic digestion [scenario 4], and bioconversion by *Hermetia illucens* for composting and animal feeds [scenario 5]) were analyzed using the LCA method. The analysis was conducted to identify the method with the least environmental impact. The results can be used to assist grocery retail stores in selecting sustainable techniques for the handling of food waste. The system boundaries (Figure 3.1) encompass all direct and indirect actions involved in the grocery retail store's food waste management, from food waste collection to its final treatment. Three important phases were investigated in this context:

(1) Collection: Collecting food waste and the packaging together (scenarios 1 and 2) or separating the packaging from food waste at the grocery retail store (scenarios 3, 4, and 5).

(2) Transportation: Transporting food waste and packaging directly from the grocery retail store to the incineration plant and landfill (scenarios 1 and 2) or the packaging and food waste from the grocery retail store to the landfill and treatment plant, respectively (scenarios 3, 4, and 5).

(3) Treatment: Processing of food waste in different plants (incineration, landfilling, composting, anaerobic digestion, and bioconversion).

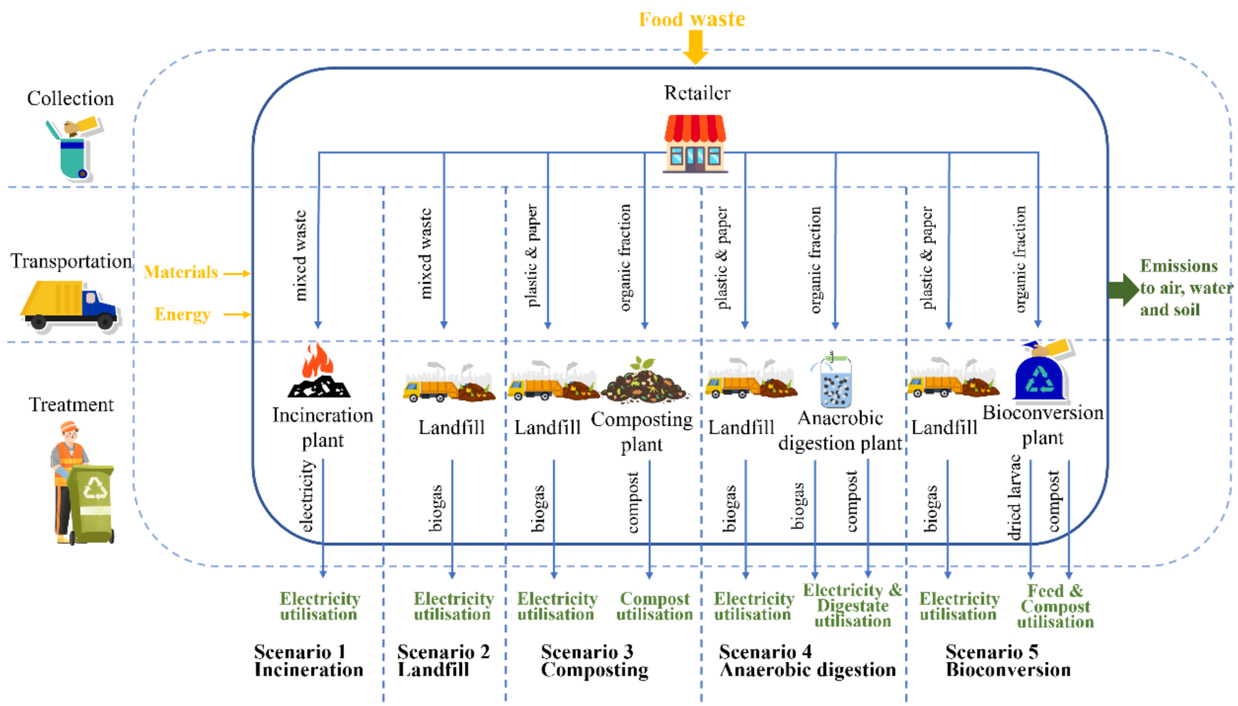

Figure 3.1 System boundary of the LCA for the management of food waste from grocery retail store.

3.1.2. Inventory analysis

The food wastes generated and pretreated by the grocery retail store in the five scenarios were as follows: (1) One ton of food waste from the grocery retail store was studied for each disposal scenario, with an average of 90% organic fraction, 5% plastic packaging, and 5% paper packaging per ton of food waste. (2) The distances from the grocery retail store to the waste incineration plant, landfill, composting plant, anaerobic digestion plant, and bioconversion plant were 250, 115, 30, 40, and 100 km, respectively. All transport operations were carried out with EURO4 standard 10-ton freight lorries. (3) Scenarios 3, 4, and 5 were for the preprocessing of the food waste at the grocery retail store and separating the plastic and paper packaging for transport to the landfill with the rest of the waste (Yang et al., 2022). The pretreatment process was completed at the same time as the food waste collection by the store employees, so there was no additional power and fuel consumption or environmental impact.

In scenario 1, food waste and packaging were incinerated in a mass-burn incinerator, with heat and power recovered. During the process, the inventory data included chemicals, power, and natural gas usage. The analysis also took into account direct emissions from the transportation and disposal of ashes in landfills. In scenario 2, food wastes with their packaging were delivered to landfills, which reflects the most typical treatment system used in the local waste management system. Data on power and diesel usage and direct emissions from waste treatment were also taken into account. In scenario 3, the food waste fraction obtained during the pre-process at the grocery retail store was treated in a composting plant to produce compost fertilizer. The remaining plastic and paper packaging were transported to the same landfill for disposal, as in scenario 2. Data on the consumption of water, electricity, and diesel, emissions, and leachate disposal were considered. In scenario 4, the pretreated food waste was transported to an anaerobic digestion plant to obtain usable digestate and electricity. The separated plastic and paper packaging were transported to the landfill for disposal in the same way as in scenario 2. Material, electricity, and water usage and direct emissions from the treatment process are all part of the system's inputs and outputs. In scenario 5, the paper and plastic separated by pretreatment at the grocery retail store were sent to the landfill used in scenario 2, while the organic fraction obtained was sent to the bioconversion plant. The organic fraction was handled in a bioconversion plant by the activity of *Hermetia illucens* to generate compost and dried larvae, which are utilized as fertilizers and prospective sources for animal feed formulation (Guo et al., 2021). The insects are fed with food waste; after bioconversion and composting, *Hermetia illucens* larvae are dried to produce dried larvae feed (Gligorescu et al., 2020). The inventory analysis was based on the data on materials, water, and electricity usage and direct emissions.

3.2. Cost-benefit analysis

Cost-benefit analysis can be used to evaluate the overall economics of systems or products (Ahamed et al., 2016). The present study applied this method to assess the cost of each food waste disposal scenario for further economic comparisons. The same system boundary and scope were set for both decision-supporting instruments to maintain consistency between the economic and environmental analyses. The average total cost per ton of food waste disposed was calculated for each of the five scenarios using the following equation:

$$C_N = C_T + C_t - B \tag{1}$$

where C_n is the net cost per ton of food waste treated (Canadian dollar/ton–C$/ton); C_T is the transportation cost per ton of food waste (C$/ton); C_t is the treatment cost per ton of food waste treated (C$/ton); and B is the benefit of by-products generated per ton of food waste (C$/ton).

Transportation costs were dependent on the distance from the grocery retail store to each waste treatment plant. The grocery retail store had its own multipurpose freight lorries, drivers, and general workers, who loaded and unloaded the waste, so there were no additional labor costs to consider. In scenarios 3, 4, and 5, the separated food wastes were transported to different plants according to the inventory analysis. A 10-ton freight lorry was used in each scenario to transport food waste, with a fuel efficiency of 2.5 km/L (Sivak and Tsimhoni, 2009). The price of diesel was C$2.27 per liter. The transportation cost per ton of food waste in the five scenarios was calculated using the following equation:

$$C_T = \sum_i R_i \times \frac{D_i \times P_d}{L \times E_f} \tag{2}$$

where R_i is the proportion of component i in food waste; D_i is the transport distance of component i in food waste (km); P_d is the diesel price (C$/L); L is the load of the freight lorry (ton); and E_f is the fuel efficiency (km/L).

The treatment costs for food waste included labor (salary, allowance), net (electricity, water consumption, fuel cost, depreciation, waste treatment costs, and taxes), material, and general management costs. In this study, the cost of the treatment of one ton of food waste was C$68.35 for incineration, C$18.91 for landfilling, C$93.36 for composting, C$84.94 for anaerobic digestion, and C$135.88 for bioconversion (Alvarez, 2012; Kim et al., 2011). The costs of the paper, plastic, and organic fractions were assumed to be the same for the same treatment method. The treatment cost per ton of food waste in the five scenarios was calculated using the following equation:

$$C_t = \sum_j R_j \times C_j \tag{3}$$

where R_j is the proportion of food waste treatment method j and C_j is the treatment cost of treatment method j (C$/ton).

The benefits of each scenario were dependent on the types, yields, and market prices of the available by-products generated per ton of food waste treated using different methods. The types and yields of the by-products from the different processes used in this study to treat one ton of food waste were 564 kWh of electricity from incineration, 30 kWh of electricity from landfilling, 210 kg of compost from composting, 220 kg of digestate and 256 kWh of electricity from anaerobic digestion, and 335 kg of compost and 30 kg of dried larvae feed from bioconversion (Kim et al., 2011; Mondello et al., 2017; Salomone et al., 2017; Sanscartier et al., 2012). The market prices of the by-products were C$0.128 per kWh for electricity, C$0.24 per kg for compost, C$0.014 per kg for digestate, and C$0.96 per kg for dried larvae feed (Golkowska et al., 2014; Madau et al., 2020; Muhammad and Rosentrater, 2020). We assumed that using the same treatment method would result in the same output for the paper, plastic, and organic fractions. The benefits per ton of food waste for the five scenarios were calculated using the following equation:

$$B = \sum_j R_j \times (\sum_k P_k \times Y_k) \quad (4)$$

where P_k is the market price of by-product k (C$/kg or kWh) and Y_k is the yield of by-product k (kg or kWh/ton).

3.3. Multi-criteria decision analysis

Despite that LCA is a widely used environmental management tool, decision makers have the issue of improperly incorporating data obtained through LCA into their decisions (Tsang et al., 2014). The large amount of data, the multiple user-defined types, the different media to which materials outflow, and the judgmental value systems to be applied all contribute to the difficulty, which is exacerbated when LCA results show trade-offs between various scenarios (Zanghelini et al., 2018). Thus, for environmental managers, the MCDA approach can be used to address the methodological challenge of making comprehensive decisions about environmental performance based on the various indicators evaluated using the LCA method (Benoit and Rousseaux, 2003). The MCDA method can be used to help achieve favorable results using LCA, particularly for preference evaluation (Myllyviita et al., 2012). The application of MCDA to environmental problems is regarded as extremely useful, as the explicit evaluation of competing criteria is important in the domain of waste management (Linkov and Moberg, 2011).

3.3.1. Selection and calculation

An appropriate MCDA approach was determined on the basis of certain criteria to consider various weights, compare criteria based on quantitative scales, and produce a ranking. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a tool that selects the optimal option by simultaneously calculating the minimum distance to the positive ideal option and the maximum distance to the negative ideal option (Tobiszewski et al., 2015). TOPSIS is widely used as an ideal method for MCDA comparisons of different waste disposal technologies (Alao et al., 2020). This study used the TOPSIS method to compare five food waste disposal scenarios using 14 selected criteria, including eight environmental impact types, four social impact types, and two economic factors. In all criteria, the benefit ratio had a positive impact (aiming at maximization), and the rest had a negative impact (aiming at minimization). The following is a summary of the typical TOPSIS calculation steps (Çelen, 2014; Kumar et al., 2017).

(1) Create a decision matrix:

$$X = (x_{ij})_{m\times n} \tag{5}$$

where X is a decision matrix consisting of m alternatives (A_1, A_2, …, A_m) and n criteria (C_1, C_2, …, C_n), and X_{ij} is the intersection of each alternative and criterion as.

(2) Calculate the standardized decision matrix:

when the criterion is positive,

$$x'_{ij} = \frac{x_{ij}-x_j^{min}}{x_j^{max}-x_j^{min}} \tag{6}$$

when the criterion is negative,

$$x'_{ij} = \frac{x_j^{max}-x_{ij}}{x_j^{max}-x_j^{min}} \tag{7}$$

(3) Calculate the normalized decision matrix:

$$r_{ij} = \frac{x'_{ij}}{\sqrt{\sum_{k=1}^{m} x'^2_{ij}}} \tag{8}$$

where i=1, 2, …, m, and j=1, 2, …, n.

(4) Calculate the weighted normalised decision matrix:

$$v_{ij} = w_j \times r_{ij} \tag{9}$$

where i=1, 2, …, m, and j=1, 2, …, n, and w_j is the weight of the attribute.

(5) Determine the worst alternative (A_w) and the best alternative (A_b):

$$A_w = \{min(v_{ij} | i = 1, 2, \dots, m)\} \equiv \{v_{wj} | j = 1, 2, \dots, n\} \tag{10}$$

$$A_b = \{max(v_{ij} | i = 1, 2, \dots, m)\} \equiv \{v_{bj} | j = 1, 2, \dots, n\} \tag{11}$$

(6) Calculate the distance of each alternative from the worst option (d_{iw}) and the best option (d_{ib}):

$$d_{iw} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{wj})^2} \tag{12}$$

$$d_{ib} = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_{bj}\right)^2} \tag{13}$$

where i=1, 2, …, m.

(7) Calculate the similarity to the worst option (s_{iw}):

$$s_{iw} = \frac{d_{iw}}{d_{iw}+d_{ib}} \tag{14}$$

where $0 \le s_{iw} \le 1$, i=1, 2, …, m, a larger s_{iw} means closer to the optimal condition, and a smaller s_{iw} means closer to the worst condition.

(8) Rank the alternatives.

3.3.2. Determination of weights

The determination of criterion weights is important and contentious, and the weighting must be carried out with extreme caution and expertise. Such methods can be divided into a priori, in which weights are calculated before data collection, and a posteriori, in which weights are decided after data collection. A priori weights are often obtained through expert interviews or surveys, whereas a posteriori weights are derived on the basis of the data collected for each choice (Kao, 2010).

Two weighting sets were calculated and utilized for TOPSIS in this study. The first method was the equal weight method, in which each of the 14 criteria was given the same importance, that is, $w_j = 1/14$. The second approach was the entropy method, which aims to assess the uncertainty of information based on the probability theory (Li et al., 2011). Entropy is a measure of a system's degree of disorderliness. It is an objective approach for determining weight based on data from various alternatives and criteria (Oluah et al., 2020). The entropy method reduced the impact of subjectivity, incompetence, or lack of decision makers by directly generating weighted criterion values from their fluctuations (Anwar et al., 2019). The two weighting methods were applied in this study to be neutral about the importance of the indicators and to be oriented toward the outcome data rather than the subjective feelings of the decision makers. In practical applications, decision makers can still adjust the weights or choose other weighting methods according to specific practical situations and target preferences. The criterion weights using entropy were calculated as follows:

(1) Decision matrix normalization:

$$x''_{ij} = H + x'_{ij} \tag{15}$$

$$y_{ij} = \frac{x''_{ij}}{\sum_{i=1}^{m} x''_{ij}} \tag{16}$$

where j=1, 2, …, n, y_{ij} is the normalized value of the decision matrix, and H is the panning magnitude, which is assumed to be 0.01.

(2) Determine the level of entropy (E_j):

$$E_j = -\frac{1}{\ln m} \sum_{i=m}^{m} y_{ij} \ln y_{ij} \tag{17}$$

where j=1, 2, …, n, and $0<E_j<1$.

(3) Calculate the deviation rate (d_j):

$$d_j = 1 - E_j \tag{18}$$

where j=1, 2, …, n.

(4) Calculate weights

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{19}$$

Chapter 4. Environmental, social and economic impact assessment

4.1. Environmental impact assessment for various food waste disposal scenarios

The life cycle impact assessment (LCIA) was first conducted using the IMPACT 2002+ method for the development of a detailed environmental description of each scenario. By connecting all types of life-cycle inventory results (elementary flows and additional interventions) according to the 14 midpoint categories of the four damage categories, the new IMPACT 2002+ LCIA methodology provides a workable implementation of mixed midpoint/damage (Jolliet et al., 2003). New concepts and approaches have been created for IMPACT 2002+, particularly for the comparison of ecotoxicity and human toxicity (Humbert et al., 2012). The main consideration is given to seven impact categories and their corresponding characterization factors: carcinogens, non-carcinogens, ozone layer depletion, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification and nutrification, and land occupation (Li et al., 2023; Zheng et al., 2023). By analyzing and comparing the results of each characterization in the five scenarios, the degrees of impact on various aspects of the environment by the different treatment methods can be determined.

The results of the comparative analysis of the characterization results of the five scenarios (Figure 4.1) show that the significant potential environmental burdens were associated with the landfilling and incineration scenarios in all impact categories, except terrestrial acidification and nutrification. The incineration scenario had the greatest environmental impact in terms of carcinogens, non-carcinogens, ozone layer depletion, and terrestrial ecotoxicity, while the landfilling scenario had the most significant contribution in terms of aquatic ecotoxicity and land occupation. The significant contribution of the landfilling scenario to aquatic ecotoxicity was due to the higher moisture content of food wastes from grocery retail stores than those of other waste types, which led to the formation of large amount of toxic leachate. The composting scenario contributed the most to terrestrial acidification and nutrification because of the large amount of nutrients that can be leached into the land from the composting process, but it had the lowest impact on terrestrial and aquatic ecotoxicity. The anaerobic digestion scenario showed a more intermediate level of impact for all environmental categories. Overall, the bioconversion scenario performed best, contributing the least to carcinogens, non-carcinogens, ozone layer depletion, and land occupation, with a higher effect only on terrestrial acidification and nutrification. It should be noted that this comparison does not reflect the contribution of each scenario to the overall environmental hazard or proportional influence of each environmental factor. Therefore, additional analysis using the single-score IMPACT 2002+ method is necessary.

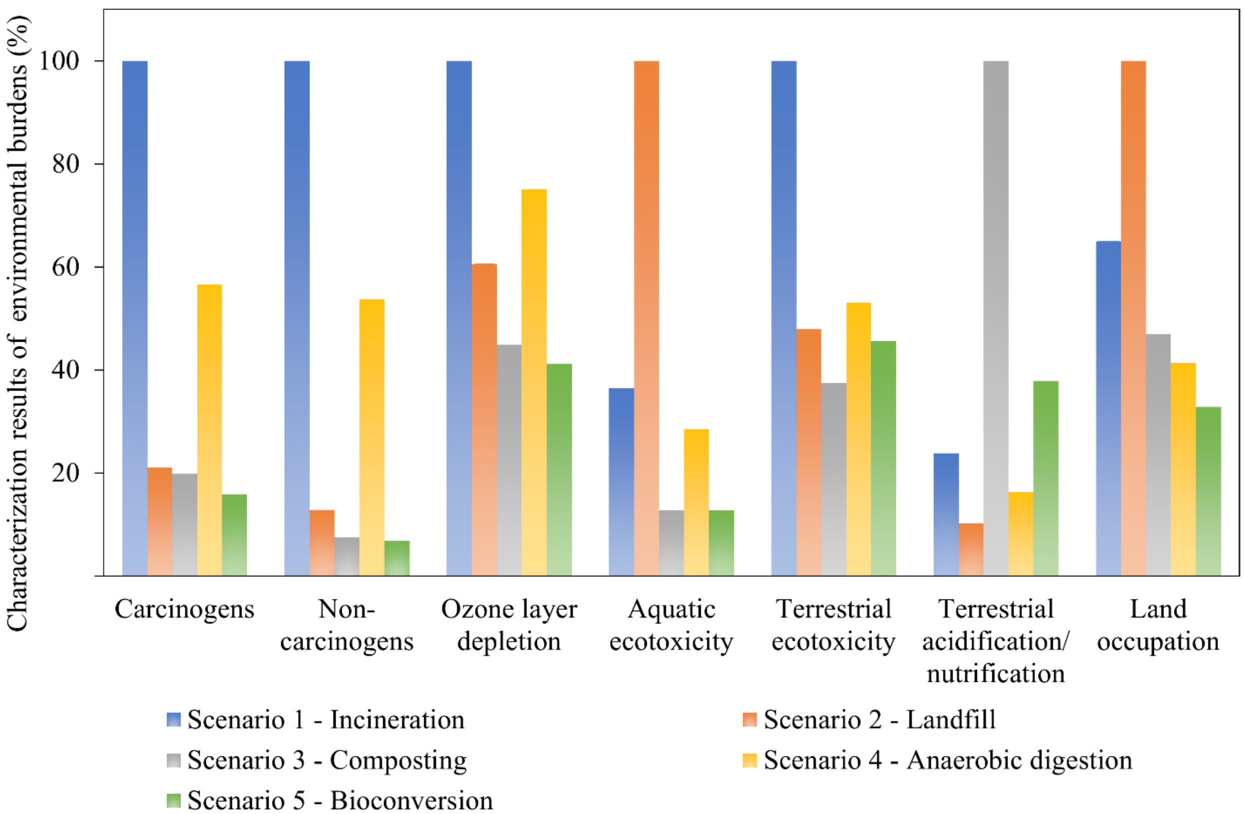

Figure 4.1 Characterization results of various environmental burdens for the five scenarios.

The environmental impacts generated by the five scenarios were summarized and integrated into four main factors: human health, ecosystem quality, climate change, and resources. The comparative analysis of the single score results in the five scenarios (Figure 4.2) underscores the fact that the incineration scenario provided the most significant impact on the four environmental factors, accounting for 27.13% of the total impact. By analyzing the impact ratio of different environmental factors in the incineration scenario, we found that the risk to human health accounted for 44.67% of the total impact and the impact was also higher than that in the other scenarios. By contrast, although the composting scenario had the second highest impact on human health after the incineration scenario, it contributed less to all other environmental factors, and composting accounted for only 17.4% of the total impact of the five scenarios. The landfilling scenario had the second highest environmental impact and the largest contribution to climate change among the various environmental factors, accounting for 56.25% of the total contribution. In addition, the landfilling scenario contributed much more to climate change than the other scenarios and almost twice as much as the incineration and anaerobic digestion scenarios. Anaerobic digestion is in the middle of the five scenarios in terms of environmental impact, with none of the environmental factors having the lowest or highest impact compared with the other scenarios. The bioconversion scenario is the least influential in all aspects, except human health, and had the lowest total contribution (12.32%) among all the scenarios. The effects of the five scenarios on ecosystem quality as an environmental factor were relatively low, and the scenarios were almost identical, except incineration. The results of the single-score analysis of the five scenarios indicate that bioconversion had the lowest environmental impact, followed by composting. By contrast, the incineration scenario consumed the most resources and had the greatest impact on human health.

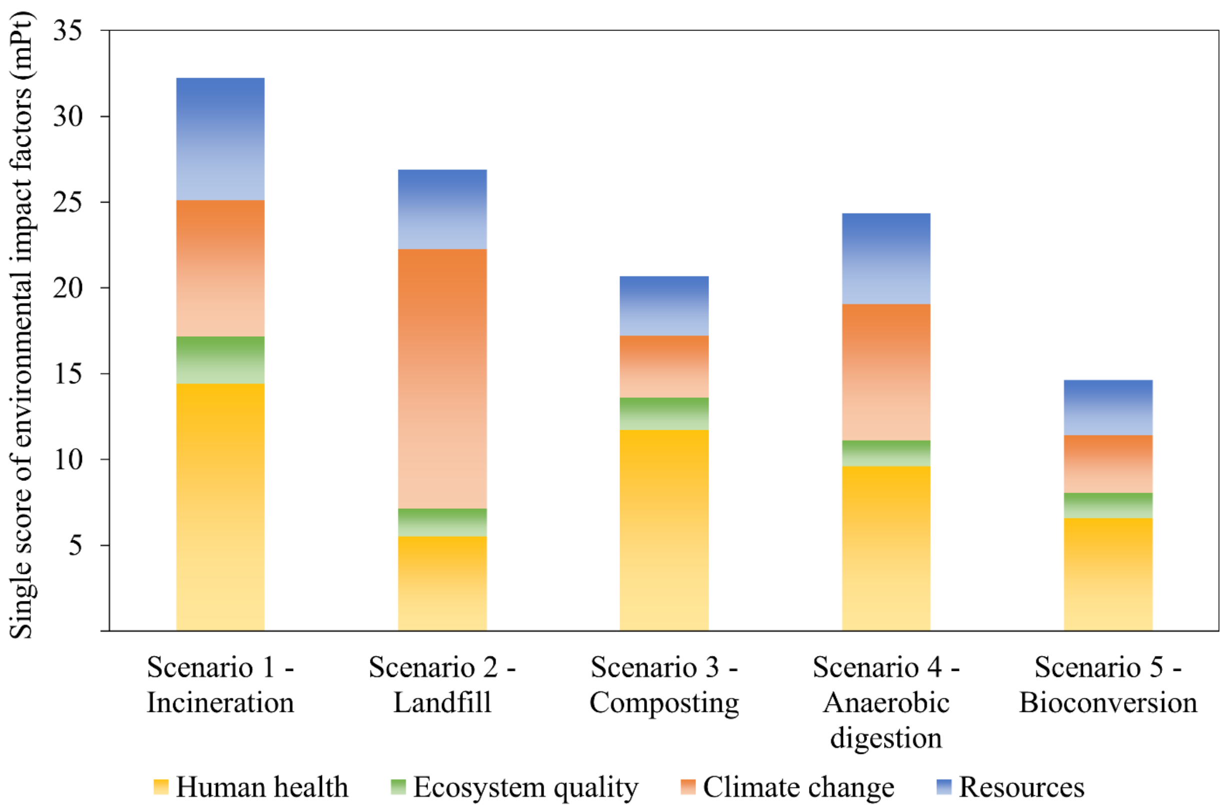

Figure 4.2 Single score results of four main environmental impact factors for the five scenarios.

Global warming is a pressing challenge (Amanatidou et al., 2023). The most prevalent gases that collect and retain heat in the atmosphere are carbon dioxide, nitrous oxide, and methane (Sangi et al., 2023). As an important factor in environmental impacts, the contributions of the five scenarios to global warming were compared and analyzed using the IPCC 2013 LCIA method, which can evaluate the climate change factors with a timeframe of 100 years (Jolliet et al., 2018). Compared with the five scenarios in the IPCC 2013 method, the characterization results (Figure 4.3) emphasize that each scenario contributed to global warming to some extent, with landfills contributing much more than the other four scenarios. The incineration scenario also had higher GHG emissions, second only to the landfilling scenario. The GHG emissions in the other three scenarios were all relatively low, with the bioconversion scenario having the lowest impact. The results indicated the landfilling of energy-dense food wastes generated by grocery retail stores can produce a large amount of GHGs.

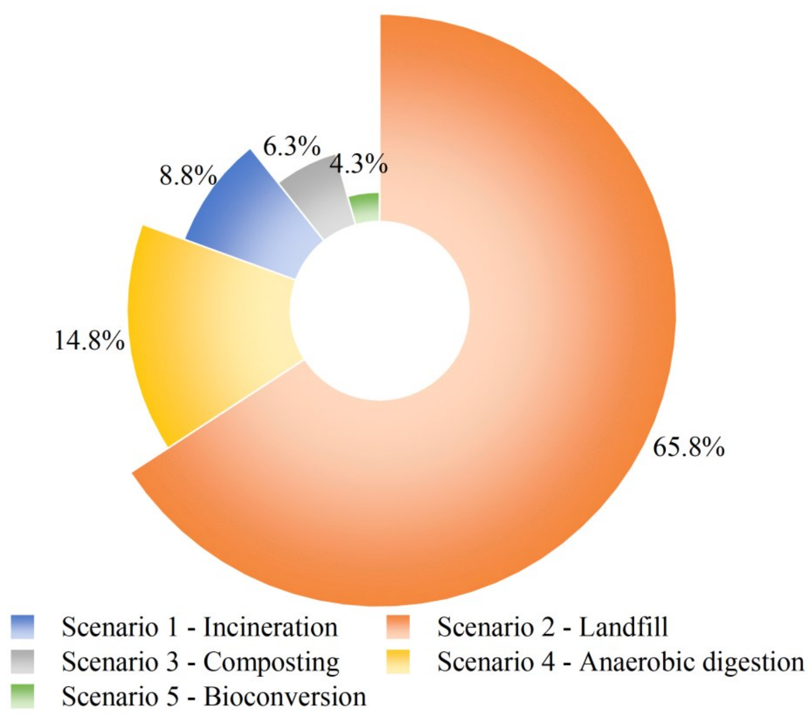

Figure 4.3 Characterization results of the five scenarios to global warming by IPCC 2013 method.

4.2. Social aspect analyses for various food waste disposal scenarios

The United Nations Department of Economic and Social Affairs released various perspectives that should be considered in the social analysis, such as changing human health and social attitudes

(Racz et al., 2018). The impacts of the five scenarios on the social aspect were assessed in this study using EPS 2015dx LCIA, which is a damage-oriented impact assessment method. This method considers 24 socially relevant impact categories and their corresponding characteristic factors such as crop growth capacity, production capacity for fruit and vegetables, cancer, fish and meat production, drinking water, irrigation water, and species extinction. A comprehensive analysis of all 24 impact categories resulted in an assessment of social damage in four areas: access to water, biodiversity, human health, and abiotic resources. This damage assessment method allowed for a more comprehensive comparison of the levels of the social impacts in the five scenarios and provided a basis for selecting the best option.

Compared with the five scenarios using the EPS 2015dx method, the damage assessment results (Figure 4.4) highlight that the bioconversion scenario had the lowest extent of environmental damage in all impact areas, except human health and abiotic resources. By contrast, the composting scenario had the lowest impact on human health and abiotic resources but was more damaging to biodiversity, ranking second among all scenarios. Moreover, the bioconversion scenario is similar to the composting scenario in all respects, except that it is significantly less damaging to biodiversity. The landfilling scenario has the highest contribution to environmental damage in terms of both biodiversity and human health. The incineration scenario had the most significant impact on both access to water and abiotic resources. The anaerobic digestion scenario had a relatively small impact on environmental damage in all aspects, except for its second highest contribution in terms of access to water.

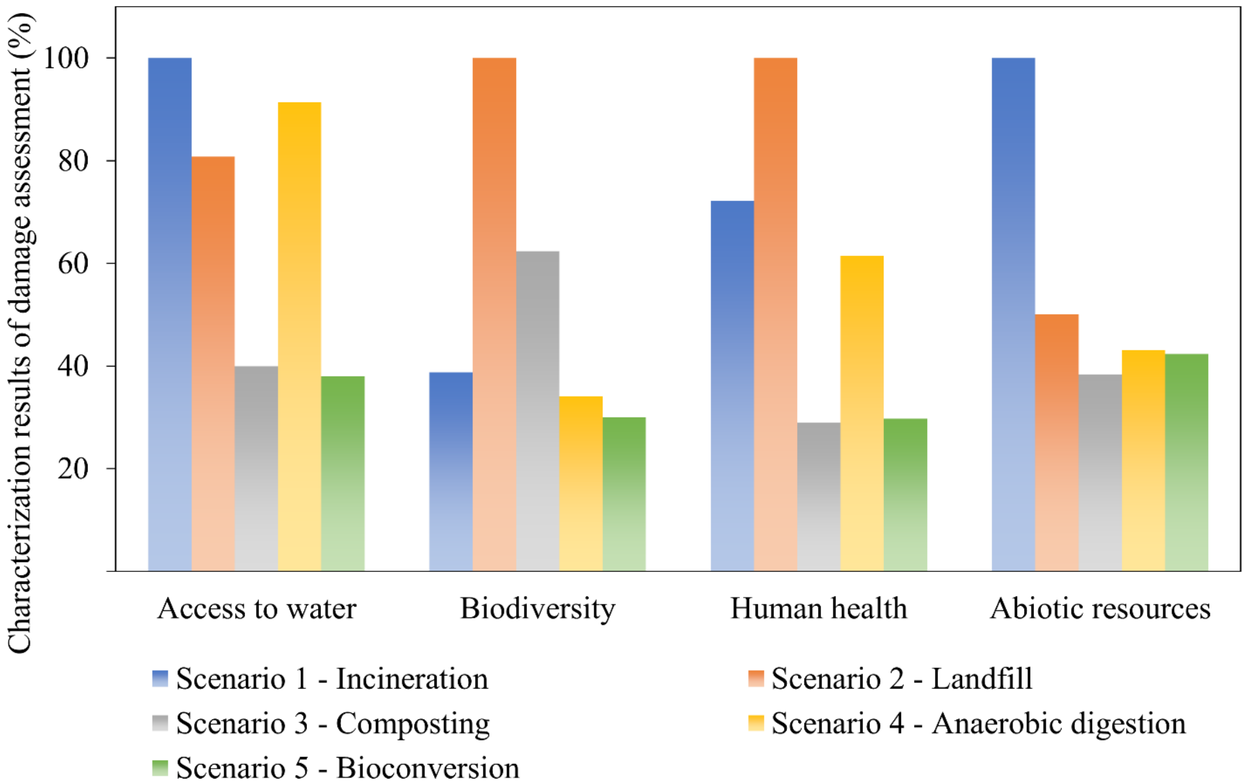

Figure 4.4 Characterization results of damage assessment for the five scenarios.

The specific types of human health impacts and resource consumption considered in the EPS 2015dx and IMPACT 2002+ approaches differ. The EPS 2015dx method tends to analyze the incidence and human health effects of diseases, including cancer, asthma, and diarrhea, whereas the IMPACT 2002+ method focuses on the potential human health effects about the toxicity of carcinogenic and non-carcinogenic substances generated in each scenario. Similarly, the EPS 2015dx method only compares abiotic resource consumptions across various scenarios, whereas the IMPACT 2002+ method considers a broader range of resource types. Therefore, the results of the two methods in comparing the environmental impacts of the five scenarios differed, but both methods had their own reference significance and value. The EPS 2015dx method was applied to the social aspect impact analysis, whereas the IMPACT 2002+ method was used in the environmental impact assessment.

4.3. Economic cost of various food waste disposal scenarios

4.3.1. Net cost and benefit-to-cost ratio

The transportation costs, treatment costs, benefits, and net costs of the five food waste disposal scenarios were quantified and expressed in Canadian dollars per ton of food waste treated (Table 4.1). On the basis of the final net cost of each scenario, the landfilling scenario had the lowest net cost of C$35.95 for the treatment of one ton of food waste, followed by the incineration scenario, which has a net cost of C$41.56. The excellent economic performance of the landfilling scenario is attributed to low treatment costs, even if the benefits are minimal. The incineration scenario can achieve a lower net cost if the high transportation cost due to the long distance to the incineration plant is reduced. Although the biotransformation scenario had the highest total cost of C$142.81, its highest benefits placed it in third place in terms of net cost. The higher net costs of the composting and anaerobic digestion scenarios were mainly due to their higher treatment costs. Furthermore, the price fluctuations of compost and electricity largely affected the net costs of both scenarios.

Table 4.1 Costs and benefits of each scenario (C$/ton).

Scenario	Transportation	Treatment	Total	Benefit	Net cost
Incineration	45.40	68.35	113.75	72.19	41.56
Landfill	20.88	18.91	39.79	3.84	35.95
Composting	6.99	85.92	92.91	45.74	47.17
Anaerobic digestion	8.63	78.34	86.97	32.65	54.32
Bioconversion	18.43	124.38	142.81	98.66	44.15

Price changes in land, labor, and resources affect the costs, benefits, and net costs of each scenario, so an avoided-impact analysis was conducted in this study. We found that the benefit-to-cost ratio was 0.63 for the incineration scenario, 0.1 for the landfilling scenario, 0.49 for the composting scenario, 0.38 for the anaerobic digestion scenario, and 0.69 for the bioconversion scenario. The results showed that although none of the scenarios had a ratio above 1, which means that none of them achieved profitability, the best-performing scenario was bioconversion, and the worst-performing scenario was landfilling.

4.3.2. Sensitive analysis

Traditional cost-benefit analysis approaches are aimed at providing a single, most likely net cost and benefit-to-cost ratio. A sensitivity analysis may improve the transparency of unconscious bias, deter misuse, and make cost-benefit analyses significantly more informative (Chen et al., 2023; Merrifield, 1997). The net costs of the five scenarios in this study were affected by the fluctuations of the yields and prices of various products such as electricity, compost, and dried larvae feed. This indicates multiple uncertainties in the cost-benefit analysis. Analyses of the sensitivity of these factors to net costs are of significant relevance and can help develop least-cost strategies for the entire food waste disposal scenario. This study used a fractional factorial design for the sensitivity analysis to identify the important factors that affect net cost. Bioconversion is the most representative non-traditional food waste disposal technology and has the highest total costs and benefits for all scenarios. All the factors included in the fractional factorial design and their values at different levels are listed in Table 4.2, with reference to the bioconversion scenario.

Table 4.2 Symbols and range of designed factors in bioconversion scenario.

Symbol	Factor	High level	Low level
A	Diesel cost (C$/L)	2.72	1.82
B	Fuel efficiency (km/L)	3	2
C	Loads (ton)	12	8
D	Landfill treatment cost (C$/ton)	22.69	15.13
E	Bioconversion treatment cost (C$/ton)	163.06	108.70
F	Electricity price (C$/kg)	0.15	0.10
G	Compost price (C$/kg)	0.29	0.19
H	Dried larvae feed price (C$/kg)	1.15	0.77
J	Electricity yield (kWh)	36	24
K	Compost yield (kg)	402	268
L	Dried larvae feed yield (kg)	36	24

Generally, only one replicate design can be performed in the model; thus, internal estimation of the error for a single replicate could not be performed (Yang et al., 2021). As a result, a single replicate factorial analysis can estimate the errors in net cost by integrating the mean squares of the high-order interactions. The number of runs necessary for a full factorial analysis increases dramatically as the number of variables in the factorial design increases (Zhou and Huang, 2011). Therefore, a 2^{11-5} fractional factorial design with resolution V was conducted in this study. Minitab was used for the factorial design and data analysis. The main effect plot for the net cost (Figure 4.5) showed that the bioconversion treatment cost had the most significant positive effect on the net cost of the bioconversion scenario, whereas diesel price had a relatively small effect. By contrast, both the price and yield of compost had a significant negative effect on net cost. In addition, fuel efficiency, loads, and dried larvae feed yield and price also had moderately negative effects on net costs.

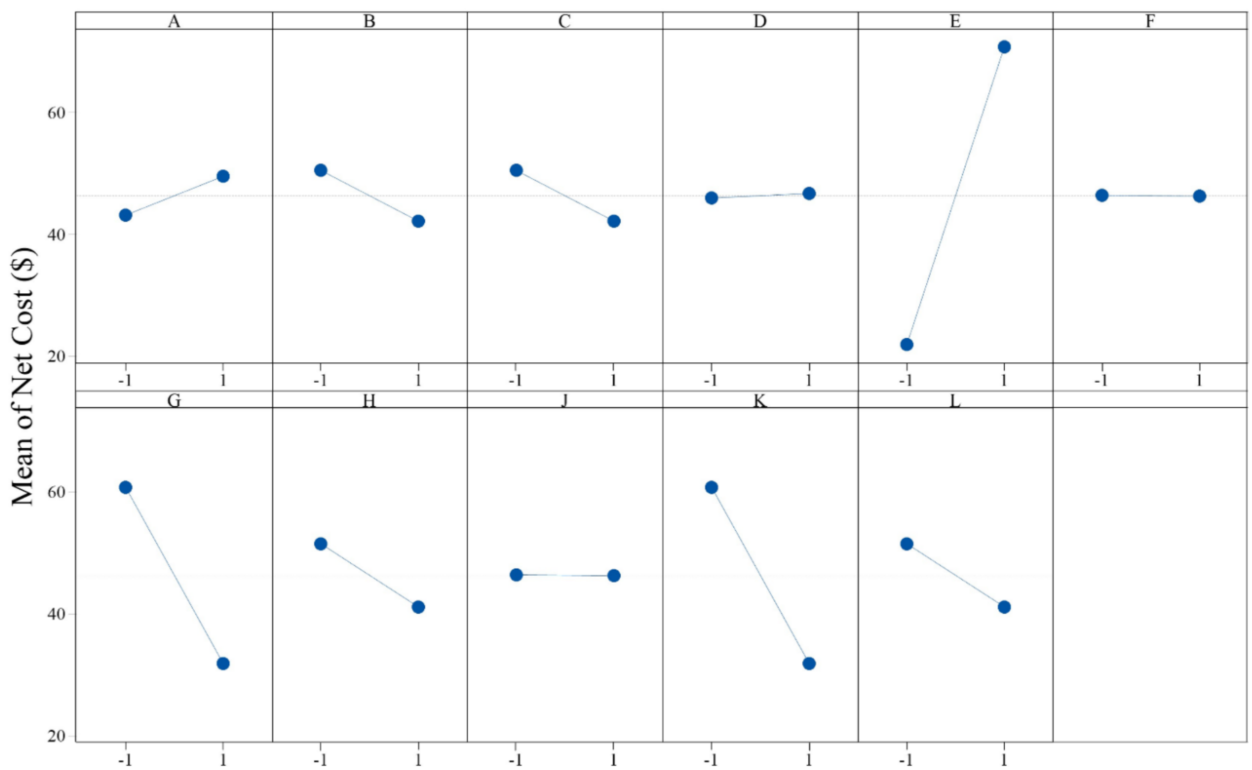

Figure 4.5 Main effect plots for net cost.

The Pareto chart of the standardized effects (Figure 4.6) was used to rank the factors in descending order of influence to indicate their significance levels. The Pareto analysis results confirmed many multi-factor interactions in addition to several important single influencing factors, some of which were more significant than the impact of a single influencing factor.

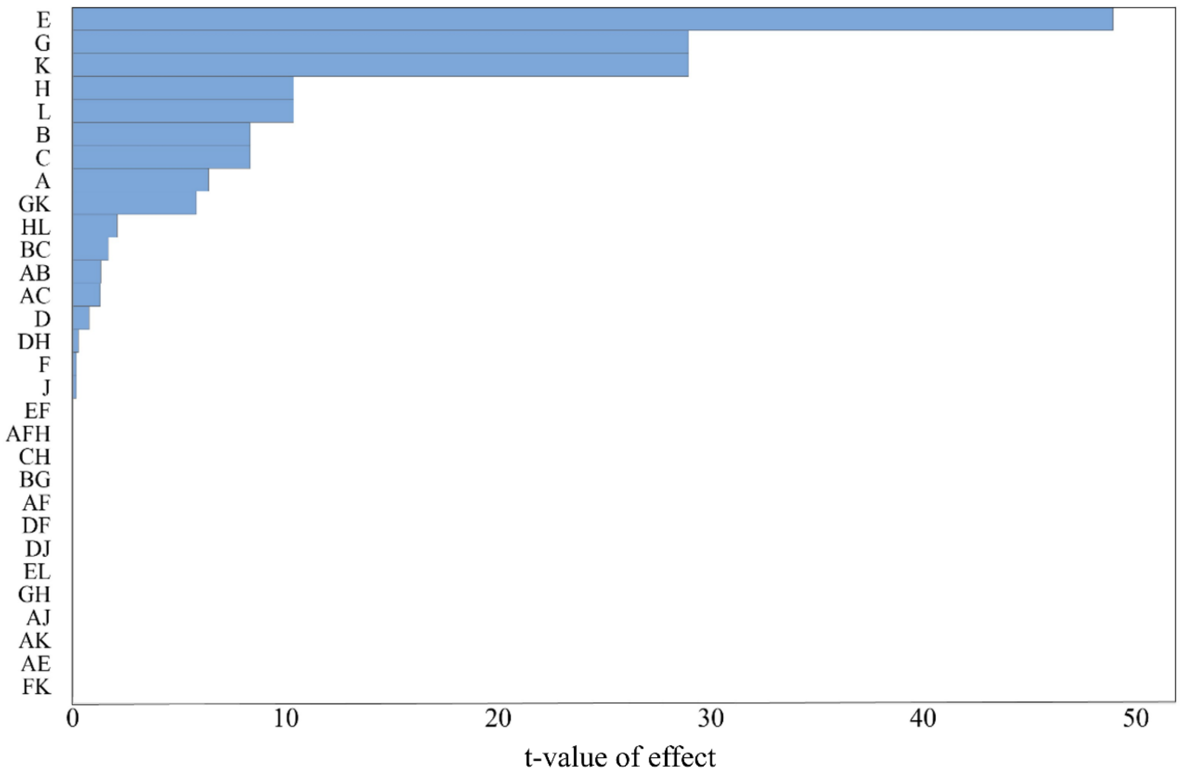

Figure 4.6 Pareto chart of the standardized effects.

Among many multi-factor interactions, the interaction of compost price and compost yield had a more significant impact on the net cost. The interaction plot for GK (Figure 4.7) shows that as the compost prices increased, the mean cost decreased at different compost yields. However, the slope of the straight line was greater at a compost yield of 402 kg than at a compost yield of 208 kg, so the contribution of the compost price to the reduction in average cost was more significant at higher compost yields than at lower compost yields. Therefore, to reduce the average cost, the focus should be on compost price changes when compost yields are high, rather than just on obtaining high yields.

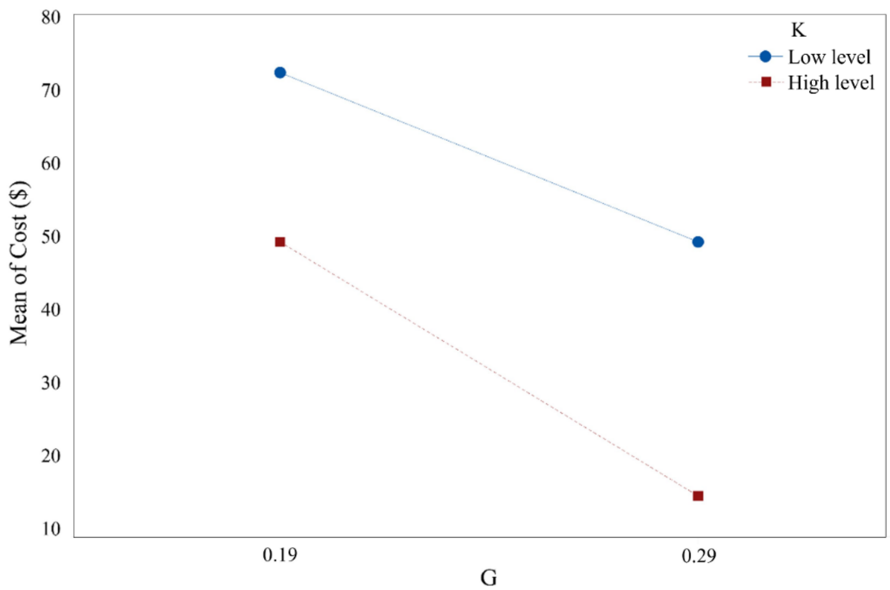

Figure 4.7 Interaction plot for GK.

Bioconversion technology using *Hermetia illucens* as the bioconversion agent still provides significant opportunities for efficiency gains (Surendra et al., 2020). If treatment costs can be reduced or by-product yields can be increased, the net cost will be significantly lower. The growing world population has led to a higher demand for food and feeds and consequently to higher feed prices (Dörper et al., 2021). Higher prices of dried larval feeds will significantly reduce the net cost of biotransformation and thus make it more competitive in terms of price.

4.4. Performance assessment and decision analysis for various food waste disposal scenarios

The TOPSIS method is used to calculate and assess the performance of five food waste disposal scenarios and to perform a decision analysis. The environmental, social, and economic aspects were evaluated as described in the previous sections, and the criteria and positively standardized results for each scenario (Table 4.3) were listed. S1–S5 represent the five scenarios. The weights of the criteria calculated using equal and entropy weights are listed in Table 4.4.

Table 4.3 Criteria and positively standardized results for each scenario.

Category	Criteria	S1	S2	S3	S4	S5
Environmental	Carcinogens	0	0.94	0.95	0.52	1
	Non-carcinogens	0	0.94	0.99	0.50	1
	Ozone layer depletion	0	0.67	0.94	0.42	1
	Aquatic ecotoxicity	0.73	0	1	0.82	0.99
	Terrestrial ecotoxicity	0	0.83	1	0.75	0.87
	Terrestrial acidification/nutrification	0.85	1	0	0.93	0.69
	Land occupation	0.52	0	0.79	0.87	1
	GWP 100a	0.93	0	0.97	0.83	1
Social	Access to water	0	0.31	0.97	0.14	1
	Biodiversity	0.87	0	0.54	0.94	1
	Human health	0.39	0	1	0.54	0.99
	Abiotic resources	0	0.81	1	0.92	0.93
Economic	Net cost	0.69	1	0.39	0	0.55
	Benefit-cost ratio	0.90	0	0.66	0.47	1

Table 4.4 Weights of the criteria calculated using equal weight and entropy weight.

Category	Criteria	Equal weight	Entropy weight
Environmental	Carcinogens	7.14%	6.82%
	Non-carcinogens	7.14%	6.95%
	Ozone layer depletion	7.14%	7.33%
	Aquatic ecotoxicity	7.14%	6.27%
	Terrestrial ecotoxicity	7.14%	6.16%
	Terrestrial acidification/nutrification	7.14%	6.26%
	Land occupation	7.14%	6.70%
	GWP 100a	7.14%	6.10%
Social	Access to water	7.14%	12.16%
	Biodiversity	7.14%	6.70%
	Human health	7.14%	7.93%
	Abiotic resources	7.14%	6.11%
Economic	Net cost	7.14%	7.50%
	Benefit-cost ratio	7.14%	7.02%

Finally, by combining the contributions and weights of the five scenarios for each criterion using the TOPSIS method, the similarities between the scenarios and the worst option (Figure 4.8) are determined. The most sustainable food waste disposal scenario was closest to the TOPSIS score of 1.00. The similarity values of the different scenarios differed depending on the weights selected. However, the rankings of the five scenarios are the same under both weight determination methods, with the bioconversion scenario performing the best, followed by the composting scenario. Therefore, decision makers should prioritize *Hermetia illucens* biotransformation and composting methods to dispose food wastes generated by grocery retail stores.

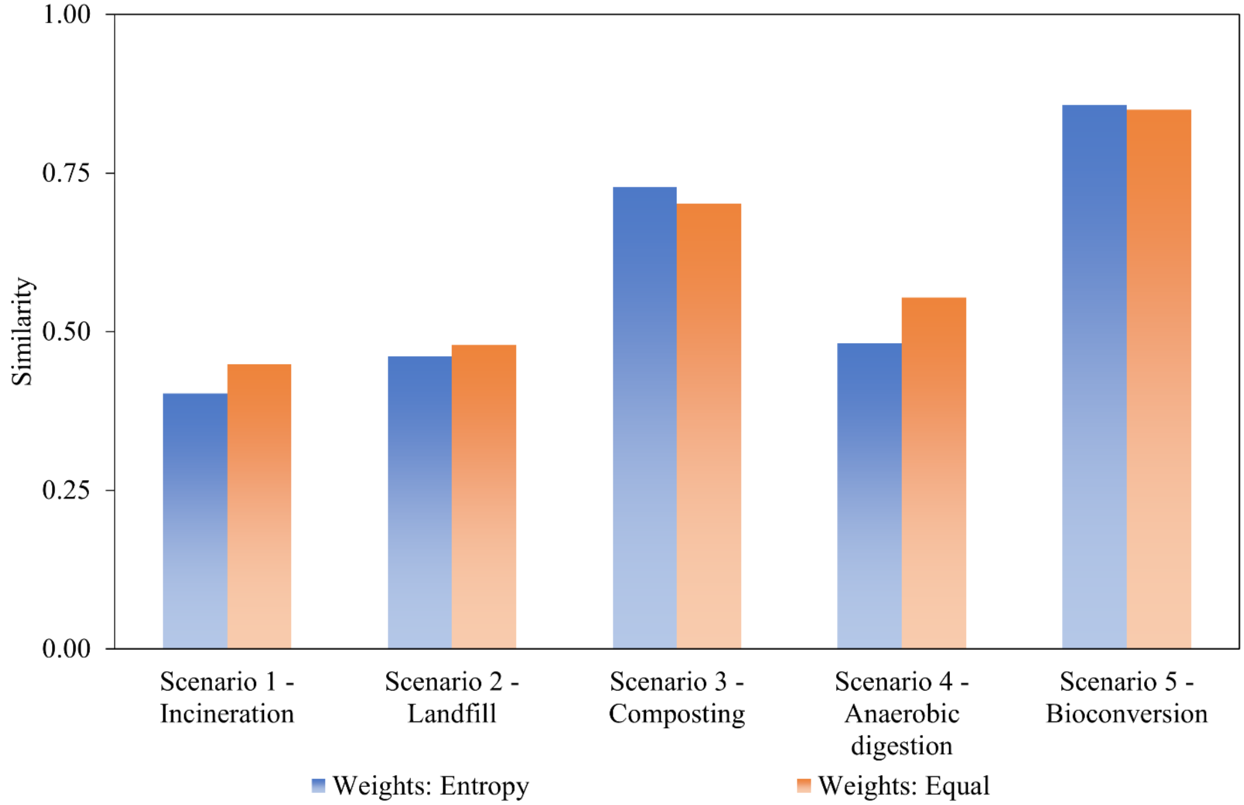

Figure 4.8 The similarity score between each scenario and the worst option (The closer the value is to 1.00, the more desirable the scenario is).

Chapter 5. Discussion

The area of interest in this study was Montreal, which is the largest and most representative city in Quebec owing to the major challenge it faces in the management of organic waste, where a large amount of organic waste is buried. Landfilling organic waste poses numerous environmental problems. In addition, landfills are rapidly becoming saturated, and opening new ones is becoming more difficult. To address these problems, the Quebec government has introduced various measures to increase the recycling of organic materials. For example, municipalities are required to divert 60% of organic materials from landfills for recycling (Joly, 2011).

Implementing sustainable organic waste disposal in Quebec is mainly affected by low landfill costs, the high infrastructure and maintenance costs of certain treatment technologies, and the low public acceptance of the odor and emissions generated. It is challenging and necessary for decision makers to create appropriate policies and assess their effectiveness in such a context. Therefore, the government can subsidize grocery retail stores that choose to dispose their food wastes in ways other than landfills or impose a tax on landfilled food waste to improve the economic competitiveness of new technologies and provide incentives for grocery retail stores to eliminate or reduce the practice of landfilling food waste (Huang et al., 2017). If the government grants subsidies to grocery retail stores in parallel with and in the same amount as the tax levied on landfills, the relationship between net costs and the amount of subsidies and taxes (Figure 5.1) can be determined for the five scenarios. As subsidies and taxes increase, the economic advantage of landfills diminishes until the net costs of the other four scenarios are lower than the landfilling scenario when both subsidies and taxes are C$10 per ton. The net costs of the bioconversion and combustion scenarios are even lower than the original net cost of the landfilling scenario before taxation.

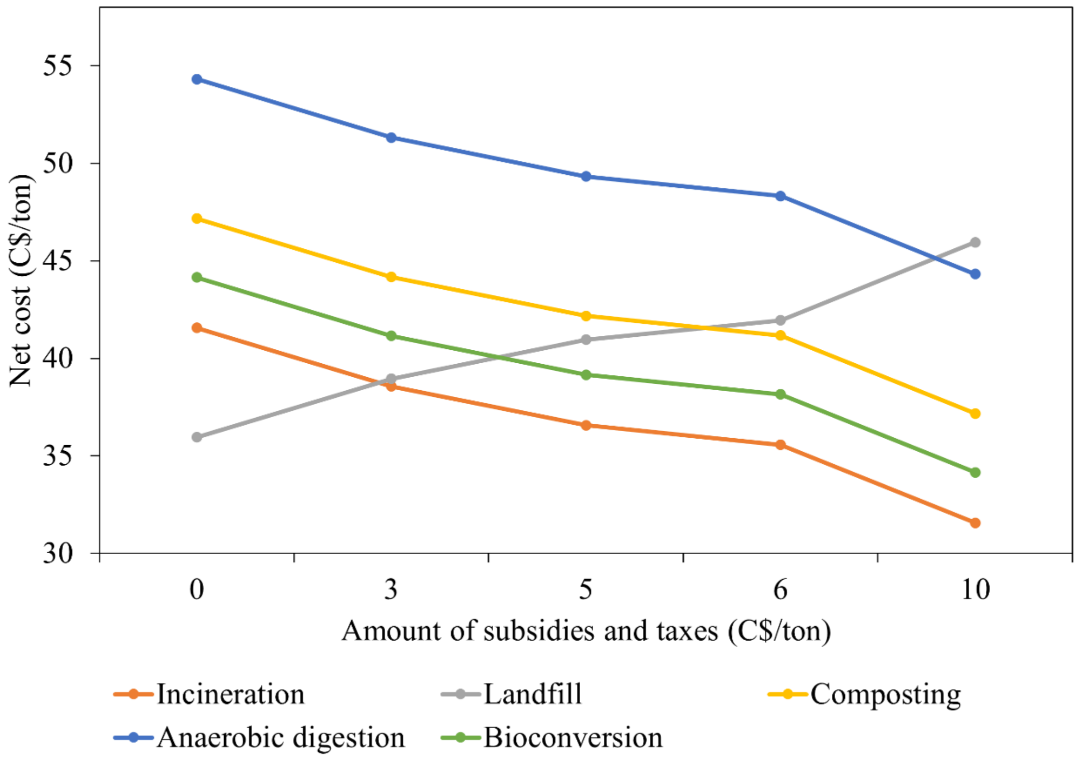

Figure 5.1 The relationship between net costs and the amount of subsidies and taxes.

This study only addresses hypothetical scenarios such as where grocery retail stores can separate food waste from plastic and paper packaging in-store and do not need to add additional processing steps and costs. Otherwise, food waste would need to be transported to a separation plant for separation, which has additional environmental impacts and economic costs, causing changes in the assessment results for some scenarios and thus affecting the final ranking. Furthermore, the results of this study are only applicable to a specific scope, as changes in factors such as transport distance, waste composition, treatment processes, and resource prices could lead to changes in the evaluation. In many cases, the distance from each grocery retail store to the treatment plant is difficult to estimate or determine. On the other hand, in some government planning schemes for specific regions, the distance from the new treatment plant to the grocery retail store is fixed, regardless of the type of treatment plant the government ultimately chooses to build in the region. Therefore, assuming that the distance from the grocery retail store to each treatment plant is the same and other things remain the same, the results of the characterization of the five scenarios using the IMPACT 2002 + method (Figure 5.2) will change. Compared with the results considering the transport distances, all five scenarios show changes in all indicators to varying degrees, most notably in the incineration scenario with the longest transport distances, with significant decreases in ozone layer depletion, terrestrial toxicity, aquatic toxicity, and land occupation, which are closely related to the reduction in fossil fuel consumption during transport.

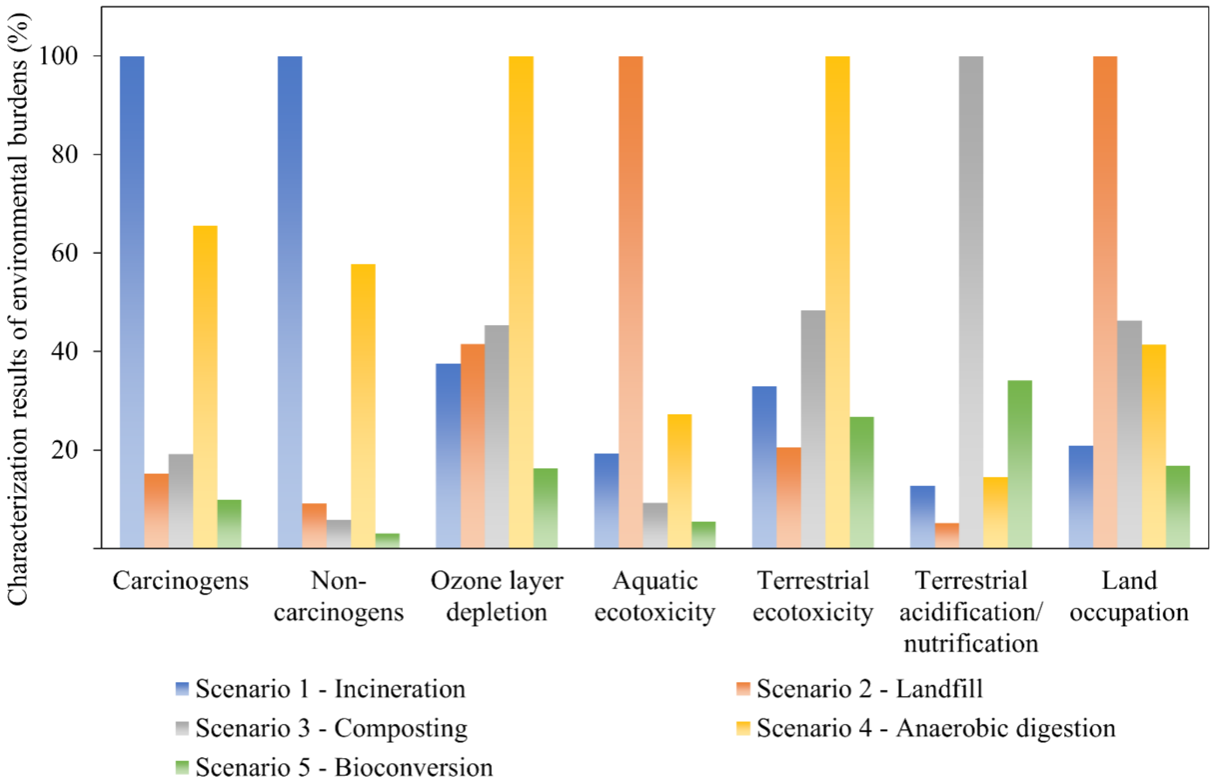

Figure 5.2 Characterization results of various environmental burdens for equal transport distance scenarios.

To aid decision-making, this study also evaluated the feasibility of integrating the MCDA method with the LCA method. Results from LCA studies for waste management are frequently challenging to understand because of the absence of a perfectly satisfactory alternative. However, without an overview of its outputs, the interpretation stage of an LCA becomes significantly more challenging for decision making. Utilizing a suitable MCDA method not only clarifies how to understand LCA data but also aids in demonstrating the desirability of alternatives. We conclude that TOPSIS helps overcome the drawbacks of LCA studies, and we concur with the earlier studies in this regard (Niero and Kalbar, 2019). TOPSIS provides a single score, making it simple to comprehend the best feasible option. However, TOPSIS does not offer a fixed conclusion because even when the same criteria and importance are considered, different calculation methods can produce different weights and thus change MCDA results. For example, although the criteria considered are the same as those in the equal weight method and each criterion is also considered to have the same importance, the criteria weights calculated using the analytical hierarchy process (Figure 5.3) still differ. Each weight calculation method is correct and applicable to TOPSIS, but the choice of method depends on the specific problem and decision maker's preferences. Owing to the excellent adaptability of TOPSIS to the views of one decision maker, this may be advantageous, but comparison of the conclusions of one study with those of similar others is difficult (Maxim, 2014).

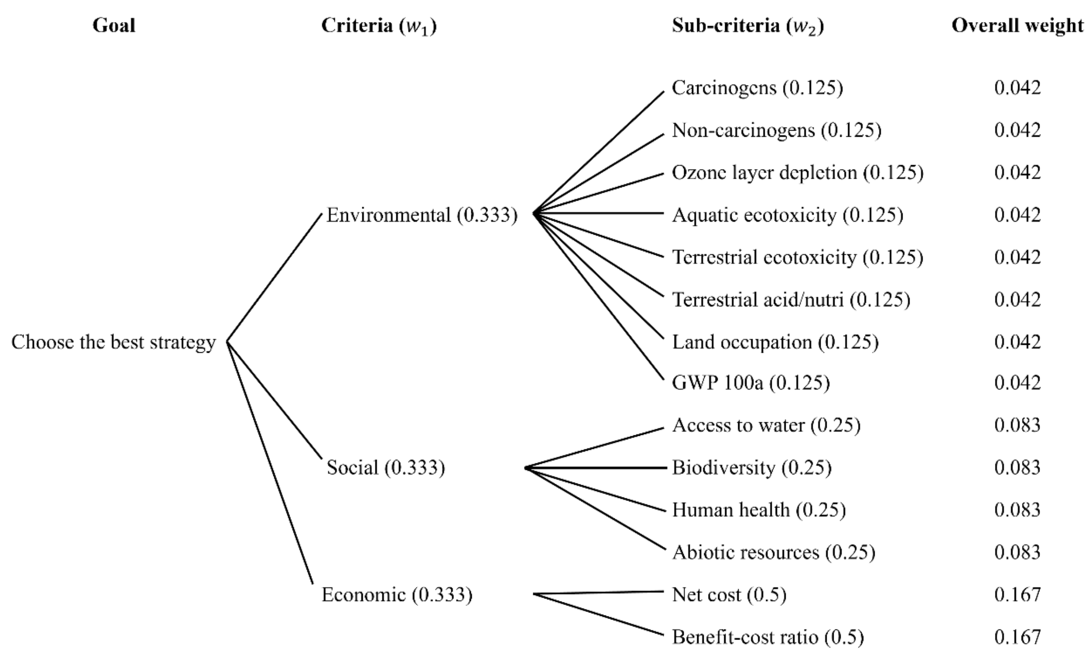

Figure 5.3 Results of the criteria weights calculated by the analytic hierarchy process.

Chapter 6. Conclusions

The main objective of this study was to inform and assist decision makers in choosing the best waste management strategy by evaluating and analyzing the environmental, economic, and social impacts of multiple alternatives to disposing food wastes generated by grocery retail stores, including the values of their beneficial by-products. This study also serves to consolidate and summarize existing literature, providing an in-depth analysis of food waste generation and exploring a diverse array of treatment technologies. Additionally, the study highlights the wealth of value-added products that can be derived from food waste transformation. By emphasizing the environmental, economic, and social dimensions of waste management and considering the potential for valuable by-products, this study contributes to a holistic understanding of sustainable food waste management practices, providing a foundation for informed decision-making in the realm of grocery retail. The scenarios closest to the best option derived using the TOPSIS method are, in descending order, the bioconversion, composting, anaerobic digestion, landfilling, and incineration scenarios. A further progression of this study is the application of this approach to the growing number of different grocery retail stores and food waste disposal planning. In addition, this study suggests that future work can incorporate other new alternative technologies for food waste disposal to provide grocery retail stores and decision makers with a wider range of options and more valuable advice.

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