

STANDARDS RESEARCH

Climate-Smart Circularity: Guiding Decision-Making Through Data-Informed Standard Protocols

December 2024

Authors

Sourabh Jain, Ph.D., Ivey Business School

Jury Gualandris, Ph.D., Ivey Business School

Project Advisory Panel

Ben Amor, LIRIDE – Université de Sherbrooke

Helen Goodland, SCIUS Advisory Inc.

Kelly Drennan, Fashion Takes Action

Paul Shorthouse, Circular Economy Leadership Canada (CLEC)

Phoebe Cullingham, EllisDon

Rocío Morales Rayas, CSA Group

Anna Copeland, CSA Group (Project Manager)

Acknowledgement

The authors would like to thank anonymous interviewees from construction and textile industries for providing information to help conduct this research.

Financial Support

This work was supported by Mitacs through the Mitacs Accelerate Program (Grant number IT35555).

Disclaimer

This work has been produced by the author and is owned by Canadian Standards Association. It is designed to provide general information in regards to the subject matter covered. The views expressed in this publication are those of the author and study participants. The author and Canadian Standards Association are not responsible for any loss or damage which might occur because of your reliance or use of the content in this publication.

Table of Contents

Executive Summary 4

1 Introduction 6

1.1 Background 6

1.2 Purpose and Objectives 7

2 Methods 9

2.1 Case Study and Scope 9

2.1.1 Definition of Discards 9

2.1.2 Linear Design of Selected Canadian Sectors 9

2.1.3 Study Scope 11

2.2 Data Gathering, Life Cycle Assessment Modeling, and Simulation 12

2.3 System Boundaries 14

3 Results and Discussion 21

3.1 Circular Pathways, Operational Structures, and Net Greenhouse Gas Impacts 21

3.1.1 Textile Sector 21

3.1.2 Construction Sector 26

3.1.3 Agrifood Sector 32

3.2 Technological Configuration, Geographical Scale, and 20% Net Carbon Savings 36

3.3 Comparative Analysis 41

4 Discussion and Conclusion 44

4.1 Recommendations for Public Policy and Standardization 44

4.2 Limitations 47

References 49

Appendix A 56

Executive Summary

While circularity is often assumed to be climate-smart, which is defined as reducing greenhouse gas (GHG) emissions relative to the emissions associated with the production of virgin materials, the goals of closing material flows and reducing net GHG emissions relative to virgin materials are not always aligned. Inappropriately designed circular pathways could unintentionally counteract efforts to catalyze the climate transition. This report investigates the conditions that make circularity climate-smart by examining multiple circular pathways for seven discarded material streams (DMSs) across three key Canadian sectors.

The research conducted for this report identified structural similarities across circular pathways that are climate-smart, with the goal of providing evidence-based guidelines to support the development of an effective circular economy. The following seven DMSs from three key sectors were assessed:

- **Textile sector:** Cotton and polyester fibres.
- **Construction sector:** Wood, concrete, and plastic.
- **Agrifood sector:** Wet spent grain and fruit and vegetable residue.

For each DMS, various circular pathways were analyzed, including reuse, recycling, repurposing materials to other sectors, downcycling to lower quality applications, and energy recovery. A life cycle assessment (LCA) approach was used to evaluate the net GHG emissions avoided when a circular pathway substituted equivalent virgin production. Primary and secondary data were collected through field interviews, reviews of academic and industry literature, and the ecoinvent database. Using openLCA software and Microsoft Excel, the study modelled diverse circular pathways focusing on their operational structures, defined as a combination of geographical scaling in the form of transportation distances and technological configuration in the form of energy intensity. The LCA approach focused primarily on the quantification of GHG emissions. Given the uncertainties in the data, sensitivity analyses were performed in the form of best and worst cases to capture the variability in GHG emissions for each operational structure. A regression analysis was also performed to explore the underlying potential relationship between carbon budget, defined as the GHG emissions associated with the production of specific virgin resources substituted by a given circular pathway, and the maximum transportation and energy intensity thresholds that characterize the circular pathway.

Key findings highlight that circularity, when designed and implemented effectively, can lead to significant GHG savings. For example, in the textile sector, all circular pathways generate net GHG savings relative to substituted virgin materials, but there are significant differences across pathways: reusing saves approximately 154 to 260% more GHG emissions than chemical recycling; chemical recycling saves 94 to 620% more GHG emissions than mechanical; and mechanical recycling saves 104 to 630% more GHG emissions than downcycling. However, the GHG savings were not as consistent and pronounced in the agrifood and construction sectors, with only some circular pathways being climate-smart.The research also identified operational thresholds for achieving a minimum of 20% net GHG emissions reduction, aligning with Canada's 2030 climate targets. The regression analysis revealed a linear relationship between carbon budgets and maximum thresholds of transportation and energy consumption

for circular pathways, finding that one standard deviation increase in carbon budget (i.e., an increase of 3910 kg CO_2e/t of virgin material) allows the energy consumption of a climate-smart circular pathway to expand by 65 686 MJ (i.e., 0.677 times the standard deviation of the energy consumption data distribution in the sample, which is about 97 025 MJ), and allows the transportation of a climate-smart circular pathway to expand by 53 288 t·km (i.e., 0.670 times the standard deviation of transportation data in the sample, which is about 79 535 t·km). While total carbon budget is an important determining factor for maximum geographical scale, GHG intensities of energy and transportation are equally important. The circular pathways in the agrifood sector use light commercial vehicles for collecting DMSs, which are GHG inefficient; and concrete recycling uses portable diesel-based electricity generators, resulting in high GHG intensity energy to run machines. These factors further explain why climate-smart circular pathways in the agrifood and construction sectors must operate within lower maximum thresholds of total energy consumption and transportation.

As diverse organizations work collaboratively to develop circular pathways, they should be mindful of design conditions that make circular pathways more likely to be climate-smart. This report concludes with several recommendations for consideration when designing circular climate-smart pathways.



"Circularity empowers organizations to valorize discarded resources into feedstock within and across supply chains, which in turn fosters a sustainable model of production and consumption that aligns with the planet's environmental boundaries."

1 Introduction

1.1 Background

The circular economy, or circularity, offers an alternative to the traditional linear economic model. Circularity not only aims to achieve the same economic outcomes as the linear model but it also does so by minimizing material usage, prolonging product life, maximizing resource use, and promoting the reuse of materials [1]. Some common circular pathways include a) prevention and reduction of discards; b) reusing products; c) recycling, which includes upcycling materials to high economically valuable applications in new industries (e.g., upcycling food discards into production inputs for pharmaceutical products or construction), recycling back into the same application (e.g., from used garment fibres to recycled garment fibres), or downcycling to lower quality resources;[1] and d) various forms of resource recovery, such as composting, anaerobic digestion, and energy recovery. These circular pathways stand in contrast to the conventional pathways of incineration[2] without energy recovery and landfilling, which are generally considered less sustainable waste management practices. Embracing circularity can significantly contribute to resource conservation and waste reduction, thus aligning with policy goals that prioritize sustainable development.

Circularity empowers organizations to valorize discarded resources into feedstock within and across supply chains, which in turn fosters a sustainable model of production and consumption that aligns with the planet's environmental boundaries. With over 200 interpretations of circularity [1], the general consensus points to its role in driving innovation, increasing economic productivity, improving supply chain resilience, advancing social justice, and promoting environmental sustainability. Policymakers and researchers have highlighted circularity as a strategic solution to reduce waste, combat climate change, and restore biodiversity [1], [2], [3], [4], simultaneously unlocking new economic potentials for businesses and communities.

While circularity aims to recover resources and reduce the reliance on extractive processes and virgin materials, its impact on climate change is not always straightforward [5], [6]. The process of assessing the environmental advantages, such as climate change mitigation, associated with circularity is complex [6], [7]. The management of discarded material streams (DMSs) through a circular pathway, from reusing to recycling and energy valorization, encompasses various steps, such as collection, transportation, sorting, processing, managing residual discards, and substituting virgin

1 The term "resource" is frequently used in this report because while some pathways recover materials, others recover energy (when material to energy conversion is involved).

2 Throughout this report, "incineration" implies incineration without energy recovery.

production.[3] Each step contributes to the net environmental impacts, defined as the difference between the negative impacts of circular activities and the positive savings from substituting virgin production, of the analyzed circular pathway. Together, all steps collectively determine the net environmental impacts of managing discards via a given circular pathway.

Four main groups of factors define a pathway's operational structure and determine its net environmental impact [5]:

1. **Geographical scale of operations:** The total distance and mode of transportation (small vs. large trucks; truck, ship, or rail), starting from the collection of discarded materials to the final substitution of virgin production. Operations that are geographically spread out, combined with emission-intensive transportation modes, can produce higher greenhouse gas (GHG) emissions.

2. **Technological configuration:** The choice and the sequence of processing/treatment steps. For example, upcycling food discards, such as wet spent grains, requires drying. Vacuum drying of wet spent grains uses more energy than air drying, while also potentially retaining more nutrients. The choice of drying technology affects the net environmental impacts of upcycling wet spent grains, but the sequence of operation is equally important. For example, deploying mechanical pressing of wet spent grain before drying can save energy, thereby improving net environmental impacts relative to a process that does not involve mechanical pressing.

3. **Quantity and quality of recovered resource (material or energy)**: A specific circular material fulfills a specific function (e.g., structural support in construction; nutrition in agrifood; strength and comfort in textile). Circular materials with high quality (i.e., fulfilling such functions in the same way or better than a virgin material) substituted for virgin materials can result, everything else being equal, in higher savings of GHG emissions.

4. **Other factors:** Includes the environmental impacts of energy sources (e.g., grid-mix or district heating) and the background infrastructure (e.g., roads, buildings) required to support circular operations.

Different circular pathways and operational structures with diverse net environmental impacts can develop for managing the same DMS [5]. Therefore, a comprehensive assessment is essential to understand what circular pathways are available for each DMS, and how their operational structures should be configured to generate net positive environmental value. In this report, circular pathways for any given DMS are distinguished from one another based on the type of resources they recover, and therefore the type of virgin materials or energy they displace. No two circular pathways recover the same type of resources. Further, for any given circular pathway, all operational structures recover identical resources but differ from one another based on the unique combination of the four factors[4] noted above. For example, two operational structures may recover the same resource but substitute different virgin resources.

Public and private organizations lack awareness and understanding regarding the differences in net GHG emissions (ranging from positive to negative) associated with alternative circular pathways for a given DMS, as well as for different operational structures associated with any given circular pathway. Traditional resource recovery hierarchies, such as the one adopted by the European Union [8] shown in Figure 1, may unintentionally lead to selecting circular pathways that are environmentally suboptimal, and do not offer guidance concerning optimal operational structures that should characterize any chosen pathway [9].

3 In this report, substituting virgin production or virgin resources implies substituting the upstream life cycle, including production of virgin resources, processing, manufacturing, and transportation up to the point of substitution.

4 Variation in one operational factor, such as geographical scale, can sometimes lead to variations in other operational factors, such as grid-mixes and quantity of resources recovered, because different countries have different grid-mixes and because longer geographical scale may involve multiple sorting and quality checks, leading to higher rejection rates.

Figure 1: A generic resource recovery hierarchy. Standard resource recovery hierarchy adopted by the European Union [9]. Reprinted from https://ec.europa.eu/environment/topics/waste-and-recycling/waste-framework-Directive_en



1.2 Purpose and Objectives

This research report identifies and evaluates circular pathways that apply to seven DMSs in three Canadian sectors, with the goal of providing data-driven guidelines to improve their design and management. To achieve this goal, the report assesses the net environmental benefits, in terms of GHG emissions, associated with managing the following diverse DMSs for three key sectors:

- **Textile sector:** Cotton and polyester fibres.
- **Construction sector:** Wood, concrete, and plastic.
- **Agrifood sector:** Wet spent grain and fruit and vegetable residue.

For each of these seven DMSs, this report identifies diverse circular pathways, and for each pathway, this report explores and analyzes diverse operational structures and their associated net GHG emissions. The net GHG emissions of a circular pathway, given a specific operational structure, are measured relative to substituting virgin production.

Depending on its operational structure, the net GHG emissions of a circular pathway could be carbon positive (i.e., releases more emissions than virgin production), carbon negative (i.e., releases less emissions than virgin production), or carbon neutral (i.e., releases the same emissions as virgin production).

This report had four key objectives:

1. **Map circular pathways:** Identify and analyze emergent circular pathways for each of the selected DMSs from three Canadian sectors: textiles, construction, and agrifood.
2. **Assess net GHG emissions:** For each identified DMS and circular pathway, assess the net GHG emissions associated with diverse operational structures adopted by real cases.
3. **Identify and improve best circular pathways:** For each analyzed DMS and circular pathway, identify the operational structure associated with the lowest net GHG emissions and derive upper thresholds of geographical scale (measured in t·km per tonne of discarded material) and technological configuration (measured in MJ/t of the discarded material) under which a circular pathway emits 20% less GHG emissions relative to the substituted virgin materials or products. A target of 20% GHG emissions reduction is aligned with Canada's 2030 net zero goals. Specifically, Canada aims to reduce its total GHG emissions by as much as 40% by 2030, with 50% of such reduction coming from cleaner energy sources and the other 50% coming from the circular economy.

4. **Generalize the findings:** Identify similarities and differences across DMSs in terms of geographical scales, technological configurations, material qualities, and other key considerations for circular pathways to achieve important carbon savings relative to virgin production. A regression analysis will estimate the admissible increase in maximum geographical scale (measured in t·km) and technological configuration (measured in MJ) of circular pathways for displaced virgin materials and energy with increasingly higher "embedded" carbon.

2 Methods

This section outlines the methodology for all four objectives, including both data collection and analytical processes. For the agrifood sector, objectives 1 through 3 were addressed in a separate study [5], and the analyses and results are reported and extended in this study. The approach adopted for analyzing the textile and construction sectors for objectives 1 through 3 mirrored the methodology used in study [5]. The methodology for objective 4 used prior insights from the agrifood sector combined with novel insights obtained from the textile and construction sectors. See Appendix A for further details about data, assumptions, and calculations.

2.1 Case Study and Scope

2.1.1 Definition of Discards

Drawing on prior research [5], "discards" are defined as materials perceived to have little to no residual economic value for the generator, and are therefore often managed reactively and inefficiently. Conventionally undesirable discards include surplus, unavoidable production residues (or byproducts), and end-of-life products [5].

This report considers unavoidable production residues from the agrifood sector and end-of-life discards from the construction and textile sectors. Unavoidable production residues are byproducts generated during the production or processing of edible items. They constitute over 30% of total food discards in Canada [5], [10]. For the textile sector, end-of-life discards refers to post-consumption discards. For the construction sector, end-of-life discards refers to any discards generated during construction, renovation, and demolition activities. End-of-life discards constitute over 80% [11] and 95%[5] [12], [13], [14], [15] of total discards generated throughout the supply chain of the textile and construction sectors, respectively.

2.1.2 Linear Design of Selected Canadian Sectors

Canada's economic model remains predominantly linear, with one report noting a circularity rate of 6.1% [16]. This rate measures the fraction of total input materials categorized as recycled[6] over the total amount of materials used in the economy [16]. In the province of Quebec, the circularity rate drops to 3.5%[7] [17]. Data from Environment and Climate Change Canada and Statistics Canada indicate that Canada generates 35 million tonnes (Mt) of municipal solid waste (MSW)[8] annually, with residential and non-residential sources contributing 15.7 Mt (45%) and 19.2 Mt (55%), respectively [18], [19]. A significant percentage (73.5%) of this MSW is either landfilled or incinerated, leaving only 26.5% to be retained or valorized within the economy [18], [19]. Specifically, 31% of residential MSW and 22.7% of non-residential MSW are diverted for circularity [18]. Based on a material flow analysis of MSW, the City of Toronto has a diversion rate of 28%, a significant portion of which is biomass [20], which means the diversion rate of other materials and minerals

5 For the construction sector, the share of end-of-life discards is based on academic literature and environmental product declaration reports. It considers upstream discards as the fraction of non-hazardous solid discards generated during the production or processing of key materials such as cement and aggregate (gravel and sand). It excludes any discards during the mining of these minerals.

6 Cited report excludes reuse discards from circularity rate calculations because they stay within the economy during their reuse cycles. Recycling includes reprocessing of organic materials but excludes backfilling and energy or fuel recovery from discarded materials. Report does not mention whether recycling contributes high quality materials or cascade materials to applications requiring lower quality material and generating lower economic and possibly environmental value.

7 Cited report includes reuse and backfilling (downcycling) along with recycling in circularity rate calculations. If only recycling is considered, per [16], Quebec's circularity rate decreases to 2.73%.

8 MSW includes waste generated by residential and non-residential sources, and primarily includes non-hazardous waste such as recyclables, organic waste, construction and demolition waste, and residual materials that cannot be recycled or composted.



"Data from Environment and Climate Change Canada and Statistics Canada indicate that Canada generates 35 million tonnes (Mt) of municipal solid waste (MSW) annually."

is even smaller. Plastic is among the least circular DMS in Canada. In 2016, 90% of total plastic discards in Canada were landfilled (86%) or incinerated (4%) [21].

The textile, construction, and agrifood sectors are key contributors to the overall linearity of Canada's current economy and its associated environmental impacts. The Canadian textile sector is largely linear and import dependent. It generates about 0.5 Mt of textile discards annually [22], and about 81% of Canada's textile discards are disposed of (77.3% landfilled and 4% incinerated), while only 19% are diverted for circularity [23]. The global textile industry also mirrors the Canadian context and significantly impacts the environment at every stage of its supply chain. For example, the global cultivation of natural fibres like cotton uses 2.5% of the world's arable land [24] and the global production of cellulosic fibres like viscose results in the logging of 70 million trees annually [25]. The global production of polyester fibres is also resource-intensive, consuming approximately 342 million barrels of oil annually, which represents about 1.35% of global oil production [24]. Furthermore, the industry's water usage is substantial, at 93 trillion litres annually, accounting for 4% of worldwide water consumption and 20% of industrial water pollution [24], [26]. Currently, only 14% of the sector's plastic fibres are recycled (mainly made from diverting plastic bottles), with less than 1% coming from textile-to-textile [27]. Globally, the textile industry releases between 1 to 1.2 billion tonnes of GHG emissions per year, or between 2 to 5% of global GHG emissions [28], [29]. Environmental impacts also occur during the post-consumption phase. Globally, 93 Mt of textile discards are produced annually, which is expected rise to 150 Mt by 2030 [30]. In most countries, 50 to 70% of textile discards are landfilled or incinerated, and only about 25 to 30% are diverted for circularity, either locally or abroad [24]. Despite these challenges, the textile sector holds significant potential for circularity. For example, in Canada, 25% of materials disposed of in MSW are of high quality grade and fit for direct use, and another 40% are fit for reuse after repairs or refurbishment [22].

In Canada, the impact of the construction sector is also significant, with buildings alone being responsible for 30% of the nation's GHG emissions; 43% of these emissions (or 13% of the nation's total GHG) are associated with the production of construction materials [31]. Annually, Canada produces approximately four Mt of construction discards, which accounts for 12% of the country's MSW [32]. A large portion of these discards are landfilled [19] and only 15 to 20% (about 0.75 Mt) of construction discards are diverted for circularity [18]. Inappropriate product design and material contamination are critical barriers to circularity in this sector. For example, wood often contains adhesives, paint, and chemicals that make reuse and recycling challenging. Globally, the construction industry is a major consumer of natural resources, using approximately 50% of all extracted

raw materials to produce construction materials [33]. The sector is also responsible for generating around 40% of the world's MSW and contributes approximately 11% of global energy related GHG emissions [33].

Finally, the Canadian agrifood sector also plays a significant role in the country's environmental footprint. It is responsible for 8% (59 Mt CO_2e) of Canada's GHG emissions due to food production alone [34]. When considering the entire supply chain (including transportation, processing, and storage), the GHG emissions rise by an additional 40 to 100 Mt CO_2e. [10], [35]. However, approximately 58% of Canada's total food production becomes discards, categorized as surplus (12%), unavoidable residuals (39%), and post-consumer leftovers (7%), with cereals and produce representing the largest material streams [10]. Policymakers are increasingly recognizing the importance of valorizing food discards through alternative circular pathways as a pivotal strategy to address climate change. For example, the Government of Ontario's Food and Organic Waste Policy Statement advocates for the reduction of food waste and the enhancement of resource recovery, laying the groundwork for a sustainable, climate-resilient circular food system [36]. Further emphasizing this commitment, the Government of Canada's Smart City Challenge allocated nearly CAD 230 million to bolster several initiatives, including CAD 10 million for an agrifood circularity project in Guelph, Ontario [37]. Current industry trends indicate a growing preference for food products containing responsibly valorized food discards, reflecting a broader move toward localized, sustainable practices over global trade dependencies [38]. In the agrifood sector, where inefficiencies and environmental impacts are pronounced, the transition to a circular economy model promises substantial benefits that align with Canada's broader environmental and economic objectives [39], [40], [41].

2.1.3 Study Scope

Within each of the three sectors, this report considered specific DMSs, which are discussed in this section.

For the textile sector, the research considered post-consumer clothing discards made from cotton and polyester, originating from the residential sector, as shown in Figure 2. This focus was driven by two primary factors. First, clothing accounts for approximately 51% of post-consumer textile discards from households [22]. Although other post-consumer textile discards, such as towels, bed sheets, and uniforms, are generated by both residential and certain non-residential entities (e.g., hotels, hospitals, and retailers), there are uncertainties regarding the volume of these discards and their management [23], [42]. Many organizations lack discard management practices or are reluctant to disclose such information [42], and charities mainly concentrate on clothing discards when considering circularity [23]. Nevertheless, the same methodologies and conclusions apply to discards from any source if the material composition, level of contamination, and level of wear and tear are similar to those assumed in the modelling. Second, cotton and polyester are the predominant fibres used in the textile industry, comprising approximately 25% and 50% of total fibre usage, respectively [27]. For these reasons, focusing on cotton and polyester DMSs provides a representative overview of the current state of textile discards in Canada.

For the construction sector, the report considered concrete, wood, and plastic discards from downstream activities, as shown in Figure 3. These materials are pivotal due to their substantial contribution by weight and volume to the sector's total material usage [43] and discard generation [44]. Studies have indicated that, by mass of the total construction discards generated in Canada, concrete constitutes 4 to 50%, wood 20 to 40%, and plastics 2 to 4% [20], [45], [46], [47]. While metals also constitute a significant portion of construction discards, their diversion from landfill through recycling and circularity strategies is better established. Of the total plastics consumed in Canada, 26% are destined for the construction sector, although the sector generates only 5% of the total plastic discards [21]. This discrepancy highlights the durable nature of construction materials and buildings, which can last for 50 to 70 years [43]. Some cities, such as Kitchener–Waterloo, have been constructing buildings and infrastructure to accommodate a growing population and economy [43]. Such expansion in their built environment will continue to "stock" more construction materials.

Figure 2: Categorization of textile discard sources. The green box highlights the scope of this report. Adapted from [22], [41].

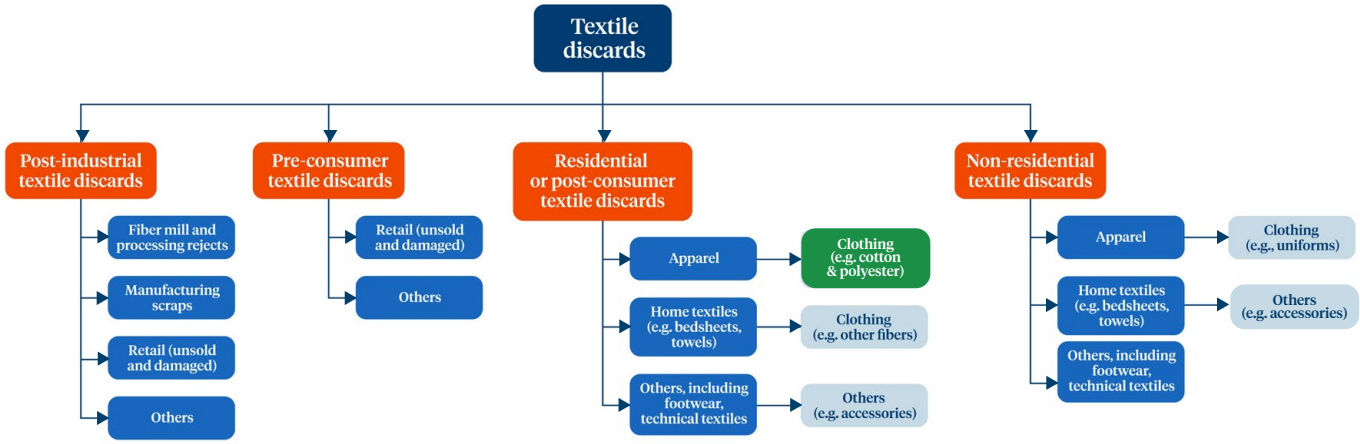
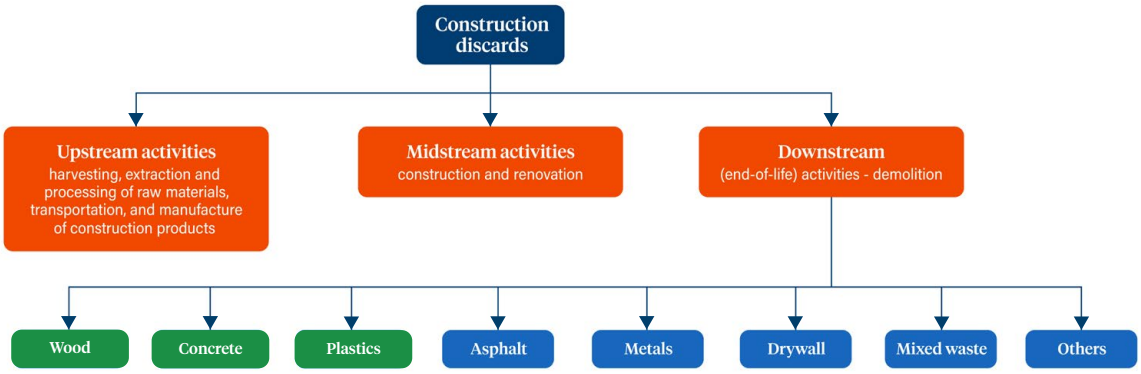


Figure 3: Categorization of construction discard sources. The green box highlights the scope of this report. Adapted from [43], [45], [47]



Nonetheless, the overall discard volume for concrete, wood, and plastics, along with other construction materials, will continue to increase in upcoming decades as older buildings (constructed in the past 60–80 years) reach end-of-life and are demolished [21], [43]. Further, because plastics were only introduced in construction starting in the 1980s, their contribution to construction discards is also expected to increase [21].

For the agrifood sector, the report considered wet spent grains and fruit and vegetable residues, which were selected based on a previous study [5]. These two DMSs account for the majority (39% of the total 58%) of total discarded food materials in several Canadian provinces [5], [10], [49].

2.2 Data Gathering, Life Cycle Assessment Modeling, and Simulation

Relevant ISO standards (ISO 14040, *Environmental management — Life cycle assessment — Principles and framework*, and ISO 14044, *Environmental management — Life cycle assessment — Requirements and guidelines)* guided the LCA process for this report [50], [51], which was completed in the following seven steps:

1. Different pathways transform the same discarded materials into different end products, so outputs cannot be directly used for comparison. Therefore, the functional unit necessary for fair comparison of different pathways was defined as "managing 1 t of discarded material" for all DMSs and circular pathways across the three sectors.

2. For each DMS, a consequential LCA perspective was adopted to assess and compare the net GHG emissions of different circular pathways and operational structures. The LCA approach adopted system boundary expansion through substitution to account for the GHG savings associated with substituting virgin resources with recovered resources [52], [53].

   The consequential LCA perspective was chosen because it provides a consistent framework to handle multi-functionality, which refers to a case when a system or pathway provides multiple outputs in the form of products or services. It addresses multi-functionality via system boundary expansion and substitution (avoided production/consumption) [54], [55]. A circular pathway managing discards often involves multiple products or services (e.g., providing discards management services and recovering useful resources that substitute virgin production to generate GHG emissions savings), and an LCA procedure must accommodate such multi-functionality to provide consistent and fair results. While ISO 14040 and ISO 14044 do not recommend substitution to address multi-functionality for an LCA study, the academic literature indicates that substitution of virgin production is an acceptable approach to address multi-functionality in an LCA study [55], [56].

3. Primary and secondary data were collected to map circular pathways and build an LCA inventory that appropriately informed the modelling of specific operational structures. Relevant organizations were identified for interviews by combining internet search, secondary databases of recyclers (e.g., a list of textile recyclers [57]), and snowball sampling [58]. Keywords for the internet search included "textile waste" OR "construction waste", "reducing", "reusing", "upcycling," "recycling," and "Canada". For the agrifood sector, a similar approach was followed in [5]. Interview protocols from past research in the agrifood sector [5] were customized for collecting primary data from the two additional sectors and were approved by the research ethics committee of Western University. Semi-structured interviews with local and international researchers and experts from different sectors also helped in validating, refining, and updating primary and secondary data. This data collection and validation approach has been adopted across sectors to document circular pathways and specific operational structures [59], [60], [5]. Table 1 summarizes the type and number of organizations interviewed for this report. Secondary sources included literature from academic and other sources, including government reports, association reports, news media articles, circularity company websites, and company reports such as environmental product declarations. The ecoinvent database 3.9.1v, with a cut-off systems model, provided the background LCA data [61].

4. System boundaries of each pathway (further described in Section 2.3) were drawn and regularly updated as data was collected. Some pathways were at experimental or pilot stages and had not yet been commercialized. For LCA calculations, only commercialized circular pathways were considered. Nevertheless, observations and data from experimental and pilot scales pathways informed the sensitivity analysis.

5. The ReCiPe 2016 mid-point (egalitarian) method was used for impact assessment [62]. Studies often select this method because it is the most precautionary and considers a longest time horizon (500–1000 years) for all types of impacts to fully unfold [63]. The LCA exercise was performed using a combination of openLCA (v1.11) software and Microsoft Excel.[9] While other impact categories were also assessed, the results primarily focused on GHG emissions. This step involved sensitivity analysis and provided a range (best and worst cases) of net GHG emissions for each identified circular pathway.

9 First, the LCA impacts of each independent unit process (e.g., electricity from different geographies, different types of transportation, and different manufacturing and production processes) were calculated in openLCA. The results were recorded in an Excel spreadsheet, and then the unit process results were used to calculate the LCA impact of an operational structure as the scaled sum of the corresponding impact of each unit process relevant for that operational structure.

Table 1: Summary of interviews conducted.

Sector (waste streams)	Types of Organizations Interviewed	Organizations Interviewed
Textile (cotton and polyester)	Collectors, resellers (including charities), graders and sorters, mechanical recyclers, chemical recyclers, manufacturers of sorting technologies, industry experts, and circularity associations	14
Construction (wood, plastics, and concrete)	Builders, collectors/waste haulers/sorters, upcyclers, recyclers, industry experts, and circularity associations	27
Agrifood (wet spent grain, fruit and vegetable residue)	Upcyclers, animal farmers, waste managers (hauling, composting, anaerobic digestions, and landfilling), industry experts, and circularity associations	10[10]

6. For each circular pathway, diverse combinations of geographical scale and technological configuration, under an average ecoefficient system (as defined in Section 3.2), were simulated to identify critical thresholds for which the circular pathway would achieve, at worst, carbon neutrality.
7. The results were compared across diverse circular pathways to identify any discernible pattern between the carbon budget, defined as the GHG emissions associated with the production of specific virgin resources substituted by a given circular pathway, and its maximum geographical scale and most ecologically inefficient technological configuration.

2.3 System Boundaries

Primary and secondary data revealed several circular pathways for each DMS from each sector. The detailed system boundaries describing all processes (preprocessing, transportation, processing, etc.) associated with each circular pathway are available in Appendix A. Landfilling was considered the default pathway for all DMSs.

It should be noted that each DMS was considered uniform and homogenous, but several factors influenced the technical and economic feasibility of a circular pathway for that DMS, including discard quantity, contamination levels, and the nature of products or materials within a DMS. For example, for wood discards, only clean wood free from chemicals was reused. Further, clean wood discards that were only available in small quantities or in smaller pieces[11] were deemed uneconomical for reuse. Table 2 shows the sector, DMS, and pathway IDs that were used, and summarizes the characteristics a DMS should have for it to be feasibly processed via a given circular pathway; the outputs that are obtained from such pathway; and how much output can be recovered from 1 t of discards and the type and quantity of substituted virgin resources. As previously mentioned, all operational structures of a given circular pathway recover identical resources, but they are distinct from one another in terms of geographical scale, technological configuration, quantity and quality of recovered resources, other factors such as grid-mix, and the virgin resources that they substitute.

The substitution ratio refers to how much virgin resources (material or energy) were substituted relative to the recovered resources (material or energy). A range indicates the values for best or worst cases considered in the sensitivity analysis. The details are based on interviews and secondary literature. The range considers the effectiveness of substitution from the recovered resources. For example, in the case of reuse, a piece of clothing is unlikely to be worn for as long as the identical piece of virgin clothing. Therefore, the range accounts for reduced lifespan compared to virgin clothing and assumes that in the worst case, the effectiveness of virgin substitution of recovered clothing would only be 60%.

[10] Interviews were conducted as part of previous agrifood study [5].

[11] Specific breakeven quantities for making a DMS circular pathway economically viable may vary for individual organizations, and documenting such quantities was outside the scope of this report.

Table 2: Expected (or identified) circular pathways for diverse sectors and discarded material streams.

Sector	Discards	Pathway	Pathway Description	Required Characteristics of Discarded Materials	Key Modeling Details
Textile (TXT)	**Cotton (CT)**	Reuse (RU)	Reusing clothing discards for at least another cycle.	Cotton discards in good reusable condition without need for repairs. Some clothing items deemed unsuitable for reuse can be reusable after cleaning or minor/major repairs, but the impacts from such additional pre-processing were not considered in this report.	▪ **# of operational structures**: 3 (A, B, C) ▪ **Variations across operational structures**[i]**:** Geographical scale and/or sequence[ii] of operations **A:** Within Canada **B:** Canada → India **C:** Canada → India → Canada ▪ **Resource recovered:** Reusable cotton clothing ▪ **Quantity recovered (per tonne of discards):** **A:** 0.85–0.95 t **B:** 0.68–0.95 t **C:** 0.68–0.95 t ▪ **Substituted resource:** Virgin cotton clothing (same for all structures) ▪ **Substitution ratio:** 60–100% (same for all structures)
		Chemical recycling (CR)	Recovering fibres via chemical processes, which preserves fibre quality almost identical to virgin fibres.	Clean cotton discards with a maximum level of contamination (zippers, buttons, and other fibres such as polyester) by mass of 10%.	▪ **# of operational structures:** 2 (A, B) ▪ **Variations across operational structures:** Geographical scale and/or sequence of operations **A:** Canada → India → Nordic country **B:** Within Canada ▪ **Resource recovered:** cotton fibre ▪ **Quantity recovered (per tonne of discards):** **A:** 0.61–0.95 t **B:** 0.76–0.95 t ▪ **Substituted resource:** Virgin cotton fibre (same for all structures structures) ▪ **Substitution ratio:** 100% (same for all structures)
		Mechanical recycling (MR)	Recovering fibres via mechanical processes, which results in some quality loss. The modelling of this pathway could also represent repurposing clothing discards as stuffing material.	No specific constraints or material requirements reported, and clothing with any composition is acceptable.	▪ **# of operational structures:** 3 (A, B, C) ▪ **Variations across operational structures:** Geographical scale and/or sequence of operations **A:** Canada → India **B:** Canada → India → Mexico **C:** Within Canada ▪ **Resource recovered:** Cotton fibre ▪ **Quantity recovered (per tonne of discards):** **A:** 045–0.90 t **B:** 0.45–0.90 t **C:** 0.56–0.90 ▪ **Substituted resource:** Virgin cotton fibre (same for all structures) ▪ **Substitution ratio:** 70–100% (same for all structures)

Sector	Discards	Pathway	Pathway Description	Required Characteristics of Discarded Materials	Key Modeling Details
Textile (TXT)	**Cotton (CT)**	Downcycling (DC)	Repurposing clothing discards for wiping purposes.	Clean cotton discards for water absorption application.	▪ **# of operational structures:** 2 (A, B) ▪ **Variations across operational structures:** Geographical scale and/or sequence of operations **A:** Within Canada **B:** Canada → India ▪ **Resource recovered:** Cotton fibre ▪ **Quantity recovered (per tonne of discards):** **A:** 0.72–0.81 t **B:** 0.58–0.81 t ▪ **Substituted resource:** Virgin paper wipers (same for all structures) ▪ **Substitution ratio:** 100% (same for all structures)
	Polyester (PE)	Reuse (RU)	Reusing clothing discards for at least another cycle.	Polyester discards in good reusable condition without need for repairs. Some clothing items deemed unsuitable for reuse can be reusable after cleaning or minor/major repairs, but the impacts from such additional pre-processing were not considered in this report.	▪ All details identical to cotton DMS, except recovered resource is reusable polyester clothing and substituted resource is virgin polyester clothing
		Chemical recycling (CR)	Recovering fibres via chemical processes, which preserves fibre quality almost identical to virgin fibres.	Clean polyester discards with a maximum level of contamination (zippers, buttons, and other fibres) by mass of 10%. Maximum level of acceptable contamination is ambiguous and depends on the recycling process. Some sources indicate it has to be 100% pure polyester, while others accept any level of contamination as long as the contaminant fibre is only cotton. For consistency, this research used the same contamination values as cotton for modelling polyester circularity.	▪ All details identical to cotton DMS, except recovered resource is polyester fibres and substituted resource is virgin polyester fibres.
		Mechanical recycling (MR)	Recovering fibres via mechanical processes, which results in some quality loss. The modelling of this pathway could also represent repurposing clothing discards as stuffing material.	No specific constraints or material requirements reported, and clothing with any composition is acceptable.	▪ All details identical to cotton DMS, except recovered resource is polyester fibres and substituted resource is virgin polyester fibres.
		Downcycling (DC)	Repurposing clothing discards for wiping purposes.	Polyester-based discards for industrial applications. Such wipers are often single-use.	▪ All details identical to cotton DMS.

Sector	Discards	Pathway	Pathway Description	Required Characteristics of Discarded Materials	Key Modeling Details
Construction (CON)	**Wood (WD)**	Reuse (RU)	Reusing wood discards for at least another cycle.	Clean wood discards, primarily dimensional lumber (discards with no contaminants other than metal parts, such as nails or fasteners). While minor levels of contaminants (glue, paint, chemicals) can be removed via milling, sawing, or chipping, organizations largely prefer clean wood discards only. Plywood is also not reused due to perceived low economic value.	▪ **# of operational structures:** 2 (A, B) ▪ **Variations across operational structures:** Technological configuration **A:** Recovery into dimensional lumber **B:** Recovery into wood chips ▪ **Resource recovered:** Reusable wood (same for all structures) ▪ **Quantity recovered (per tonne of discards):** 0.7–1 t (same for all structures) ▪ **Substituted resource:** Virgin wood (same for all structures) ▪ **Substitution ratio:** 100% (same for all structures)
		Material recovery (MA)	Recovering material from wood discards.	Any wood discards for biochar[iii] production via pyrosis. It is unclear whether unclean wood (treated wood contaminated with glue, paint, chemicals, etc.) could be safely burned.	▪ **# of operational structures:** 1 ▪ **Variations across operational structures:** NA ▪ **Resource recovered:** Biochar ▪ **Quantity recovered (per tonne of discards):** 0.1–0.3 t ▪ **Substituted resource:** Coal ▪ **Substitution ratio:** 92%
		Energy recovery (ER)	Recovering energy from wood discards.	Any wood discards for energy recovery via combustion. It is unclear whether unclean wood (treated wood contaminated with glue, paint, chemicals, etc.) could be safely burned.	▪ **# of operational structures:** 2 (A, B) ▪ **Variations across operational structures:** Type of substituted resource ▪ **Resource recovered:** Energy (same for all structures) ▪ **Quantity recovered** (per tonne of discards): **A:** 7.73–14.71 MJ (at calorific value 21 MJ/t) **B:** 1200 kWh of electricity (worst case) or 14400 MJ of heat from natural gas (best case) ▪ **Substituted resource:** **A:** Heat from coal combustion **B:** Electricity and heat from natural gas ▪ **Substitution ratio:** **A:** 46–67% **B:** 100% (for both, electricity or heat)
	Concrete (CC)	Recycling (RE)	Recovering materials from concrete discards for non-structural and other low-value applications such as backfill or road base material compared to the virgin material.	Clean cured (old) concrete discards (discards having a maximum level of contaminants, such as rebars, glass, organics, plastics, etc.) by mass of 1%. Higher share of contaminants may require additional pre-processing to recover clean concrete discards from the mix.	▪ **# of operational structures:** 3 (A, B, C) ▪ **Variations across operational structures:** Geographical scale and technological configuration **A:** On-site recovery using portable operation **B:** Off-site recovery using portable operation **C:** Off-site recovery using stationary operation ▪ **Resource recovered:** aggregates (same for all structures) ▪ **Quantity recovered (per tonne of discards):** 0.99–1 t (same for all structures) ▪ **Substituted resource:** Virgin aggregates (same for all structures) ▪ **Substitution ratio:** 100% (same for all structures)
	Plastics (PT)	Reuse (RU)	Reusing plastic discards for at least another cycle.	Only carpets, made from any materials, including nylon, polypropylene, polyester, and natural fibres, were reported being reused and no information was available about the reusability of other types of plastic discards.	▪ **# of operational structures:** 1 ▪ **Variations across operational structures:** NA ▪ **Resource recovered:** Reusable carpets ▪ **Quantity recovered (per tonne of discards):** 0.8–1 t ▪ **Substituted resource:** Virgin carpets (the same as in case of reuse of polyester clothing in textile) ▪ **Substitution ratio:** 60–100%

Sector	Discards	Pathway	Pathway Description	Required Characteristics of Discarded Materials	Key Modeling Details
Construction (CON)	**Plastics (PT)**	Mechanical recycling (MR)	Recycling plastic discards for low-value into flakes or granules; usually has low-value applications compared to the virgin material.	In the construction sector, numerous types of plastics are used and not each type is recyclable. No primary information was available to confirm the types of plastics that are recycled in Canada.	▪ **# of optional structures:** 1 ▪ **Variations across operational structures:** NA ▪ **Resource recovered:** Plastic flakes ▪ **Quantity recovered (per tonne of discards):** 0.8–1 t ▪ **Substituted resource:** Virgin polyester flakes (the same as in recycling of polyester clothing in textile) ▪ **Substitution ratio:** 60–100%
		Energy recovery (ER)	Recovering resources (material or energy) from plastic discards.	All plastics, except PVC (which is unsuitable due to chlorine content), were burned in cement kiln to produce energy.	▪ **# of operational structures:** 1 ▪ **Variations across operational structures:** NA ▪ **Resource recovered:** Heat for cement kiln ▪ **Quantity recovered (per tonne of discards):** 0.8–1 t ▪ **Substituted resource:** Heat from coal ▪ **Substitution ratio:** 100%
Agrifood (AGF)	**Wet spent grains (WG)**	Upcycling (UP)	Transforming wet spent grains into items for human consumption.	No specific constraints on material requirements reported.	▪ **# of operational structures:** 5 (A, B, C, D, E) ▪ **Variation across operational structures:** Geographical scale and technological configuration **A:** No mechanical pressing before electric drying; on-site use of recovered materials **B:** Mechanical pressing and electric drying; on-site use of recovered materials **C:** No mechanical pressing; no drying; on-site use of recovered materials **D:** No mechanical pressing; electric drying; sale of recovered materials at retail store **E:** Mechanical pressing; electric drying; sale of recovered materials at retail store ▪ **Resource recovered:** **A, B, D, E:** Spent grains flour **C:** Blended wet spent grain ▪ **Quantity recovered (per tonne of discards):** 0.22–0.67 t (dried) (same for all structures) ▪ **Substituted resource:** Virgin mix-grain flour (same for all structures) ▪ **Substitution ratio:** 70–150% (same for all structures)
		Animal feeding (AF)	Transforming wet spent grains into animal feed.	No specific constraints on material requirements reported.	▪ **# of operational structures:** 3 (A, B, C) ▪ **Variations across operational structures:** Technological configuration **A:** No processing; cattle feeding **B:** No processing; pig feeding **C:** Refrigeration and storage; insect feeding ▪ **Resource recovered:** spent grain/flour (dried) ▪ **Quantity recovered (per tonne of discards):** 0.22–0.67 t (dried) (same for all structures) ▪ **Substituted resource:** **A:** Virgin grain mixes; silage/grass **B, C:** A mix of conventional grain ▪ **Substitution ratio:** 70–150% (same for all structures)

Sector	Discards	Pathway	Pathway Description	Required Characteristics of Discarded Materials	Key Modeling Details
Agrifood (AGF)	**Wet spent grains (WG)**	Anaerobic digestion (AD)	Transforming organic waste into useful resources.	No specific constraints on material requirements reported.	▪ **# of operational structures:** 4 (A, B, C, D) ▪ **Variations across operational structures:** Technological configuration and type of substituted resource **A, B:** No decontamination step before anaerobic digestion **C, D:** Decontamination step before anaerobic digestion ▪ **Resource recovered:** **A, C:** Digestate, electricity, and heat **B, D:** Digestate and heat ▪ **Quantity recovered (per tonne of discards):** **A:** 700–1580 MJ heat; 230–880 kWh electricity **B:** 1640–4475 MJ heat **C:** 560–1500 MJ heat;184–836 kWh electricity **D:** 1312–4251 MJ heat **A, B:** Equivalent nutrients from digestate: 0.14–8.4 t (Nitrogen); 0.16–3.44 kg (P_2O_5); 1.18–6.3 kg (K_2O) **C, D:** Equivalent nutrients from digestate: 0.11–8 t (Nitrogen); 0.13–3.27 kg (P_2O_5); 0.94–6 kg (K_2O) ▪ **Substituted resource:** **A, C:** Heat from natural gas; grid electricity; mineral fertilizers **B, D:** Heat from natural gas; mineral fertilizers ▪ **Substitution ratio:** 100% (same for all structures)
		Composting (CP)	Transforming organic waste into useful resources.	No specific constraints on material requirements reported.	▪ **# of operational structures:** 3 (A, B, C) ▪ **Variations across operational structures:** Technological configuration and type of substituted resource **A:** Home composting **B:** No decontamination step industrial composting **C:** Decontamination step before industrial composting ▪ **Resource recovered:** Compost (same for all structures) ▪ **Quantity recovered[iv] (per tonne of discards):** **A:** 0.285 t **B:** 0.285 t; equivalent soil nutrient from compost: 6.55 kg (Nitrogen); 6.9 kg (P_2O_5); 18.5 kg (K_2O) **C:** 2.28–2.71 t; equivalent soil nutrient from compost: 5.24–6.22 kg (Nitrogen); 5.5–6.55 kg (P_2O_5); 14.8–17.6 kg (K_2O) ▪ **Substituted resource:** **A:** Peat moss **B, C:** Peat moss and mineral fertilizers ▪ **Substitution ratio:** 100% (same for all structures)

Sector	Discards	Pathway	Pathway Description	Required Characteristics of Discarded Materials	Key Modeling Details
Agrifood (AGF)	**Fruit and vegetable residue (FR)**	Upcycling (UP)	Transforming wet fruit and vegetable residues into items for human consumption.	No specific constraints on material requirements reported; however, some contaminants such as labels and seeds are unacceptable.	▪ **# of operational structures:** 3 (A, B, C) ▪ **Variations across operational structures:** Geographical scale; technological configuration; and type of substituted resource **A:** No mechanical pressing; electric drying; on-site use of recovered materials **B:** Shredding; no drying; on-site use of recovered materials **C:** No mechanical pressing; no drying; on-site use of recovered materials ▪ **Resource recovered:** **A:** Powder/flakes **B:** Zest **C:** Blended fruit and vegetable residues ▪ **Quantity recovered (per tonne of discards):** 0.22–0.67 t (dried) (same for all structures) ▪ **Substituted resource:** **A:** The same material from a different country; so the differences in the grid-mix is saved. **B:** The same material from a different country; so the differences in the grid-mix is saved. **C:** Carrots ▪ **Substitution ratio:** 70–150% (same for all structures)
		Animal feeding (AF)	Transforming wet spent grains into animal feed.	No specific constraints on material requirements reported.	▪ **# of operational structures:** 1 ▪ **Variations across operational structures:** NA ▪ **Resource recovered:** Fruit and vegetable residues ▪ **Quantity recovered (per tonne of discards):** 0.22–0.67 t (dried) ▪ **Substituted resource:** Carrots ▪ **Substitution ratio:** 70–150% (same for all structures)
		Anaerobic digestion (AD)	All details identical to wet spent grains.		
		Composting (CP)	All details identical to wet spent grains.		

Notes

[i] Primarily distinguishing criterion among different operational structures specifies only the key driver of difference among all operational structures. The differences, if any, in other factors such as grid-mix are a result of the primary difference.

[ii] The geographical sequence represents the country of origin of the discards, the intermediary country for sorting/grading, and the country of substitution where the final recovered resources substitute the virgin production.

[iii] Biochar is a stable, carbon-rich form of charcoal that is produced by heating organic material (biomass such as wood) in a low-oxygen environment. This process of heating in low-oxygen environment is known as pyrolysis.

[iv] The values of NPK fertilizers substituted are available in [5].



"A climate-smart circular pathway is characterized by an operational structure that achieves carbon neutrality at worst, which is having a value of zero or negative net GHG emissions."

3 Results and Discussion

This section presents the key results of each DMS for each of the three sectors.

3.1 Circular Pathways, Operational Structures, and Net Greenhouse Gas Impacts

This section provides a summary of the net GHG emissions associated with different operational structures of various circular pathways for each DMS across the three sectors. Each figure in this section presents a range of GHG emissions for each operational structure within a pathway, highlighting the minimum (best case scenario) and maximum (worst case scenario) net GHG emissions. These ranges were based on parameter combinations that represent the least and most emission-intensive operations, which were identified through primary and secondary research. Where relevant, stars denote the GHG emissions reported by organizations interviewed for this report (represented by anonymized IDs). The net GHG emissions of an operational structure are the difference between GHG emissions released during the recovery process and those avoided by substituting virgin resource. The emissions released and avoided depend on several parameters, such as the emission intensity of the utilized energy (e.g., grid-mix), the energy intensity of the utilized technology (e.g., sorting technology), transportation distance and modes, the quality of resources recovered, and the amount of virgin resources substituted.

Depending on the operating conditions, the net GHG emissions from an operational structure can be either carbon positive, carbon negative, or carbon neutral, indicating whether the structure produces more, less, or the same amount of GHG emissions relative to the substituted virgin resources. A climate-smart circular pathway is characterized by an operational structure that achieves carbon neutrality at worst, which is having a value of zero or negative net GHG emissions. It should be noted that net GHG emissions are relative to substituted virgin resources, so carbon negative only indicates that a circular pathway saves GHG emissions relative to substituted virgin resources and should not be confused with carbon sequestration.

3.1.1 Textile Sector

3.1.1.1 Cotton Discards

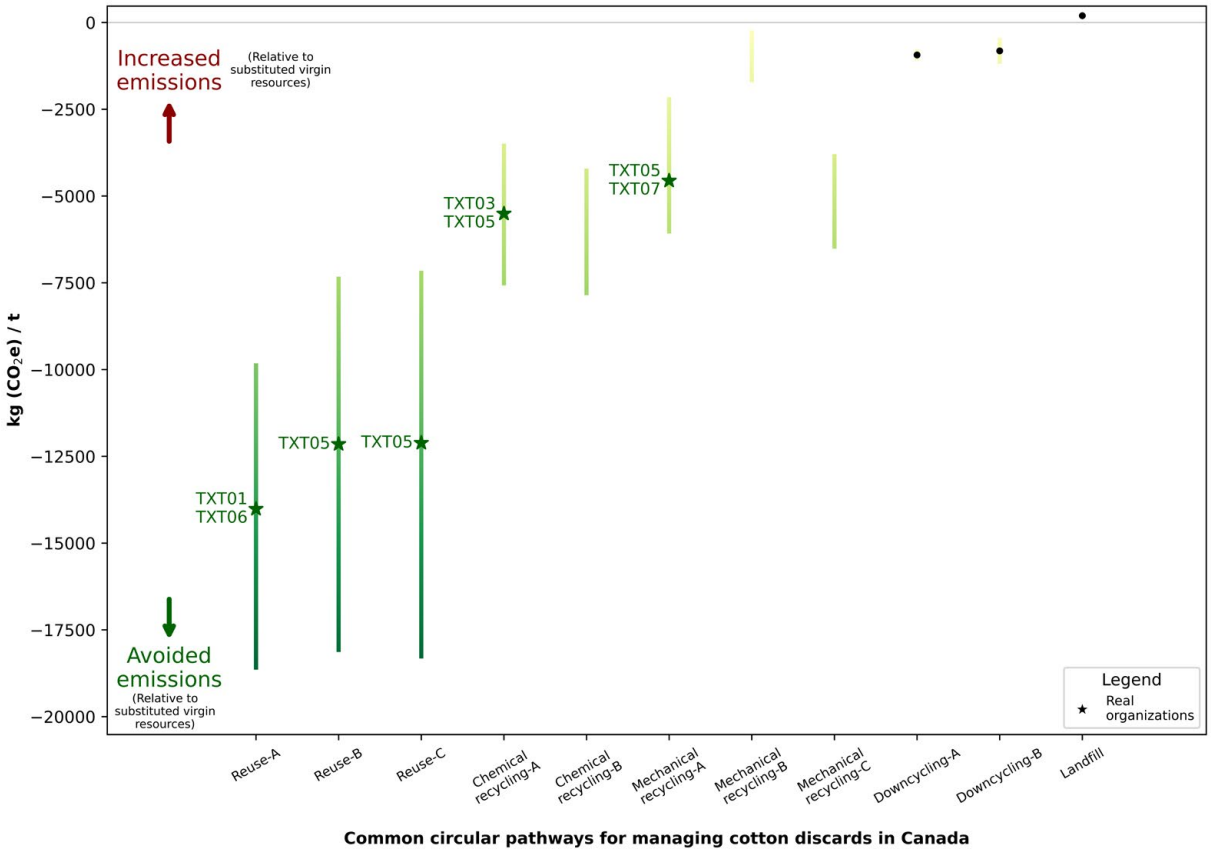
The analysis uncovered four circular pathways for cotton discards: reuse, chemical recycling into fibres, mechanical recycling into fibres, and downcycling into wipers. Each circular pathway comprised one or more unique operational structures. Reuse and mechanical recycling each featured three distinct operational structures (A, B, and C), while chemical recycling and downcycling each featured two (A and B). Altogether,

there were ten distinct operational structures across the four identified circular pathways. Landfill was the default conventional pathway.

While each operational structure exhibited a unique net GHG emission profile, as shown in Figure 4, they were carbon negative across all four circular pathways. This was for several reasons, such as low operational energy use, relative cleanliness of energy and transportation used, and high savings from substitution of virgin materials (see Table 2). The existing configuration of each pathway can be further optimized to release less GHG emissions than those that are saved from substituting virgin resources.

For example, Reuse-A (adopted by TXT01 and TXT06) involved collecting and reselling recovered clothing in Canada, achieving a recovery rate[12] of 0.85 to 0.95 t for 1 t of discards. This not only minimized the transportation of discards but also reduced the need for virgin material imports, avoiding 0.6 to 1 t of virgin clothing for 1 t of recovered clothing, leading to significant GHG savings. Reuse-B and Reuse-C involved extensive sorting and transportation,

Figure 4: Net greenhouse gas emissions of different circular pathways for managing cotton discards. The black circle markers for downcycling and landfill are for better visibility of the bars.



[12] Adjusted for the fraction rejected after sorting and grading, which was landfilled.

including international shipping to India for additional warehousing operations, and sorting and grading (performed by TXT05). Reuse-B involved reselling used clothing and achieved a recovery rate of 0.68 to 0.95 t for 1 t of discards in India. Reuse-C achieved the same recovery rate as Reuse-B, but the sorted and graded clothing was reimported to Canada for reselling, incurring additional transportation emissions.

All reuse operational structures substituted the same type of virgin cotton with the same substitution ratio (0.6–1 t of virgin clothing for 1 t of recovered clothing). However, due to the lower recovery rate in Reuse-B and Reuse-C, less virgin production was displaced compared to Reuse-A. Nevertheless, despite the additional steps, Reuse-B and Reuse-C achieved a net GHG performance comparable to Reuse-A, largely because the substantial GHG emissions avoided by displacing the need for virgin production far outweighed the GHG emissions from recovery operations.

Table 3 summarizes the GHG emission values for operational structures managing cotton discards, showing the average of the best and worst cases, with real case values in parentheses. The geographical sequence represents the country of origin of the discards, the intermediary country for sorting/grading, and the country of substitution where the final recovered material substituted the virgin material. Green rows indicate the pathways with the highest net GHG savings.

Similarly, Chemical recycling-A (as practiced by TXT03) involved transporting discards via India (performed by TXT05) to a Nordic country for recycling, whereas Chemical recycling-B involved a hypothetical but realistic case of recycling discards in Canada. While energy (electricity and heating from natural gas) in Canada generated higher GHG emissions relative to energy emissions from the Nordic country, Chemical recycling-B retained all operations in Canada, which

Table 3: Average greenhouse gas emissions (in kg CO_2e) Profiles for different operational structures of managing cotton discards The GHG emission values show the average of the best and worst cases. Green rows indicate the operational structure of a pathway generating the highest net GHG performance.

Pathway–Operational Structure	Geography	Released (real case)	Avoided (real case)	Net (real case)
Reuse-A	Canada	47 (48)	14 280 (14 062)	-14 233 (-14 014)
Reuse-B	Canada → India	360 (340)	13 089 (12 488)	-12 729 (-12 148)
Reuse-C	Canada → India → Canada	550 (541)	13 290 (12 655)	-12 740 (-12 114)
Chemical recycling-A	Canada → India → Nordic country	360 (340)	13 089 (12 488)	-12 729 (-12 148)
Chemical recycling-B	Canada	1089	7121	-6032
Mechanical recycling-A	Canada → India	691 (780)	4808 (5338)	-4117 (-4558)
Mechanical recycling-B	Canada → India → Mexico/US	598	1570	-972
Mechanical recycling-C	Canada	164	5319	-5155
Downcycling-A	Canada	173	1109	-936
Downcycling-B	Canada → India	418	1236	-818
Landfill	Canada	196	0	196

reduced sorting and rejection quantity, warehousing operations, and transportation needs. Chemical recycling-A recovered 0.61 to 0.95 t of fibres from 1 t of discards, whereas Chemical recycling-B recovered 0.76 to 0.95 t of fibres from 1 t of discards. Both operational structures had the same substitution ratio of 100%, which indicated the recovered fibre had the same quality as virgin fibres. Nevertheless, local operations had higher recovery rates, and as a result, substituted a higher amount of virgin material, which in turn contributed to higher net GHG performance (-6032 vs. -5534 kg CO_2e for 1 t of discards).

Downcycling-A involved converting discards into cloth rags/wipers within Canada, whereas Downcycling-B involved transporting discards to India for the same application. While downcycling into single-use cloth wipers, which substituted paper wipers, was carbon negative, it generated the least net GHG savings.

The reuse and chemical recycling pathways had similar average recovery rates (0.84 t for reuse vs. 0.82 t for chemical recycling) for 1 t of discards, but chemical recycling had a higher substitution ratio (1 compared to an average of 0.8 for reuse). However, reuse generated significantly higher GHG savings relative to chemical recycling for two reasons: (a) chemical recycling operations were highly energy intensive compared to reuse operations, which increased GHG costs of recovering fibres, and (b) while both pathways substituted virgin fibres, reuse also avoided processes such as knitting, dyeing, and manufacturing clothing from virgin fibres, which also incur significant GHG costs.

Both chemical and mechanical recycling pathways had similar operations, but some differences reduced the net GHG performance of mechanical recycling. First, mechanical recycling achieved a slightly lower recovery rate of 0.65 to 0.90 t for 1 t of discards. Second, the quality of recovered fibres, and hence the substitution ratio, was smaller (0.7–1 t virgin fibres for 1 t of recovered fibres). Third, while chemical recycling (A and B) and mechanical recycling (A and C) substituted virgin fibres produced in India, Mechanical recycling-B substituted virgin fibres produced in the US.[13] Based on the ecoinvent database, because cotton production in India generates higher GHG emissions than in the US, the net GHG performance of Mechanical recycling-B was substantially lower compared to the other operational structures of both recycling pathways.

3.1.1.2 Polyester Discards

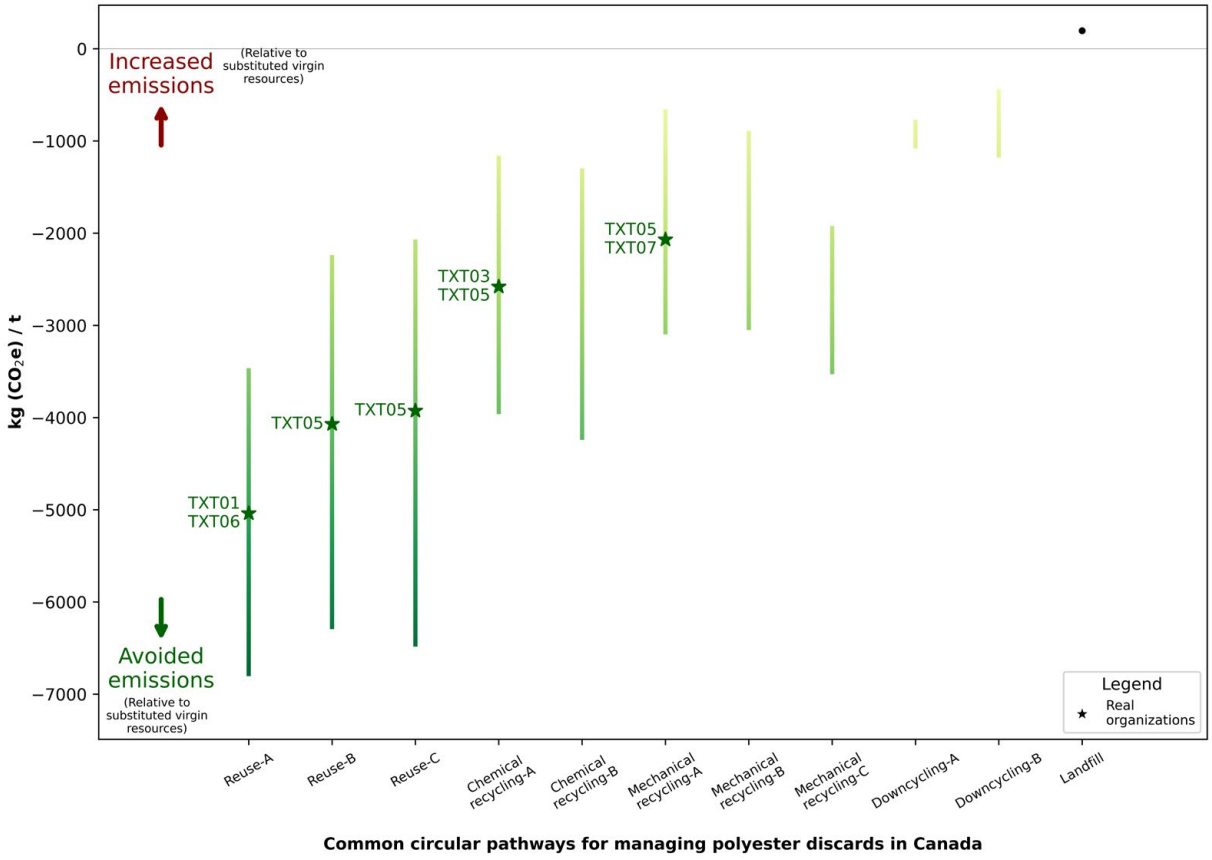
The analysis uncovered four circular pathways for polyester discards: reuse, chemical recycling into fibres, mechanical recycling into fibres, and downcycling into wipers. Each circular pathway comprised one or more unique operational structures. Reuse and mechanical recycling each featured three distinct operational structures (A, B, and C), while chemical recycling and downcycling each featured two (A and B). Altogether, there were ten distinct operational structures across the four identified pathways. Landfill was the default conventional pathway.

While each operational structure exhibited a unique net GHG emission profile, as shown in Figure 5, they were carbon negative across all four circular pathways. This was for several reasons, such as low operational energy use, relative cleanliness of energy and transportation used, and high savings from substitution of virgin materials (see Table 2). The existing configuration of each pathway can be further optimized to release less GHG emissions than those that are saved from substituting virgin resources.

The findings for polyester discards exhibited similar patterns (see Figure 5 and Table 4) as those for managing cotton discards. However, there were two notable differences. First, because the production of virgin cotton fibres generates higher GHG emissions (7085 kg CO_2e for 1 t of fibres) than the production of virgin polyester fibres (3778 kg CO_2e for 1 t of fibres), the GHG savings from avoided polyester production

[13] The ecoinvent database has no representative process for US cotton production, so it was assumed that the global average represented US cotton production. It was discovered that total energy (electricity in particular) contributed to less than 10% of the total impacts. Because the electricity mix covered a wide variety of countries, it was unlikely the total impacts would change significantly if grid-mix was adapted to the US, and therefore, the existing assumptions are reasonable.

Figure 5: Net greenhouse gas emissions of different circular pathways for managing polyester discards. Black dot is for better visibility of landfill bar.



were significantly lower compared to the savings from avoided cotton production. Second, unlike virgin cotton fibre, virgin polyester fibre production in India and the US had similar GHG costs, so the GHG savings of Mechanical recycling-B were similar to those of Mechanical recycling-A.

Table 4 summarizes the GHG emission values for operational structures managing polyester discards, showing the average of the best and worst cases, with real case values in parentheses. The geography sequence represents the country of origin of the discards, the intermediary country for sorting/grading, and the country of substitution where the final recovered resource substituted the virgin material. Green rows indicate the pathways with the highest net GHG savings.

Overall, for both cotton and polyester DMSs, the average net GHG performance of all operational structures of each circular pathway exhibited three patterns:

1. The net GHG emissions were mostly negative, implying circularity outperformed virgin production.
2. For the operational structures of all pathways, retaining operations in Canada generated the highest net GHG savings, from lower rejects, reduced transportation, fewer operational steps, and higher substitution savings.
3. The average performance ranking of the pathways aligned with the priorities in a typical resource recovery hierarchy: reuse > chemical recycling > mechanical recycling > downcycling > landfilling.

Table 4: Average greenhouse gas emissions (in kg CO_2e) Profiles for different operational structures of managing polyester discards. The GHG emission values show the average of the best and worst cases. Green rows indicate the operational structure of a pathway generating the highest net GHG performance.

Pathway–Operational Structure	Geography	Released (real case)	Avoided (real case)	Net (real case)
Reuse-A	Canada	47 (48)	5181 (5087)	-5134 (-5040)
Reuse-B	Canada → India	360 (340)	4626 (4411)	-4266 (-4071)
Reuse-C	Canada → India → Canada	550 (541)	4826 (4468)	-4276 (3927)
Chemical recycling-A	Canada → India → Nordic country	951 (878)	3512 (3458)	-2561 (-2580)
Chemical recycling-B	Canada	1089	3860	-2771
Mechanical recycling-A	Canada → India	691 (780)	2568 (2849)	-1877 (-2069)
Mechanical recycling-B	Canada → India → Mexico/US	598	2570	-1972
Mechanical recycling-C	Canada	164	2891	-2727
Downcycling-A	Canada	182	1109	-936
Downcycling-B	Canada → India	426	1236	-810
Landfill	Canada	196	0	196

This report did not consider circular pathways for polycotton discards. However, the circular pathways identified for cotton and polyester could be generalizable to polycotton, but the net GHG emissions may differ. Under the modelling assumptions used in this report, the net GHG emissions of a circular pathway for polycotton discards could be equal to the weighted average of net GHG emissions of corresponding values of cotton and polyester DMSs. However, in terms of chemical recycling, TXT13 noted that polycotton discards required an additional step for separating the two fibres, so energy consumption for chemical recycling of polycotton would likely be higher during the chemical transformation process. Because no information on the energy needed to separate the two fibre types was available, a more focused investigation is required for polycotton.

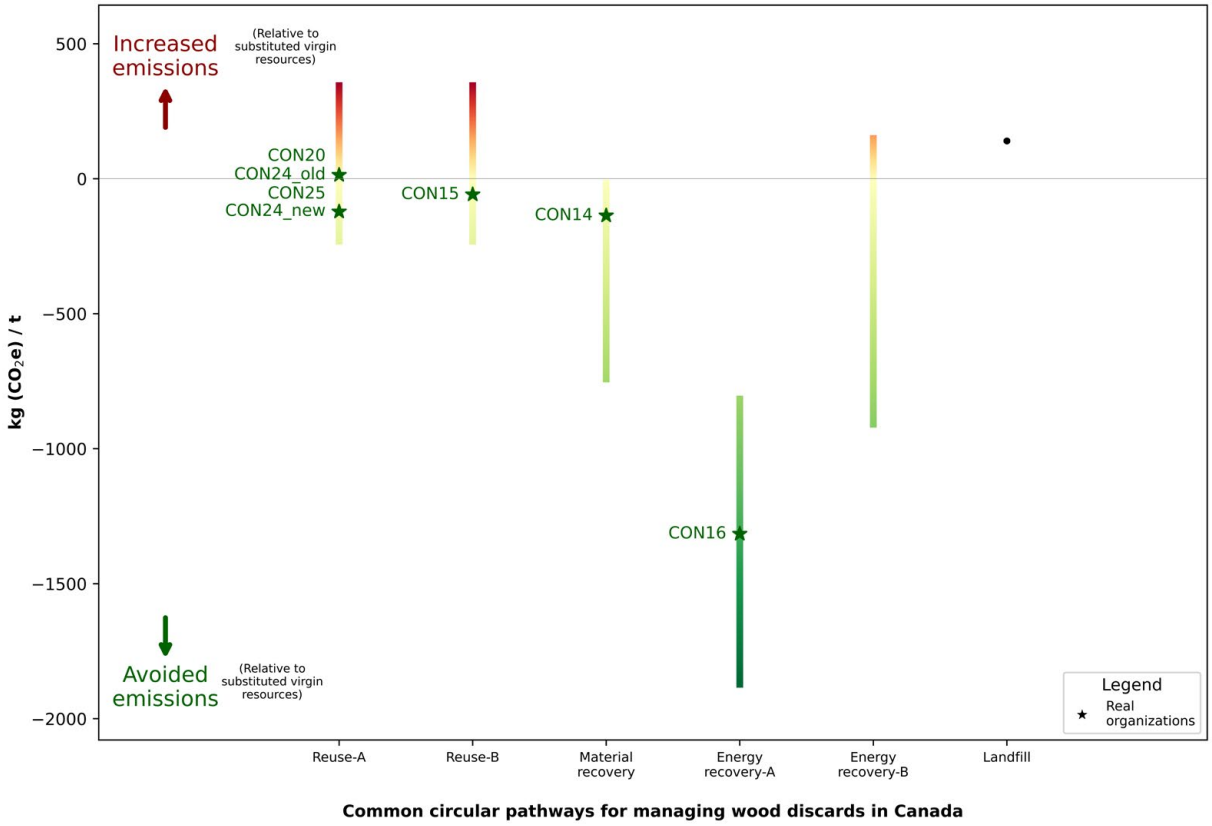
3.1.2 Construction Sector

3.1.2.1 Wood Discards

The analysis uncovered three circular pathways for wood discards: reuse, material recovery into biochar, and energy recovery in the form of heat and electricity. Each circular pathway comprised one or more unique operational structures. Reuse featured two distinct operational structures (A and B), material recovery featured one operational structure, and energy recovery featured two (A and B) distinct operational structures. Altogether, there were five distinct operational structures across the three identified circular pathways. Landfill was the default conventional pathway.

While each operational structure exhibited a unique net GHG emission profile, as shown in Figure 6, most were,

Figure 6: Net greenhouse gas emissions of different circular pathways for managing wood discards. Black dot is for better visibility of landfill bar.



on average, carbon negative. This was for several reasons, such as low operational energy use, relative cleanliness of energy and transportation used, and high savings from substitution of virgin materials (see Table 2). The existing configuration of each pathway can further be optimized to release less GHG emissions than those that are saved from substituting virgin resources.

Reuse-A (adopted by CON20, CON24, and CON25) recovered dimensional wood. CON24 noted that their existing (CON24_old) operations were experimental and used significant electricity, but their new optimized operations (CON24_new) and processes involving new machines were more efficient, meaning that while their existing net GHG emissions were slightly positive, their future net GHG emissions would be negative. Reuse-B (adopted by CON15) recovered wood chips from wood discards. Both operational structures had nearly identical operations, recovering 0.7 to 1 t from 1 t of wood discards and substituting the same type of virgin wood with a substitution ratio of 1 t for 1 t of recovered wood. Therefore, both generated similar net GHG emissions (see Table 5).

Material recovery (adopted by CON14) converted wood discards into biochar through pyrolysis, recovering 0.12 to 0.3 t (0.11 t for CON14) of biochar from 1 t of discards, with 1 t of biochar substituting 0.92 t of coal in steel manufacturing. Energy recovery-A (adopted by CON16) used wood discards instead of coal in the cement kiln for thermal energy, with a recovery rate of 0.9 t of useful wood, and with 1 t of recovered wood substituting 0.46 to 0.67 t (0.57 t for CON16) of coal. Energy recovery-B represented standard energy recovery operations, with the worst case recovering only electricity (and

substituting already clean electricity mix in Ontario for minimum GHG savings) and the best case recovering only heat (and substituting natural gas for maximum GHG savings).

Table 5 summarizes the GHG emission values for operational structures managing wood discards, showing the average of the best and worst cases, with real case values in parentheses. All operations occurred within Canada. Green row indicates the pathway with the highest net GHG savings.

While all resource recovery operational structures were mostly carbon negative, Energy recovery-A generated the highest net GHG performance because of high recovery rates and the substitution of the virgin resource, coal, whose production and burning is associated with high GHG emissions. This result challenges existing waste recovery hierarchies, which suggest prioritizing reuse over pathways that recover energy or generate materials with lower economic value (lumber and wood chips tend to have higher price per tonne than coal). Future research should explore whether Energy recovery-A generates any unintended ecological consequences, and if not, its widespread adoption in Canada should be incentivized (at least while steel manufacturing still relies on coal to produce energy).

3.1.2.2 Concrete Discards

The analysis uncovered one circular pathway for concrete discards: recycling into aggregates. The pathway comprised three distinct operational structures (A, B, and C). Landfill was the default conventional pathway. This recycling pathway, which is commonly reported in Canada [64] and other countries [60], [65], repurposes concrete aggregates into low-value applications such as road base materials and non-structural construction. Low-value applications are adopted because the egates derived from concrete discards have inferior technical performance properties compared to virgin aggregates. Although new technological developments may facilitate the recycling of discarded aggregates in structural applications with a replacement ratio[14] of 100%, it is recommended to

Table 5: Average greenhouse gas emissions (in kg CO_2e) profiles for different operational structures of managing wood discards The GHG emission values show the average of the best and worst cases. Green rows indicate the operational structure of a pathway generating the highest net GHG performance. Old and new real case values are based on the old and new processes adopted by CON24.

Pathway–Operational Structure	**Released** (real case)	**Avoided** (real case)	**Net** (real case)
Reuse-A	206 (old: 199) (new: 64)	149 (185) (185)	57 (14) (-121)
Reuse-B	232 (148)	175 (207)	57 (-59)
Material recovery	140 (147)	519 (283)	-379 (-136)
Energy recovery-A	135 (134)	1480 (1449)	-1345 (-1315)
Energy recovery-B	135	515	-380
Landfill	139	0	139

[14] Replacement ratio refers to the fraction of recycled aggregates as the share of total aggregates used in concrete.

keep the replacement ratio in the range of 10 to 50% at this time [66]. While each operational structure exhibited a unique net GHG emission profile, as shown in Figure 7, most were carbon positive. This was for several reasons, such as high operational energy use, high relative GHG intensity of energy used, and low savings from substitution of virgin materials (see Table 2). The existing configuration of each operational structure can further be optimized to release less GHG emissions than those that are saved from substituting virgin resources.

All operational structures achieved similar recovery rates (0.99 t of recovered aggregates from 1 t of discards) and substituted the same virgin material with the same substitution ratio (1 t of virgin aggregate for 1 t of recovered aggregate), indicating that each generated the same GHG savings (Table 6). However, each operational structure had different GHG emissions from operations and transportation. Recycling-A (adopted by CON10) involved mobile operations for recycling discards into aggregates on-site and avoided transporting discards to other locations, which reduced transportation emissions. Recycling-B (adopted by CON10 and CON21), while using similar transformation technologies, involved hauling discards to off-site locations and transporting recycled aggregates back to construction sites, which increased its transportation emissions. While both Recycling-A and Recycling-B adopted mobile operations using only diesel as energy, Recycling-C adopted stationary operations, which use less diesel and more electricity. Different to mobile operations that involve transporting equipment rather than discards, stationary operations can deploy multi-stage operations to generate higher quality aggregates [67].

Figure 7: Net greenhouse gas emissions of different circular pathways for managing concrete discards.

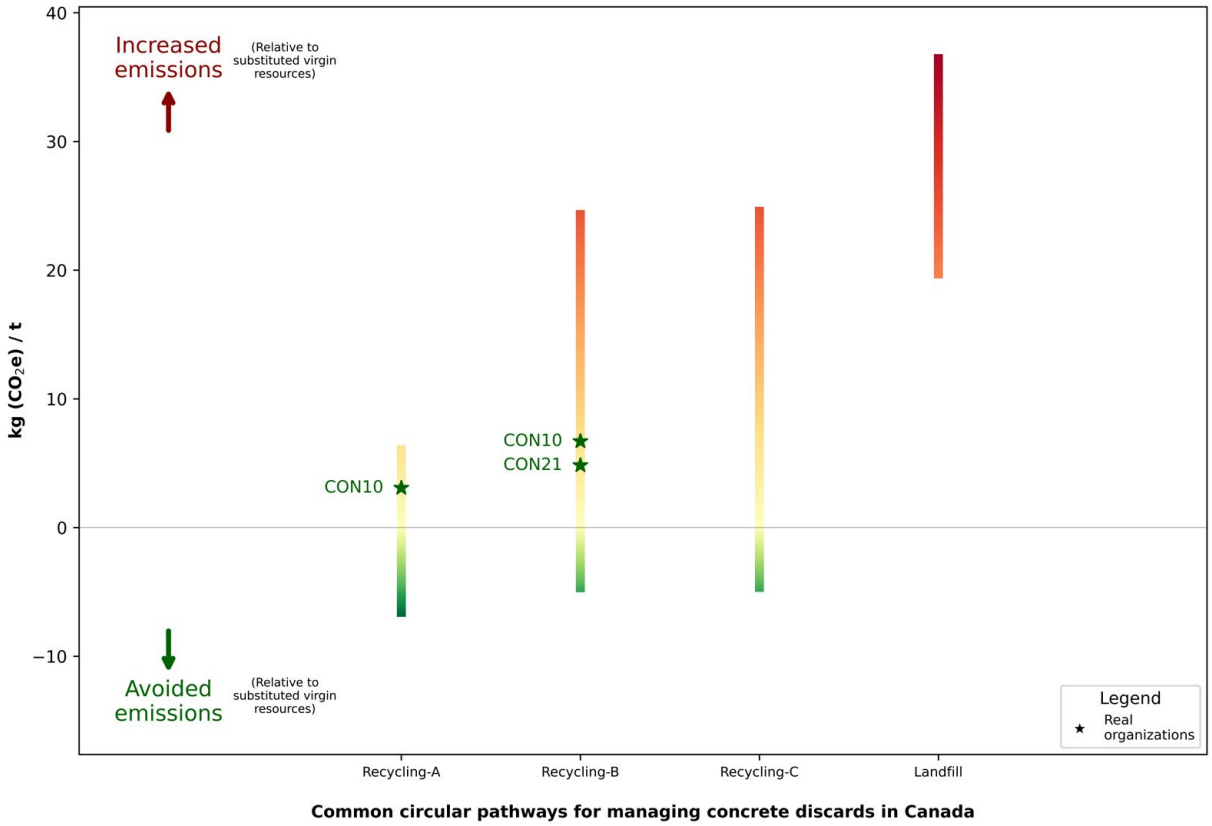


Table 6 summarizes the GHG emission values for operational structures managing concrete discards, showing the average of the best and worst cases, with real case values in parentheses. All operations occurred within Canada. Green row indicates the pathway with the highest net GHG savings.

3.1.2.3 Plastics Discards

The analysis uncovered three circular pathways for plastics discards, including reuse, mechanical recycling, and energy recovery in the form of heat. Each pathway comprised one operational structure. Landfill was the default conventional pathway.

While each operational structure exhibited a unique net GHG emission profile, as shown in Figure 8, most were carbon negative. This was for several reasons, such as low operational energy use, relative cleanliness of energy and transportation used, and high savings from substitution of virgin materials (see Table 2). The existing configuration of each pathway can further be optimized to release less GHG emissions than those that are saved from substituting virgin resources.

Reuse (adopted by CON27) involved reusing carpets, recovering 0.8 to 1 t from 1 t of discarded carpets and substituting the same type of virgin carpet with a substitution ratio of 0.6 to 1 t for 1 t of reused carpet, generating significant net GHG savings (see Table 7). Mechanical recycling involved converting plastic discards into granules or flakes, recovering 0.8 to 1 t from 1 t of plastic discards and substituting the same type of virgin plastic flakes with a substitution ratio of 0.6 to 1 t for 1 t of plastic discards. Energy recovery (adopted by CON16) used plastic discards instead of coal in cement kilns for thermal energy with a recovery rate of 0.9 t of useful plastic, with 1 t of recovered plastic substituting 1 t of coal, but generated marginal net GHG savings because plastic burning also released GHG emissions, offsetting some of the benefits of avoiding coal burning. It should be noted that burning wood releases biogenic CO_2 emissions, which are not considered in GHG calculations [68], [69]. Therefore, the net GHG savings were far higher in the case of wood burning in cement kilns because it releases sequestered biogenic CO_2 emissions, which were excluded from the calculations.

Table 7 summarizes the GHG emission values for operational structures managing plastics discards, showing the average of the best and worst cases, with real case values in parentheses. All operations occurred within Canada. Green row indicates the pathway with the highest net GHG savings.

Table 6: Average greenhouse gas emissions (in kg CO_2e) profiles for different operational structures of managing concrete discards The GHG emission values show the average of the best and worst cases. Green rows indicate the operational structure of a pathway generating the highest net GHG performance.

Pathway–Operational Structure	**Released** (real case)	**Avoided** (real case)	**Net** (real case)
Recycling-A	9.47 (10.73)	9.74 (7.65)	-0.27 (3.08)
Recycling-B	19.56 (14.35 and 12.48)	9.74 (7.65 and 7.65)	9.82 (6.7 and 4.83)
Recycling-C	19.69	9.74	9.95
Landfill	28.1	0	28.1

Figure 8: Net greenhouse gas emissions of different circular pathways for managing plastic discards. Black dot is for better visibility of landfill bar.

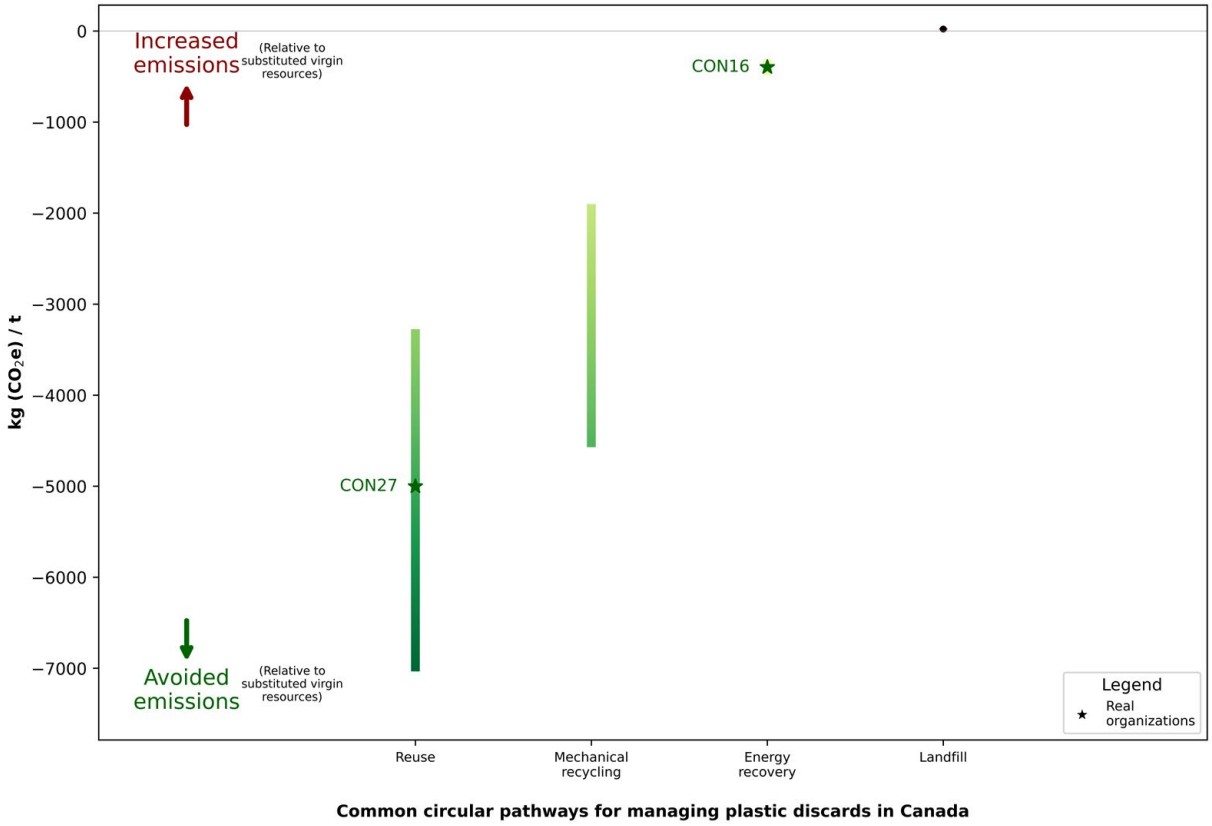


Table 7: Average greenhouse gas emissions (in kg CO_2e) profiles for different operational structures of managing plastic discards The GHG emission values show the average of the best and worst cases. Green rows indicate the operational structure of a pathway generating the highest net GHG performance.

Pathway-Operational Structure	**Released** (real case)	**Avoided** (real case)	**Net** (real case)
Reuse	31 (30)	5185 (5031)	-5154 (-5001)
Mechanical recycling	135	3771	-3636
Energy recovery	2168 (2180)	2364 (2566)	-196 (-386)
Landfill	22	0	22

3.1.3 Agrifood Sector

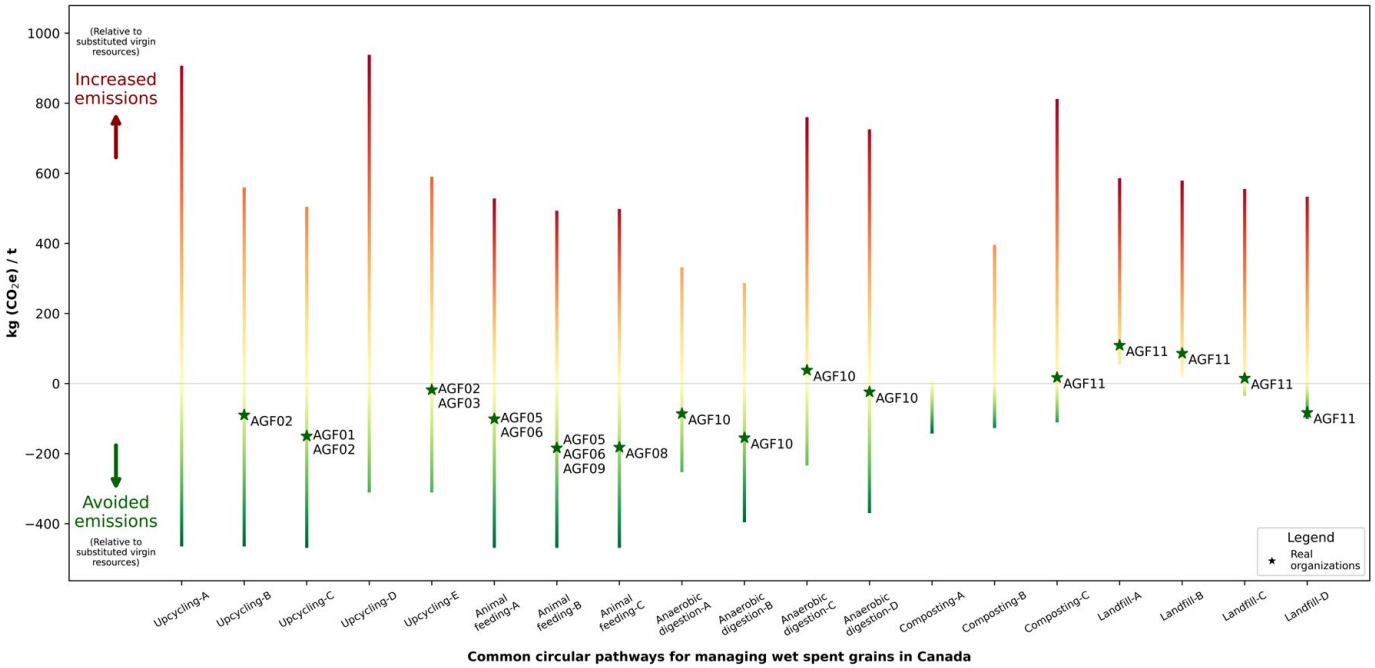
3.1.3.1 Wet Spent Grains Discards

The analysis uncovered four circular pathways for wet spent grains discards, including upcycling, animal feeding, anerobic digestion, and composting. Each circular pathway comprised one or more unique operational structures. Upcycling featured five distinct operational structures (A, B, C, D, and E); animal feeding featured three distinct operational structures (A, B, and C); anaerobic digestion featured four distinct operational structures (A, B, C, and D); and composting featured three distinct operational structures (A, B, and C). Altogether, there were 15 distinct operational structures across the four identified circular pathways. Landfill was the default conventional pathway.

While each operational structure exhibited a unique net GHG emission profile, as shown in Figure 9, most operational structures were carbon positive, but most real cases were carbon negative. This was for several reasons, such as high operational energy use and low savings from substitution of virgin materials (see Table 2 and [5] for additional details). The existing configuration of each pathway can further be optimized to release less GHG emissions than those that are saved from substituting virgin resources.

Upcycling-A did not involve mechanical pressing before drying wet spent grains, while Upcycling-B (adopted by AGF02) involved mechanical pressing before drying wet spent grains into flour. Both operational structures used the flour on-site for making cookies and other baked goods. Upcycling-C (adopted AGF01 and AGF02) used wet spent grains directly for making cookies without mechanical pressing or drying. Upcycling-D and Upcycling-E (adopted AGF02 and AGF03) were analogous to Upcycling-A and Upcycling-B, respectively, but both sold the recovered flour in retail markets instead of using it on-site. Because mechanical pressing is quite efficient in reducing water content and the subsequent need for electricity, Upcycling-B and

Figure 9: Net greenhouse gas emissions of different circular pathways for managing wet spent grains, based on earlier research (modified from [5] © 2023 by the International Society for Industrial Ecology).





"The type of animal had little influence on the overall net GHG emissions of the animal feeding pathway."

Upcycling-E were more GHG efficient than Upcycling-A and Upcycling-D. All of these operational structures recovered 0.22 to 0.67 t of flour from 1 t of wet spent grains discards depending on the initial moisture content, which substituted virgin flour made from a mix of grains (e.g., wheat, oats, corn, etc.). The substitution ratio was 0.7 to 1.5 t for 1 t of upcycling flour. A substitution ratio greater than one incorporated higher nutritional quality (e.g., higher fibre and protein content) of the upcycled flour.

Animal feeding-A, Animal feeding-B, and Animal feeding-C involved feeding wet spent grains to cattle, pig, and insects, respectively. All cases of animal feeding substituted virgin grain for the worst case of cattle feeding, which substituted silage/grass and lowered the net GHG savings. Therefore, the type of animal had little influence on the overall net GHG emissions of the animal feeding pathway.

For the remaining three pathways (anerobic digestion, composting, and landfill), it was assumed that wet spent grains were mixed with other municipal organic waste streams and processed as generic organic waste. Anaerobic digestion-A and Anerobic digestion-B involved processing pure organic discard without any decontamination steps (cleaning and removing impurities such as plastic packaging) to recover heat and electricity or pure renewable natural gas, respectively. The recovered resources substituted natural gas for heat and grid electricity in the case of Anaerobic digestion-A, and only natural gas for heat in the case of Anaerobic digestion-B. Because the Canadian provinces selected for this report had cleaner grid electricity, recovering electricity along with heat produced less GHG savings than recovering renewable natural gas. Anaerobic digestion-C and Anaerobic digestion-D were similar to Anaerobic digestion-A and Anaerobic digestion-B, respectively, but involved decontamination steps due to impure organic waste, which reduced the net GHG savings. All of these operational structures also recovered digestate, which substituted mineral fertilizers.

Composting-A involved home composting with limited processing, thereby generating the highest net GHG savings. The other two composting operational structures involved industrial composting with significant operations, which reduced net GHG savings compared to Composting-A. Further, Composting-A a nd Composting-B processed pure organic waste, while Composting-C involved decontamination steps, which further reduced the net GHG savings. All composting operational structures recovered soil nutrient, which substituted peat moss and mineral fertilizers.

Some landfill operational structures were similar to the anaerobic digestion pathways. Landfill-A involved flaring-off landfill gas without any recovery; Landfill-B recovered gas for use as electricity; Landfill-C recovered gas for use as electricity and heat; and Landfill-D recovered gas for use only as renewable natural gas.

Landfill-D generated highest net GHG savings because it recovered only natural gas. Overall, in terms of net GHG savings, anerobic digestion was superior to composting, which was superior to landfilling.

Table 8 summarizes the GHG emission values for operational structures managing wet spent grains discards, showing the average of the best and worst cases, with real case values in parentheses. All operations occurred within Canada. Green rows indicate the pathways with the highest net GHG savings.

3.1.3.2 Fruit and Vegetable Residues

The analysis uncovered five circular pathways for fruit and vegetable residues, including upcycling, animal feeding, anerobic digestion, and composting. Each circular pathway comprised one or more unique operational structures. Upcycling featured three distinct operational structures (A, B, and C); animal feeding (insects) featured one operational structure; anaerobic digestion featured four distinct operational structures (A, B, C, and D); and composting featured three distinct

Table 8: Average greenhouse gas emissions (in kg CO_2e) profiles for different operational structures of managing wet spent grains. The GHG emission values show the average of the best and worst cases. Green rows indicate the operational structure of a pathway generating the highest net GHG performance (modified from [5] © 2023 by the International Society for Industrial Ecology).

Pathway–Operational Structure	**Released** (real case)	**Avoided** (real case)	**Net** (real case)
Upcycling-A	487	266	221
Upcycling-B	313 (100)	266 (190)	47 (-90)
Upcycling-C	283 (40)	266 (190)	-18 (-150)
Upcycling-D	532	219	313
Upcycling-E	358 (150)	219 (168)	139 (-18)
Animal feeding-A	283 (92)	253 (194)	30 (-102)
Animal feeding-B	283 (9)	270 (194)	12 (-185)
Animal feeding-C	285 (11)	270 (194)	15 (-183)
Anaerobic digestion-A	192 (31)	153 (117)	39 (-86)
Anaerobic digestion-B	192 (31)	247 (186)	-55 (-155)
Anaerobic digestion-C	405 (145)	142 (107)	263 (38)
Anaerobic digestion-D	405 (145)	227 (169)	178 (-24)

Pathway–Operational Structure	**Released** (real case)	**Avoided** (real case)	**Net** (real case)
Composting-A	10	76	-66
Composting-B	215	81	134
Composting-C	425 (111)	75 (94)	350 (17)
Landfill-A	321 (109)	0 (0)	321 (109)
Landfill-B	321 (109)	21 (22)	300 (87)
Landfill-C	321 (109)	61 (93)	260 (16)
Landfill-D	321 (112)	105 (196)	216 (-84)

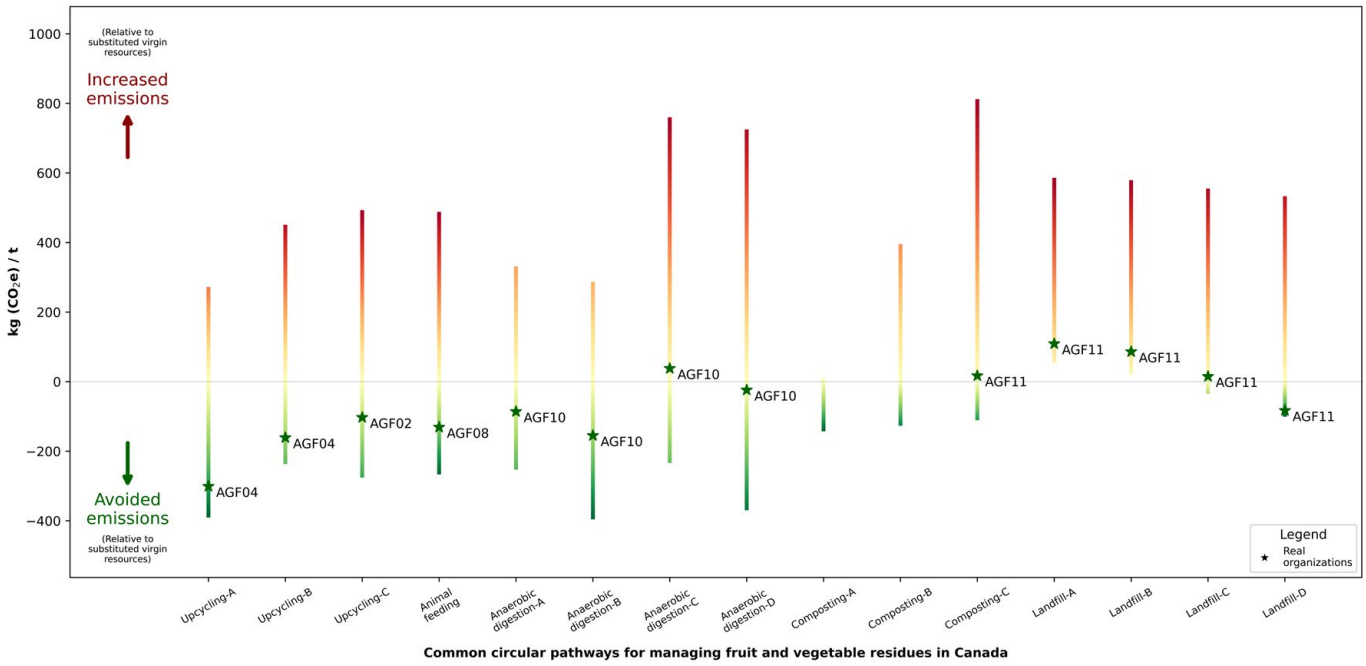
operational structures (A, B, and C). Altogether, there were 11 distinct operational structures across the five identified circular pathways. Landfill was the default conventional pathway.

While each operational structure exhibited a unique net GHG emission profile, as shown in Figure 10, most operational structures were carbon positive, but most real cases were carbon negative. This was for several reasons, such as high operational energy use and low savings from substitution of virgin materials (see Table 2 and [5] for additional details). The existing configuration of each pathway can further be optimized to release less GHG emissions than those that are saved from substituting virgin resources. It should be noted that fruit and vegetable residues were treated identically to wet spent grains for the anerobic digestion, composting, and landfill pathways, so the operational structures and GHG emission profiles were identical to those of wet spent grains.

Upcycling-A (adopted by AGF04) did not involve mechanical pressing to manufacture dried powder for retail markets, whereas Upcycling-B (adopted by AGF04) did not involve drying and manufactured wet products (e.g., zest of citrus shells) for retail markets. Upcycling-C (adopted by AGF02) also did not involve drying and used wet blend for on-site cookie production. The recovered quantities and substitution ratios in all fruit and vegetable residues operational structures were similar to those of wet spent grains, that is, between 0.22 to 0.67 t recovered for 1 t of fruit and vegetable residues and 0.7 to 1.5 t of virgin material substituted for 1 t of upcycled product. Upcycling-A substituted regular flour mix, the same as wet spent grains; Upcycling-B substituted the same type of zest material but from other countries; and Upcycling-C substituted carrots. The net GHG savings of the circular pathways for animal feeding (cattle, pigs, and insects), composting, and anaerobic digestion, as well as landfilling, was identical to those from the same pathways for wet spent grains. Only in the case of animal feeding involving insects, Animal feeding-C of wet spent grains substituted virgin grains, whereas Animal feeding of fruit and vegetable residues substituted carrots. Being less GHG intensive than grains, carrots lowered the net GHG savings.

Table 9 summarizes the GHG emission values for operational structures managing fruit and vegetable residues, showing the average of the best and worst cases, with real case values in parentheses. All operations occurred within Canada. Green rows indicate the pathways with the highest net GHG savings.

Figure 10: Net greenhouse gas emissions of different circular pathways for managing fruit and vegetable residues. Based on earlier research (modified from [5] © 2023 by the International Society for Industrial Ecology).



3.2 Technological Configuration, Geographical Scale, and 20% Net Carbon Savings

When does circularity mitigate climate change? A circular pathway is carbon negative when its operational structure generates less GHG emissions relative to those released by the production of substituted virgin resources. For each circular pathway analyzed in Section 3.1, the following simulation determined a "frontier" of operational structures that ensured a 20% reduction in carbon emissions relative to virgin production. The simulation used the following equation to determine the desired set of operational structures:

$$Net\ GHG\ emissions = Operational\ emissions - Avoided\ emissions\ from\ virgin\ production, \quad (1)$$

where *Net GHG emissions* represents the net GHG emissions from a circular pathway with a specific operational structure, determined based on different combinations of processing technologies and transportation modes and distances. A negative value indicates carbon negative operations, whereas a zero value indicates carbon neutral operations.

Two components in Equation (1) determine the net GHG emissions of a circular pathway. The first component, *Operational emissions,* is GHG emissions from operations, which depend on the total energy consumption and transportation required for managing 1 t of discards, starting from the collection to the final recovery of materials. Accordingly, this component of Equation (1) can be broken down further, as shown in Equation (2):

$$Operational\ emissions = TotEnerCon * GHGEnerOps + TotTransOps * GHGTransOps, \quad (2)$$

where *TotEnergyCon* represents the total energy consumption (in MJ) for managing 1 t of discards, and *GHGEnerOps* represents the life cycle GHG emissions per MJ of energy supply. *GHGEnerOps* is calculated as the weighted average of the quantity and GHG intensities of different energy types (e.g., natural gas,

Table 9: Average GHG emissions (in kg CO_2e) profiles for different operational structures of managing fruit and vegetable residues. The GHG emission values show the average of the best and worst cases. Green rows indicate the operational structure of a pathway generating the highest net GHG performance based on earlier research (modified from [5] © 2023 by the International Society for Industrial Ecology).

Pathway–Operational Structure	**Released** (real case)	**Avoided** (real case)	**Net** (real case)
Upcycling-A	486 (116)	546 (416)	-60 (-300)
Upcycling-B	286 (3)	179 (164)	107 (-161)
Upcycling-C	283 (40)	175 (143)	108 (-103)
Animal feeding	284 (11)	173 (143)	111 (-132)
Anaerobic digestion-A	192 (31)	153 (117)	39 (-86)
Anaerobic digestion-B	192 (31)	247 (186)	-55 (-155)
Anaerobic digestion-C	405 (145)	142 (107)	263 (38)
Anaerobic digestion-D	405 (145)	227 (169)	178 (-24)
Composting-A	10	76	-66
Composting-B	215	81	134
Composting-C	425 (111)	75 (94)	350 (17)
Landfill-A	321 (109)	0 (0)	321 (109)
Landfill-B	321 (109)	21 (22)	300 (87)
Landfill-C	321 (109)	61 (93)	260 (16)
Landfill-D	321 (112)	105 (196)	216 (-84)

diesel, electricity grid-mix) used during operations. *TotTransOps* captures the total transportation in t·km[15] (a commonly used transportation measure in LCA [70]), whereas *GHGTransOps* represents the life cycle GHG emissions per t·km of transportation, and is the weighted average of quantity and GHG intensities of different transportation modes (e.g., light truck, big truck, rail, shipping) used during operations.

The second component in Equation (1), *Avoided emissions from virgin production,* captures the GHG emissions of avoided virgin production, which can also be referred to as a carbon budget. Such carbon budgets represent the maximum amount of GHG emissions that a circular pathway can release while staying carbon neutral at worst relative to the virgin production. This component can be broken down further, as shown in Equation (3) and Equation (4):

[15] The unit t·km combines mass and distance in transportation. For example, transporting 0.5 t of discards for 20 km has a transportation value of 10 t·km.

$$Avoided\ emissions = AvoidVirMat * GHGEnerVir + TotTransVir * GHGTransVir. \quad (3)$$

$$AvoidVirMat = QuanRecovMat * QualRecovMat. \quad (4)$$

AvoidVirMat represents the total quantity in tonnes of avoided virgin materials. As described in Equation (4), this value depends on the quantity of materials recovered from discards (*QuanRecovMat*) as well as the quality of the recovered materials (*QualRecovMat*) relative to virgin production. *GHGEnerVir* in Equation (3) captures the life cycle GHG emissions in producing 1 t of virgin materials. Analogous to *GHGEnerOps* in Equation (2), this value is calculated as the weighted average of the quantity and GHG intensities of different energy types (e.g., natural gas, diesel, electricity grid-mix) used during the production of virgin materials. *TotTransVir* captures the total transportation in t·km associated with the virgin production; *GHGTransVir* in Equation (3) represents the life cycle GHG emissions per t·km of transportation associated with the production and delivery of virgin materials. Analogous to *GHGTransOps* in Equation (2), this value is calculated as the weighted average of quantity and GHG intensities of different transportation modes (e.g., light truck, big truck, rail, shipping) used during production and delivery of virgin materials.

The parameters described in equations (1) through (4) can be classified as either endogenous or exogenous. Endogenous parameters are those that organizations can partially or fully control, whereas exogenous parameters are beyond their control. For the simulation performed in this study, three parameters (*TotEnerCon, TotTransOps, and QualRecovMat*) were considered endogenous and four (*GHGEnerOps, GHGTransOps, GHGEnerVir, GHGTransVir*) were considered exogenous. It should be noted that the parameter *QuanRecovMat* is partially endogenous and partially exogenous because the quantity of recovered material depends on the recovery efficiency of a circular pathway, which organizations can control, but it also depends on the quality and contamination level of discards, which is often beyond organizations' control, being determined during the design phase of the virgin material as well as during the production and use phases of such material.

A circular pathway was characterized by energy consumption, transportation, and the quality of recovered material, so the goal of the simulation was to find the values of *TotEnerCon*, *TotTransOps*, and *QualRecovMat* such that the value of *Net GHG emissions* in Equation (1) was zero. To identify maximum thresholds of *TotEnerCon* (proxy for technological configuration) and *TotTransOps* (proxy for geographical scale), for which the operational structure of a given circular pathway would result in 20% carbon savings relative to virgin production, *Avoided emissions from virgin production* (proxy for carbon budgets) was reduced by 20%.

To limit the total number of simulations, only three quality levels (low, average, and high) were considered for each circular pathway. Further, to consider the effect of the four exogenous parameters on the net GHG emissions associated with a circular pathway, the concept of *system ecoefficiency* was used. This captured the level of cleanness, in terms of GHG emissions, of the overall system in which circular pathways are embedded. For example, the four exogenous parameters can determine lower GHG emissions in a more ecoefficient system than in a less ecoefficient system. There were two important reasons to account for system ecoefficiency in the analysis. First, identifying desirable, climate-smart operational structures for diverse circular pathways requires consideration of different system ecoefficiencies, because such operational structures should be designed contingently to exogenous factors for optimal environmental gains. Second, there was a huge number of combinations of these exogenous parameters, so system ecoefficiency grouped them to further limit the number of simulations.

Simulations were conducted for three levels of system ecoefficiencies: most ecoefficient, average ecoefficient, and least ecoefficient, with each level representing different GHG intensity values for each exogenous parameter. The average ecoefficient system represented the arithmetic average of ecoefficiencies of the least and most ecoefficient systems. The most ecoefficient system used Quebec's grid-mix with a GHG intensity of 0.024 kg CO_2e/kWh, whereas the least ecoefficient system used

British Columbia's[16] grid-mix with a GHG intensity of 0.082 kg CO_2e/kWh. This range also contained grid-mixes of other regions, including the Nordic country where chemical recycling of textile discards occurred, and Ontario, where some concrete and wood circularity pathways were reported. However, for the textile sector, some mechanical recycling operations were performed in India or Mexico, with much higher values of GHG intensities of the grid-mix. To account for such GHG intensive operations in the case of mechanical recycling, the most ecoefficient system used Mexico's grid-mix with a GHG intensity of 0.59 kg CO_2e/kWh, whereas the least efficient ecoefficient system used northern India's grid-mix with a GHG intensity of 1.21 kg CO_2e/kWh. For natural gas and diesel, as well as transportation modes, the respective GHG intensity values remained the same for all levels of system ecoefficiency. This assumption was reasonable because while electricity GHG intensity is highly sensitive to regional grid-mixes, the GHG intensities of other types of energy and of different transportation modes do not vary significantly across regions or countries.

In the case of virgin production, the inverse logic was used. Operations in a more ecoefficient system compared to a less ecoefficient system avoided GHG intensive virgin materials and associated energy use and transportation. For example, cotton fibre production generates between 2304 to 7085 kg CO_2e GHG emissions for 1 t of fibre. Therefore, the most ecoefficient system avoided GHG intensive fibre production (7085 kg CO_2e/t), whereas the least ecoefficient system avoided the cleaner fibre production. Tables A.3.1 and A.3.2 in Appendix A summarize the GHG intensities of key unit processes and key parameter values, respectively, under three quality levels and three system ecoefficiency levels. These values were derived to reflect the average of real cases as closely as possible. Using this data, the simulations were performed in two steps:

1. Carbon budgets were calculated according to equations (3) and (4). Table 10 shows the carbon budget for different DMSs under different system ecoefficiencies and quality levels. For each DMS, the carbon budget that a circular pathway can consume increased with the quality of recovered materials as well as system ecoefficiency. In the textile sector, for example, because the production of cotton fibres releases, on average, higher GHG emissions than the production of polyester fibres, the cotton DMS, on average, had a higher carbon budget than the polyester DMS.
2. In Equation (2), for each DMS pathway, the value of operational emissions was set as equal to 80% of the carbon budget of the substituted virgin production to find the values of $TotEnerCon$ and $TotTransOps$ that resulted in a 20% net decrease in carbon emissions. The simulation generated carbon negative frontiers. Figure 11 provides an example for the mechanical recycling of cotton under average system ecoefficiency.

In Figure 11, any point on the frontier for a given quality level represents a possible combination of energy consumption and transportation that is 20% carbon negative relative to virgin production. For this pathway, all operational structures under the frontier saved more than 20% CO_2e emissions per 1 t of valorized materials, whereas all operational structures above the frontier saved exactly 20%. The figure also includes four dots, each representing a unique operational structure for the analyzed DMS pathway. OS-real represents the average operational structure (energy consumption and transportation) of real cases identified through the research. OS1 and OS2 represent hypothetical carbon negative operational structures that would be obtained if real cases were to expand or reduce energy consumption (OS1) or transportation (OS2) to the maximum threshold beyond which the circular pathway would save less than 20% of CO_2e emissions per 1 t of valorized materials. OS-avg is the centre point on the frontier, representing an operational structure where transportation and energy consumption contribute equally to consuming 80% of the available carbon budget.

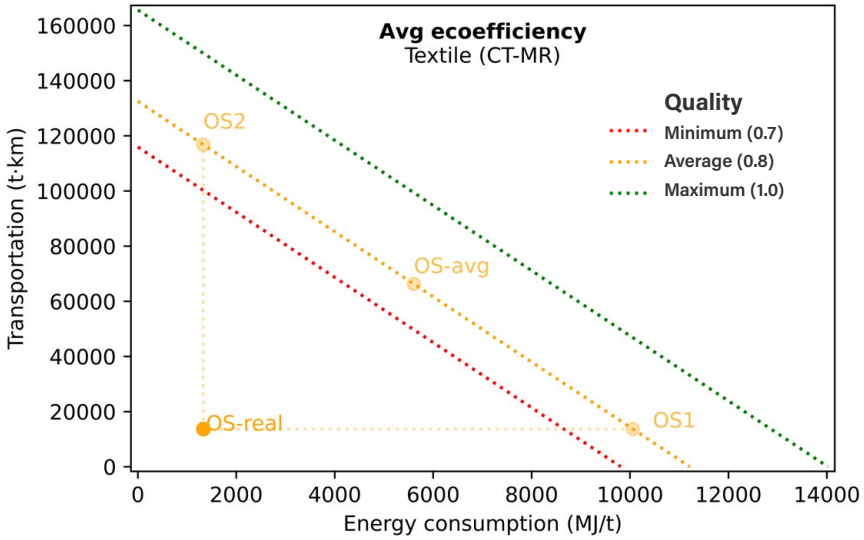
[16] While GHG intensities of the grid-mix of Alberta and other provinces are higher than GHG intensity of British Columbia's grid-mix, most of the interviewed organizations were in Ontario, Quebec, or British Columbia, so only these provinces were considered in this report.

Table 10: Carbon budget of different discarded material streams (DMSs) under different system ecoefficiency and quality levels.

			Carbon Budget (kg CO_2e)								
			System Ecoefficiency – Least			System Ecoefficiency – Average			System Ecoefficiency – Most		
			Quality Levels			Quality Levels			Quality Levels		
Sector		**Virgin resource substituted**	**Low**	**Avg**	**High**	**Low**	**Avg**	**High**	**Low**	**Avg**	**High**
Textile DMS Pathways	CT-RU	Virgin cotton clothing[i]	7535	10 675	12 559	11 294	16 000	18 823	15 729	22 283	26 215
	CT-CR	Virgin cotton fibre	1885	1885	1885	4549	4549	4549	7948	7948	7948
	CT-MR	Virgin cotton fibre	1312	1500	1874	3058	3495	4369	5190	5932	7414
	CT-DC	Virgin paper wipers	1084	1084	1084	1348	1348	1348	1641	1641	1641
	PE-RU	Virgin polyester clothing	8285	11 737	13 808	10 761	15 244	17 935	13 561	19 212	22 602
	PE-CR	Virgin polyester fibre	3052	3052	3052	3685	3685	3685	4336	4336	4336
	PE-MR	Virgin polyester fibre	2145	2451	3064	2794	3193	3922	2794	3193	3992
	PE-DC	Virgin paper wipers	1084	1084	1084	1348	1348	1348	1641	1641	1641
Construction DMS Pathways	WD-RU	Virgin wood	5	5	5	15	15	15	26	26	26
	WD-MA	Heat from coal	267	467	667	301	526	752	335	586	838
	WD-ER	Heat from coal	896	1198	1500	1012	1353	1694	1128	1509	1890
	CC-RC	Virgin aggregates	5	5	5	9	9	9	13	13	13
	PT-RU	Virgin carpets	7834	10 446	13 057	10 012	13 349	16 687	12 454	16 605	20 756
	PT-MR	Virgin polyester flakes	1853	2471	3089	2127	2836	3545	2408	3210	4013
	PT-ER	Heat from coal	2264	2264	2264	2554	2554	2554	2845	2845	2845
Agrifood DMS Pathways	WG-UC	Virgin mix-grain flour	56	80	120	145	207	310	310	443	664
	WG-AF	Virgin grain mixes; silage/grass	56	80	119	143	205	307	307	439	659
	WG-AD	Heat from natural gas; electricity; mineral fertilizers	85	85	85	146	146	146	212	212	212
	WG-CP	Peat moss; mineral fertilizers	10	10	10	64	64	64	178	178	178
	FR-UC	Carrots; differential grid-mix	17	24	36	45	65	97	92	131	197
	FR-AF	Carrots	64	91	137	93	132	198	121	174	260
	FR-AD	Heat from natural gas; electricity; mineral fertilizers	10	10	10	64	64	64	178	178	178
	FR-CP	Peat moss; mineral fertilizers	70	100	149	100	142	214	131	187	281

Note. [i]Although all circular pathways for textile substitute the same type (either cotton or polyester fibre) and almost the same quantity of virgin material, the carbon budget of the reuse pathway was considerably higher than the other circular pathways. This is because reuse avoids the manufacturing of clothing from virgin fibres (knitting, weaving, dyeing), which releases significant GHG emissions [71].

Figure 11: Carbon neutral frontiers of mechanical recycling of cotton discarded material stream.



3.3 Comparative Analysis

This section summarizes the findings of objective 4 and compares the results across and within sectors to identify any generalizable patterns linking 2030 carbon budgets to maximum thresholds of geographical scale and technological configuration for the studied climate-smart circular pathways. As previously defined, climate-smart circular pathways are those that save 20% GHG emissions relative to virgin production. Table 11 summarizes key operational thresholds of geographical scale and technological configuration derived per the analysis documented in Section 3.2 and illustrated with Figure 11. The data revealed several differences across circular pathways between and within sectors.

The first finding was that compared to climate-smart circular pathways in other sectors, circular pathways in the textile sector could afford operations with much larger geographical scale and technological configurations and higher energy intensity. For example, for cotton chemical and mechanical recycling (CT-CR and CT-MR), the maximum transportation distance ranges from 116 763 to 178 303 t·km, but for upcycling pathways in the agrifood sector (WG-UC and FV-UC), it ranges from 45 to 930 t·km, and for concrete recycling (CC-RC), it is 16 t·km (indicating a need for shrinkage, not expansion, from the real value). One reason for this is that the carbon budgets for textile operations are significantly higher than the carbon budgets in the other two sectors; virgin production in the textile sector emits more GHGs per unit of production relative to materials and productions in the other two sectors. While total carbon budget is an important determining factor for maximum geographical scale, GHG intensities of energy and transportation are equally important. The circular pathways in the agrifood sector use light commercial vehicles for collecting DMSs, which are GHG inefficient, and concrete recycling uses portable diesel-based electricity generators, resulting in high GHG intensity energy (in the range of 1.2-2 kg CO_2e/kWh) [72]. Real-world cases also suggest that as geographical scale increases beyond a region, operations begin to involve more efficient transportation modes (large trucks instead of small trucks; railways instead of large trucks; and maritime transport for international transportation in the textile sector). According to the ecoinvent dataset used in this report, maritime transport is highly GHG efficient (4.5 times more efficient than rail transport; 9 times more efficient than a large truck; 50 times more efficient than a small truck; and 180 times more efficient than a light commercial vehicle). The use of such highly GHG efficient transport with a significant carbon budget suggests that textile circularity can achieve global

Table 11: Operational parameters for different discarded material streams (DMSs) under average system ecoefficiency and quality level.

Sector		2030 Carbon Budget (kg CO_2e/t)	Real Case (MJ/t, t·km)	Operational Parameters for Climate-Smart Pathways		
				OS1 (MJ/t, t·km/t)	OS2 (MJ/t, t·km/t)	Mid-Range Point (MJ/t, t·km/t)
Textile DMS Pathways	CT-RU	12 800	(177, 12 034)	(754 363, 12 034)	(177, 628 989)	(384 537, 314 567)
	CT-CR	3639	(44 104, 23 358)	(220 389, 23 358)	(44 104, 178 303)	(123 482, 108 534)
	CT-MR	2796	(1331, 13 656)	(10 059, 13 656)	(1331, 116 763)	(5608, 66 241)
	CT-DC	1078	(613, 7010)	(56 033, 7010)	(613, 34 366)	(35 117, 17 334)
	PE-RU	12 195	(177, 12 034)	(718 024, 12 034)	(177, 599 263)	(366 367, 299 704)
	PE-CR	2948	(44 104, 23 358)	(173 483, 23 358)	(44 104, 137 075)	(100 029, 87 920)
	PE-MR	2256	(1331, 13 656)	(7893, 13 656)	(1331, 91 177)	(4525, 53 448)
	PE-DC	1078	(613, 7010)	(56 033, 7010)	(613, 34 366)	(35 117, 17 334)
Construction DMS Pathways	WD-RU	12	(1776, 143)	**Infeasible**	**Infeasible**	(341, 13)
	WD-MA	421	(1981, 178)	(19 546, 178)	(1981, 805)	(12 257, 438)
	WD-ER	1082	(1300, 172)	(46 651, 172)	(1300, 2199)	(25 256, 1128)
	CC-RC	7	(94, 24)	(54, 24)	**Infeasible**	(39, 40)
	PT-RU	10 679	(153, 160)	(21 8968, 160)	(153, 117 272)	(109 634, 58 677)
	PT-MR	2269	(1477, 160)	(47 573, 160)	(1477, 24 163)	(23 940, 12 466)
	PT-ER	2043	(1300, 160)	(94 670, 160)	(1300, 22 147)	(47 675, 11 226)
Agrifood DMS Pathways	WG-UC	166	(1990, 696)	(4324, 696)	(1990, 930)	(5624, 565)
	WG-AF	164	(0, 50)	(4925, 50)	(0, 90)	(5570, 45)
	WS-AD	117	(0, 300)	(6079, 300)	(0, 1284)	(3967, 642)
	WS-CP	51	(95, 200)	(419, 200)	(95, 480)	(325, 281)
	FV-UC	52	(1866, 34)	(2273, 34)	(1866, 45)	(1766, 48)
	FV-AF	106	(0, 5)	(6551, 5)	(0, 58)	(3586, 29)
	FV-AD	117	(0, 300)	(6079, 300)	(0, 1284)	(3967, 642)
	FV-CP	51	(95, 200)	(419, 200)	(95, 480)	(325, 281)

Note. For CT-DC and PE-DC, no real case was discovered, so the average values of all operational structures were assumed to represent the real case values. For WD-RU and CC-RC, real-world operations were carbon positive and can only become carbon negative in OS1 and OS2 when energy or transportation values are below zero, making it infeasible.

geographical scale and still stay carbon negative. However, if some textile operational structures of a pathway fail to involve maritime transport and rely only on road or rail transport, then the thresholds identified in Table 11 will not be valid, and circular operations would likely become carbon negative or even carbon positive.

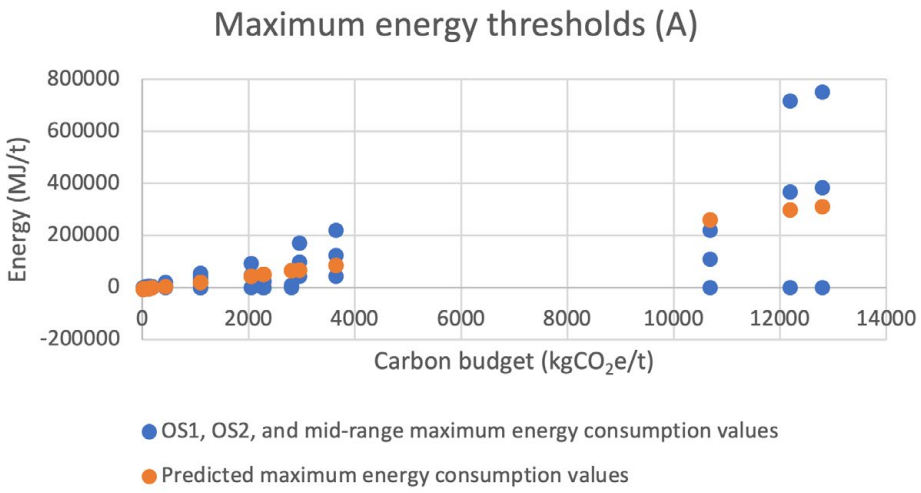
The second finding was that while critical thresholds did not display ample internal variability within the agrifood and construction sectors, critical thresholds for circular pathways in the textile sector were subject to substantial variability in terms of both energy and transportation thresholds (see green dots in plots). As shown in Table 11, the reuse and chemical recycling pathways (CT-RU, PE-RU, CT-CR, and CT-CR) could consume much higher energy than mechanical recycling (CT-MR and PE-MR) and remain carbon negative or, at worst, carbon neutral. This variability is because reuse and chemical recycling deployed their operations in countries with low carbon grid electricity (Canada and the Nordic country), whereas mechanical recycling was done in India, which has high GHG intensity of grid electricity.

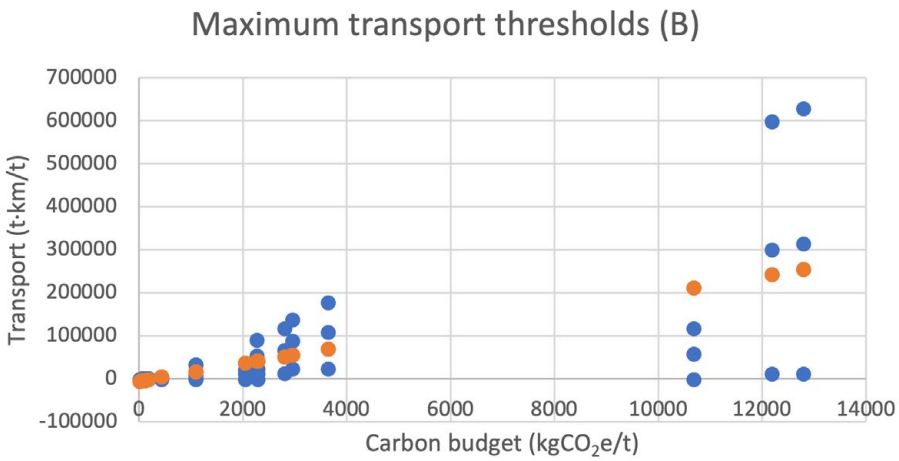
An ordinary least squares regression model was used for further examination. In the model, energy and transportation threshold values were set as the dependent variables and carbon budget as the independent variable. For each energy and transportation, a total of 66 threshold values were considered (22 from OS1, 21 from OS2, and 23 from mid-range, after discarding infeasible sets). The modelling setup was aligned with objective 4, to identify generalizable patterns connecting avoided carbon emissions from virgin production and maximum thresholds for climate-smart circular pathways. Carbon budgets were significantly correlated with energy and transportation thresholds at 99% confidence level, implying a linear relationship between the carbon embedded in virgin resources and the transportation and energy consumption involved in circular pathways to remain carbon negative.

Figure 12 shows the results of the regression analysis, which found that one standard deviation increase in carbon budget (i.e., an increase of 3910 kg CO_2e/t of virgin material) allows:

- the energy consumption of a climate-smart circular pathway to expand by 65 686 MJ (i.e., 0.677 times the standard deviation of the energy consumption data distribution in the sample, which is about 97 025 MJ); and
- the transportation of a climate-smart circular pathway to expand by 53 288 t·km (i.e., 0.670 times the standard deviation of transportation data in the sample, which is about 79 535 t·km).

Figure 12: Actual and fitted thresholds versus carbon budget for different discarded material streams.





4 Discussion and Conclusion

This section contextualizes the results, presenting recommendations for policymakers and industry managers to consider when designing circular climate-smart pathways, and discussing limitations to help inform future research.

4.1 Recommendations for Public Policy and Standardization

While circularity is often perceived to be climate-smart, the goals of closing material flows and reducing net GHG emissions relative to virgin materials are not always aligned. As policymakers and organizations work collaboratively to develop circular pathways for managing a variety of discards, they should be mindful of design conditions that make such pathways more likely to be climate-smart. Inappropriately designed circular pathways could unintentionally counteract efforts to reduce GHG emissions. The findings from this research report are relevant for these decision-makers in several ways, which are discussed in this section.

Mixing difficult-to-separate materials makes circularity more economically and environmentally costly.

Discard quality refers to material homogeneity. The presence of mixed materials or contamination in a DMS stream can decrease the quality and value of discards and the potential for climate-smart circular pathways. For example, in the construction sector, wood discards with nail holes cannot be reused for structural applications, and wood discards contaminated with glue, fire retardant materials, or paint require a costly separation process and can even make salvaging wood for reuse impossible. Such discards are either landfilled or burned for energy recovery. Similarly, clothing discards largely made of a single fibre type (e.g., > 90% cotton or 100% polyester) have higher circular pathway potential than mixed discards. For example, chemical recycling requires different set ups for each fibre type and the mixing of fibres introduces numerous technical difficulties and increases energy consumption.

Discards with sufficiently high quality must also be available in sufficient quantities to make collection and processing economically viable. In the case of reusing clean wood discards, some interviewees indicated that they use smaller wood pieces and finger-join them into bigger dimensional pieces for reuse, whereas other interviews stated that large pieces of higher quality dimensional lumber are more desirable than smaller pieces. Larger pieces are often available from large non-residential buildings. Smaller pieces are usually available from deconstruction or demolition of residential buildings and tend to have more contaminants per unit of volume, such as metals (e.g., nails, fasteners) or mortar/concrete, and therefore involve higher cleaning and processing costs per unit of volume. Subject to the economic viability of collection, smaller wood pieces can also be used for manufacturing engineering wood [75].

While there is greater potential for recovering wood for reuse from older residential buildings (built prior to the 1950s using old-growth timber), newer residential buildings (built in the 1960s and later) tend to have wood that is diverse and of low quality, and thus have less potential for recovering wood for reuse. The research also found that discards like plywood are not economically viable for reuse because the nailing/denailing process substantially lowers its quality and integrity, but it can be repurposed for formwork [76].

Quality and quantity restrictions mean that only certain quantities of clean wood discards are likely to be reused; only clean concrete can be recycled into aggregates; and only close-to-pure cotton or polyester discards can be chemically recycled in economically viable ways. Any deviation from the expected purity levels summarized in Table 2 will affect both the economic viability and the GHG benefits of a particular circular pathway. Such constraints imply that there may not be enough discards for certain high-value circular pathways such as reuse, whereas low-value pathways such as recycling, downcycling, or even incineration and landfilling may be overwhelmed with discards.

Recommendation: Adopting as many of the 12 design principles of green engineering [73], which complements other frameworks such as the Golden Design Rules for packaging and cradle-to-cradle design practices, could foster circularity by simplifying valorization processes and reducing their ecological and economic costs [74]. Some of these design principles include minimizing material diversity in products or adopting product designs that ease material separation at the end-of-life stage.

The absence of two key processes hinders circularity: (a) a fast, economical process for testing and grading recovered materials for future use, and (b) a trustworthy certification process for recovered materials.

The findings indicated that the construction industry largely prefers virgin over recovered materials due to performance and quality concerns as well as the need for certified materials. The research conducted for this report did not identify any standardized procedures for certifying wood discards or recycled concrete aggregates, which restricts their use in structural applications. The importance of quality standards and certification processes has been discussed in the literature in the context of extended producer responsibility frameworks for plastics and paper [77].

Recommendation: Developing quality standards and certification processes for recovered materials to foster circularity.

Demand for circular materials is currently weak, if not entirely absent, for certain circular pathways.

Interviewees noted that the government could stimulate demand for reusing and recycling pathways through minimum imposed recycled content legislation, sliding taxes, or public procurement, similar to what has been proposed and endorsed for plastics packaging [77], [78]. However, as new demand stimuli are introduced, it is important to avoid developing circular pathways and operational structures with suboptimal ecological performance relative to the substituted virgin materials. This report offers important insights to avoid unintended adverse consequences, directly informing the development of climate-smart circular standards.

Recommendation: Stimulating demand for climate-smart reuse and recycling pathways to help to promote circularity.

If configured inappropriately, certain circular pathways emit more GHG emissions than they save.

This report contributes to the literature by providing evidence that this phenomenon is more pronounced for certain circular pathways than it is for others. For example, some of the circular pathways valorizing wet spent grains, fruits and vegetable residues, wood discards, and concrete discards, while outperforming traditional incineration and disposal to landfill, released more GHG emissions than the carbon budgets associated with the substituted virgin materials (Table 9). However, all circular pathways for cotton, polyester, and plastics discards, reflecting real or simulated cases under a variety of operational structures, were at worst carbon neutral, and these pathways generally followed the high-level recommendations of established resource recovery hierarchies.



> **"Demand for circular materials is currently weak, if not entirely absent, for certain circular pathways."**

Further, within the textile sector, all circular pathways generated net GHG savings relative to substituted virgin materials, but there were significant differences across pathways. Reusing saved 154 to 260% more GHG emissions than chemical recycling; chemical recycling saved 94 to 620% more GHG emissions than mechanical; and mechanical recycling saved 104 to 630% more GHG emissions than downcycling. The findings suggest that if large garment brands and policymakers want to achieve significant climate change mitigation, they should prioritize reuse and chemical recycling over other circular options. However, the supply of used clothing far exceeds the demand, raising questions about the economic competitiveness of reuse businesses [79]. Some businesses have shown that reusing can be economically viable, such as Patagonia's Worn Wear program, which encourages repairs and reuse of clothing [80]. Interviews with thrift and charity stores also showed that reusing clothing can be profitable.

Recommendations: Standards developing bodies could prioritize the development of climate-smart standards for circular pathways in the agrifood and construction sectors because there is a lower risk of unintentional adverse ecological consequences in the textile sector.

Large garment brands and policymakers could allocate greater budgets toward reuse and chemical recycling pathways, and introduce educational programs for consumers and incentives for suppliers (via carbon tax, subsidies, innovation grants, and supply chain financing).

As new climate-smart standards are developed for circular pathways in construction and agrifood, which circular pathways have the greatest potential to generate GHG savings?

In the construction sector, the findings suggest that Energy recovery-A (burning wood in a cement kiln) is superior to other circular pathways involving wood, while Recycling A is superior to other circular pathways involving concrete. In the agrifood sector, from a GHG perspective, upcycling food discards to human consumption has similar performance to animal feeding and anaerobic digestion, but higher performance than composting.

As new climate-smart circular standards are developed, what maximum thresholds of energy consumption and transportation should be considered?

The analyses summarized in Table 11 and Figure 12 offer critical guidance on the structural characteristics of climate-smart circular pathways for diverse materials across diverse industries.

One key finding is that circular pathways in the textile sector can be globalized and still be carbon negative relative to virgin production, whereas circular pathways

in the construction and agrifood sectors must remain local or regional because of lower carbon budgets, less ecoefficient transportation modes, and more energy intensive processing technologies.

Further, the regression analysis revealed a linear relationship between carbon budgets and maximum thresholds of transportation and energy consumption for circular pathways. Specifically, it found that one standard deviation increase in carbon budget (i.e., an increase of 3910 kg CO2e/t of virgin material) allows the energy consumption of a climate-smart circular pathway to expand by 0.677 times the standard deviation of the energy consumption, which is about 97 025 MJ, and allows the transportation of a climate-smart circular pathway to expand by 0.670 times the standard deviation of the transportation, which is about 79 535 t·km.

Finally, although a generalizable pattern linking carbon budgets to circular pathways' operational structures was identified, the net GHG impacts of circular pathways remain contextual. Key contingent factors include the GHG intensity of adopted transportation modes, the GHG intensity of energy used, and the GHG savings from avoided virgin materials (carbon budgets).

Recommendation: As the economy adopts cleaner modes of transport (e.g., electric vehicles), decarbonizes grid-mix by adding renewables, and becomes more circular, policymakers and standards setting organizations should reevaluate the eco-effectiveness of the circular pathways and critical climate-smart thresholds identified in this research report. Without considering the effects of such transitions at regular intervals, policymakers and standard setting bodies may overestimate net GHG savings from circularity.

4.2 Limitations

The findings in this report are subject to several limitations, which are outlined in this section.

First, the research considered only pathways that were either fully commercialized or at the early stages of commercialization. Future research may consider other emerging circular pathways.

Second, the analysis assumed internal homogeneity for each DMS, but materials from the same category may have different characteristics and properties. For example, not all plastic discards are the same. Each of the seven common categories of plastics has different processes and technological requirements for different circular pathways [21]. Therefore, the findings are unlikely to accurately represent every plastic category, other than polyester.

Third, primary data were difficult to access and verify. Organizations experience fatigue in supporting research and sharing data due to the multiple requests they receive. Therefore, limited availability of and uncertainties within the existing primary and secondary data introduced potential inaccuracies in assessing net GHG emissions.

Fourth, while the report adopted a consequential LCA perspective, it not only deviated from how consequential LCA is often implemented but also ignored some key characteristics of a consequential perspective. Such deviations were done to minimize methodological complexities, reduce data requirements, and maintain an ease of understanding for non-technical audiences:

a. A consequential LCA perspective typically incorporates the consequences of all decisions, for example, choosing a particular new pathway compared to the existing/baseline pathway (e.g., landfilling), which implies that it calculates the GHG impacts of differences between the two pathways, starting from the discard production step (e.g., demolition vs. deconstruction) to the final step (landfilling vs. recovery). In this report, these pathways were modelled independently. However, according to a consequential perspective, the GHG impacts of reusing would be equal to the impacts of "reusing vs. landfilling" or "reusing vs. energy recovery" because reuse pathways divert discards from landfilling and energy recovery, so all GHG costs and benefits from landfilling or energy recovery are substituted and should be subtracted from reusing.

b. Due to its conceptual and procedural characteristics, a consequential LCA perspective requires a unique LCA database, such as marginal suppliers or technological mix rather than an average mix [81], [82]. While the ecoinvent database provides separate databases for this purpose, it has some counterintuitive inconsistencies. For example, in the ecoinvent consequential database, Canadian electricity mix had higher GHG footprints for Ontario, Quebec, and British Columbia than the corresponding values in the attributional database, which uses an average grid-mix. This was the result of the assumptions on the marginal suppliers. Unlike other countries where wind and solar dominate new technologies, in Canada, per the database, it is natural gas. So in provinces with cleaner grid-mix, dominated by nuclear and hydro, the marginal suppliers to be phased out are often hydro or nuclear rather than fossil fuels. Therefore, for simplicity and ease of understanding, the calculations considered a cut-off database, which considers an average rather than marginal grid-mix. As a result, the foreground LCA model is properly aligned with the consequential LCA perspective, but the background is not. In future, such inconsistencies might be addressed by selecting a dedicated database for a consequential LCA and ensuring that the data truly represents a consequential perspective.

Further, while the LCA assessment method (ReCiPe 2016) generates impacts for up to 18 impact categories [62], this report considered GHG emissions as the key environmental impact for comparing different pathways. Due to the difficulty of accessing and validating primary data, other forms of environmental impact were not calculated. For example, in the case of wood recovery in cement kilns, impacts from the emission of other air pollutants and chemicals or the management of wood residues were ignored [83]. Similarly, for cotton, while the impacts associated with the use of chemicals and water are just as significant as carbon emissions [84], this report does not identify potential trade-offs between diverse ecological impacts. Some circular pathways and operational structures could be superior in terms of net GHG emissions, but may be inferior in other impact categories such as scarcity of finite, non-renewable resources (e.g., fossil fuels, non-metallic minerals such as limestone), water consumption, land use, toxicity, and so on.

Finally, some discards can potentially be repurposed through the same circular pathway multiple times (e.g., multiple reuses of clothing items or clean wood discards). However, quantifying the cumulative benefits from cascading, multiple reuses was outside the scope of this report. Further, the difference in the quality of a recovered material relative to the virgin material was captured by varying the quantity of the virgin material substituted for each tonne of the recovered material. However, this approach does not consider the impact of consumers' comfort with and perceptions of products made from the recovered materials compared with products made from virgin materials.

Future research can address the limitations discussed in this section and enrich the findings by improving the reported operational structures and collecting accurate and reliable operational data for LCA.

References

[1] J. Kirchherr, N.-H. N. Yang, F. Schulze-Spüntrup, M. J. Heerink, and K. Hartley, "Conceptualizing the circular economy (revisited): An analysis of 221 definitions," *Resour. Conserv. Recycl.,* vol. 194, 2023, Art. no. 107001, https://doi.org/10.1016/j.resconrec.2023.107001.

[2] M. A. Camilleri, "European environment policy for the circular economy: Implications for business and industry stakeholders," *Sustain. Dev.,* vol. 28, no. 6, pp. 1804–1812, 2020, https://doi.org/10.1002/sd.2113.

[3] Ellen MacArthur Foundation, "Growth within: A circular economy vision for a competitive Europe," Ellen MacArthur Foundation, Isle of Wight, United Kingdom, 2015. [Online]. Available: https://www.ellenmacarthurfoundation.org/growth-within-a-circular-economy-vision-for-a-competitive-europe

[4] T. Forslund, A. Gorst, C. Briggs, D. Azevedo, and R. Smale, "Tackling root causes: Halting biodiversity loss through the circular economy," Sitra, Helsinki, Finland, 2022. [Online]. Available: https://www.sitra.fi/wp/wp-content/uploads/2022/05/sitra-tackling-root-causes-1.pdf

[5] S. Jain and J. Gualandris, "When does upcycling mitigate climate change? The case of wet spent grains and fruit and vegetable residues in Canada," *J. Ind. Ecol.,* vol. 27, no. 2, pp. 522–534, 2023, https://doi.org/10.1111/jiec.13373.

[6] S. Boldoczki, A. Thorenz, and A. Tuma, "Does increased circularity lead to environmental sustainability?: The case of washing machine reuse in Germany," *J. Ind. Ecol.,* vol. 25, no. 4, pp. 864–876, 2021, https://doi.org/10.1111/jiec.13104.

[7] H. Corvellec, A. F. Stowell, and N. Johansson, "Critiques of the circular economy," *J. Ind. Ecol.,* vol. 26, no. 2, pp. 421–432, 2022, https://doi.org/10.1111/jiec.13187.

[8] G. D'Inverno, L. Carosi, and G. Romano, "Meeting the challenges of the waste hierarchy: A performance evaluation of EU countries," *Ecol. Indic.,* vol. 160, 2024, Art. no. 111641, https://doi.org/10.1016/j.ecolind.2024.111641.

[9] S. Van Ewijk and J. A. Stegemann, "Limitations of the waste hierarchy for achieving absolute reductions in material throughput," *J. Clean. Prod.,* vol. 132, pp. 122–128, 2016, https://doi.org/10.1016/j.jclepro.2014.11.051.

[10] M. Gooch *et al.,* "The avoidable crisis of food waste: Technical report," Value Chain Management International and Second Harvest, ON, Canada, 2019. [Online]. Available: https://www.niagaraknowledgeexchange.com/wp-content/uploads/sites/2/2019/01/Avoidable-Crisis-of-Food-Waste-Technical-Report-January-17-2019.pdf

[11] Danielle Bozarth *et al.,* "Closing the loop: Increasing fashion circularity in California," McKinsey & Company, Jul. 2022. Accessed: Oct. 1, 2023. [Online]. Available: https://www.mckinsey.com/industries/retail/our-insights/closing-the-loop-Increasing-fashion-circularity-in-california

[12] L. P. Rosado, P. Vitale, C. S. G. Penteado, and U. Arena, "Life cycle assessment of natural and mixed recycled aggregate production in Brazil," *J. Clean. Prod.,* vol. 151, pp. 634–642, 2017, https://doi.org/10.1016/j.jclepro.2017.03.068.

[13] R. Woodward and N. Duffy, "Cement and concrete flow analysis in a rapidly expanding economy: Ireland as a case study," *Resour. Conserv. Recycl.,* vol. 55, no. 4, pp. 448–455, 2011, https://doi.org/10.1016/j.resconrec.2010.12.006.

[14] Portland Cement Association, "Environmental product declaration: Portland cement," Portland Cement Association, Washington, DC, United States, 2023. Accessed: Dec. 6, 2023. [Online]. Available: https://www.cement.org/wp-content/uploads/2024/07/pca_epd_portland_athena_final_revised_nov2023-1.pdf

[15] NCC, "Environmental product declaration for aggregates from Nyrand gravel pit – Svebølle," NCC, Solna, Sweden, 2021. Accessed: Mar. 13, 2024. [Online]. Available: https://api.environdec.com/api/v1/EPDLibrary/Files/663ebd25-0b69-42ef-fb99-08d9bd3aaab3/Data

[16] Council of Canadian Academies, "Turning point: The expert panel on the circular economy in Canada," Council of Canadian Academies, Ottawa, ON, Canada, 2021. [Online]. Available: https://cca-reports.ca/wp-content/uploads/2022/01/Turning-Point_digital.pdf

[17] L. Haigh *et al.,* "The circularity gap report: Quebec," Circularity Gap Reporting Initiative, Circle Economy, Amsterdam, The Netherlands, 2021. Accessed: Sep. 17, 2023. [Online]. Available: https://www.circularity-gap.world/quebec

[18] Environment and Climate Change Canada. "Solid waste diversion and disposal." Accessed: Apr. 24, 2024. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/solid-waste-diversion-disposal.html

[19] Environment and Climate Change Canada, "National waste characterization report: The composition of Canadian residual municipal solid waste," Environment and Climate Change Canada, Gatineau, QC, Canada, 2020. [Online]. Available: https://publications.gc.ca/collections/collection_2020/eccc/en14/En14-405-2020-eng.pdf

[20] Y. Beaudoin *et al.,* "Baselining for a circular Toronto: Material flow analysis," Circle Economy, David Suzuki Foundation, and the City of Toronto, Tech. Memo 2, May 2021. Accessed: Feb. 5, 2024. [Online]. Available: https://www.toronto.ca/wp-content/uploads/2021/06/96b8-technical-memorandum-2-material-flow-analysis.pdf

[21] Deloitte and Cheminfo Services Inc., "Economic study of the Canadian plastic industry, markets, and waste," Environment and Climate Change Canada, Gatineau, QC, Canada, 2019. Accessed: Dec. 29, 2023. [Online]. Available: https://publications.gc.ca/collections/collection_2019/eccc/En4-366-1-2019-eng.pdf

[22] S. Weber, O. Weber, K. Habib, and G. M. Dias, "Textile waste in Ontario, Canada: Opportunities for reuse and recycling," *Resour. Conserv. Recycl.,* vol. 190, 2023, Art. no. 106835, https://doi.org/10.1016/j.resconrec.2022.106835

[23] Cheminfo Services Inc., "Characterizing reuse, recycling and disposal of textiles in Canada," Environment and Climate Change Canada, Gatineau, QC, Canada, 2022. Accessed: Sep. 15, 2023. [Online]. Available: https://nactr.ca/wp-content/uploads/2022/07/Characterizing-Reuse-Recycling-andDisposal-of-Textiles-in-Canada.pdf

[24] Ellen MacArthur Foundation, "A new textile economy: Redesigning fashion's future," Ellen MacArthur Foundation, Isle of Wight, United Kingdom, 2017. [Online]. Available: https://www.ellenmacarthurfoundation.org/a-new-textiles-economy

[25] J. Conca. "Making climate change fashionable – The garment industry takes on global warming." Forbes.com. Accessed: Aug. 3, 2023. [Online]. Available: https://www.forbes.com/sites/jamesconca/2015/12/03/making-climate-change-fashionable-the-garment-industry-takes-on-global-warming/?sh=57dd2e6c79e4

[26] European Parliament. "The impact of textile production and waste on the environment (infographics)." Accessed: Jul. 26, 2023. [Online]. Available: https://www.europarl.europa.eu/news/en/headlines/society/20201208STO93327/the-impact-of-textile-production-and-waste-on-the-environment-infographics

[27] Textile Exchange, "Preferred fibre and materials market report," Textile Exchange, Lamesa, TX, United States, Oct. 2022. Accessed: Jul. 27, 2023. [Online]. Available: https://textileexchange.org/app/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf

[28] M. Sadowski and C. Cummis. "A roadmap to net-zero emissions for the apparel sector." World Resources Institute. Accessed: Jul. 22, 2024. [Online]. Available: https://www.wri.org/technical-perspectives/roadmap-net-zero-emissions-apparel-sector

[29] "The price of fast fashion," *Nat. Clim. Chang.,* vol. 8, no. 1, 2018, https://doi.org/10.1038/s41558-017-0058-9.

[30] Textile Exchange, "Material pathways: Accelerating action towards climate+ goals," Textile Exchange, Lamesa, TX, United States, Mar. 2023. [Online]. Available: https://textileexchange.org/app/uploads/2023/03/Material-Pathways_March-2023.pdf

[31] Canada Green Building Council. "Building climate solutions: A proven path to lower carbon emissions." Accessed: Nov. 13, 2023. [Online]. Available: https://www.cagbc.org/why-green-building/building-climate-solutions/

[32] Environment and Climate Change Canada. "Reducing municipal solid waste." Accessed: Oct. 1, 2023. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/municipal-solid/reducing.html

[33] Delphi Group, "Circular economy and the built environment sector in Canada," Delphi Group, Ottawa, ON, Canada, Apr. 2021. [Online]. Available: https://delphi.ca/wp-content/uploads/2021/04/Circularity-in-Canadas-Built-Environment-Final-Report-April-14-2021.pdf

[34] Environment and Climate Change Canada, "National inventory report 1990–2019: Greenhouse gas sources and sinks in Canada, Part 1," Environment and Climate Change Canada, Gatineau, QC, Canada, 2021. [Online]. Available: https://publications.gc.ca/collections/collection_2021/eccc/En81-4-2019-1-eng.pdf

[35] F. N. Tubiello *et al.,* "Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems," *Earth Syst. Sci. Data,* vol. 14, no. 4, pp. 1795–1809, 2022, https://doi.org/10.5194/essd-14-1795-2022.

[36] Government of Ontario, "Food and organic waste policy statement," Government of Ontario, Toronto, ON, Canada, Apr. 30, 2018. [Online]. Available: https://www.ontario.ca/page/food-and-organic-waste-policy-statement

[37] Infrastructure Canada. "Smart Cities Challenge." Accessed: Jun. 30, 2022. [Online]. Available: https://www.infrastructure.gc.ca/pd-dp/transition/2021/infc/4/book-cahier-4-eng.html#9

[38] Ecovia Intelligence. "Upcycled foods to take off." Accessed: Jun. 30, 2022. [Online]. Available: https://www.ecoviaint.com/upcycled-foods-to-take-off/

[39] O. Spratt, R. Suri, and J. Deutsch, "Defining upcycled food products," *J. Culin. Sci. Technol.,* vol. 19, no. 6, pp. 485–496, 2021, https://doi.org/10.1080/15428052.2020.1790074.

[40] Upcycled Food Association. "Membership directory." Accessed: Jan. 15, 2022. [Online]. Available: https://www.upcycledfood.org/member-directory

[41] F. Fassio and N. Tecco, "Circular economy for food: A systemic interpretation of 40 case histories in the food system in their relationships with SDGs," *Systems,* vol. 7, no. 3. 2019, Art. no. 43, https://doi.org/10.3390/systems7030043.

[42] K. Drennan, S. Weber, C. Jacob-Vaillancourt, A. Kozlowski, and L. Fiset-Sauvageau, "A feasibility study of textile recycling in Canada," Fashion Takes Action, Toronto, ON, Canada. 2021. [Online]. Available: https://www.fashiontakesaction.com/wp-content/uploads/2021/06/FTA-A-Feasibility-Study-of-Textile-Recycling-in-Canada-EN-June-9-2021.pdf

[43] A. Mollaei, N. Ibrahim, and K. Habib, "Estimating the construction material stocks in two Canadian cities: A case study of Kitchener and Waterloo," *J. Clean. Prod.,* vol. 280, pt. 2, 2021, Art. no. 124501, https://doi.org/10.1016/j.jclepro.2020.124501.

[44] Light House, "Watching our waste: A national construction waste analysis in Canada using LEED™ certified project data," Light House, Vancouver, BC, Canada, 2021. Accessed: Jan. 29, 2024. [Online]. Available: https://nzwc.ca/Documents/WatchingOurWaste-Analysis.pdf

[45] A. Abbas, G. Fathifazl, O. B. Isgor, A. G. Razaqpur, B. Fournier, and S. Foo, "Environmental benefits of green concrete," in *2006 IEEE EIC Climate Change Conference,* Ottawa, ON, Canada, May 10–12, 2006, pp. 1–8, https://doi.org/10.1109/EICCCC.2006.277204.

[46] Light House, "Residential construction waste analysis," Light House, Vancouver, BC, Canada, 2021. [Online]. Available: https://www.light-house.org/wp-content/uploads/2021/05/Residential-Construction-Waste-Analysis-May-27-2021.pdf

[47] G. Perry and M. VanderPol. (2014). "Characterization and management of construction, renovation, and demolition waste in Canada." Accessed: Jan. 13, 2024. [Online]. Available: https://recycle.ab.ca/wp-content/uploads/2014/10/VanderPol_Perry.pdf

[48] M. Yeheyis, K. Hewage, M. S. Alam, C. Eskicioglu, and R. Sadiq, "An overview of construction and demolition waste management in Canada: A lifecycle analysis approach to sustainability," *Clean Technol. Environ. Policy,* vol. 15, pp. 81–91, 2013, https://doi.org/10.1007/s10098-012-0481-6.

[49] Dillon Consulting, "Our food future: Food and food waste flow study – Work package 1," Dillon Consulting Guelph, ON, Canada, Jun. 2021. [Online]. Available: https://guelph.ca/wp-content/uploads/Food-and-Food-Waste-Flow-Study-Report-WP1.pdf

[50] *Environmental Management — Life Cycle Assessment — Principles and Framework,* ISO 14040, International Organization for Standardization, Geneva, Switzerland, 2006, [Online]. Available: https://www.iso.org/standard/37456.html

[51] M. Finkbeiner, A. Inaba, R. Tan, K. Christiansen, and H.-J. Klüppel, "The new international standards for life cycle assessment: ISO 14040 and ISO 14044," *Int. J. Life Cycle Assess.,* vol. 11, pp. 80–85, 2006, https://doi.org/10.1065/lca2006.02.002.

[52] X. Tanguay, G. G. Essoua Essoua, and B. Amor, "Attributional and consequential life cycle assessments in a circular economy with integration of a quality indicator: A case study of cascading wood products," *J. Ind. Ecol.,* vol. 25, no. 6, pp. 1462–1473, 2021, https://doi.org/10.1111/jiec.13167.

[53] B. Weidema, "Avoiding co-product allocation in life-cycle assessment," *J. Ind. Ecol.,* vol. 4, no. 3, pp. 11–33, 2000, https://doi.org/10.1162/108819800300106366.

[54] D. Schrijvers, P. Loubet, and G. Sonnemann, "Archetypes of goal and scope definitions for consistent allocation in LCA," *Sustainability,* vol. 12, no. 14, 2020, Art. no. 5587, https://doi.org/10.3390/su12145587.

[55] T. Schaubroeck *et al.,* "Definition of product system and solving multifunctionality in ISO 14040–14044: Inconsistencies and proposed amendments—toward a more open and general LCA framework," *Front. Sustain.,* vol. 3, 2022, https://doi.org/10.3389/frsus.2022.778100.

[56] R. Heijungs, "Ten easy lessons for good communication of LCA," *Int. J. Life Cycle Assess.,* vol. 19, pp. 473–476, 2014, https://doi.org/10.1007/s11367-013-0662-5.

[57] Accelerating Circularity. "Recyclers directory." Accessed: Oct. 15, 2023. [Online]. Available: https://airtable.com/appRSUeyqwqfqjiSM/shrPUG4Q77eL9rpu5/tblYu82a6egDBm4LD

[58] S. Leipold, K. Weldner, and M. Hohl, "Do we need a 'circular society'? Competing narratives of the circular economy in the French food sector," *Ecol. Econ.,* vol. 187, 2021, Art. no. 107086, https://doi.org/10.1016/j.ecolecon.2021.107086.

[59] K. Hartley, J. Roosendaal, and J. Kirchherr, "Barriers to the circular economy: The case of the Dutch technical and interior textiles industries," *J. Ind. Ecol.,* vol. 26, no. 2, pp. 477–490, 2022, https://doi.org/10.1111/jiec.13196.

[60] S. Jain, S. Singhal, and S. Pandey, "Environmental life cycle assessment of construction and demolition waste recycling: A case of urban India," *Resour. Conserv. Recycl.,* vol. 155, 2020, Art. no. 104642, https://doi.org/10.1016/j.resconrec.2019.104642.

[61] Ecoinvent. "System models." Accessed: Dec. 1, 2021. [Online]. Available: https://ecoinvent.org/the-ecoinvent-database/system-models/

[62] M. A. J. Huijbregts *et al.,* "ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level," *Int. J. Life Cycle Assess.,* vol. 22, pp. 138–147, 2017, https://doi.org/10.1007/s11367-016-1246-y.

[63] J. Krupanek *et al.,* "Environmental performance of an autonomous laser weeding robot — a case study," *Int. J. Life Cycle Assess.,* vol. 29, pp. 1021–1052, 2024, https://doi.org/10.1007/s11367-024-02295-w.

[64] A. Assadi, "The benefits of using recycled crushed aggregates in infrastructure projects," EXP Services Inc., Brampton, ON, Canada, Nov. 17, 2022. Accessed: Oct. 1, 2023. [Online]. Available: https://www.ossga.com/multimedia/2022-12-06-140628-15051/exp-benefits_of_using_recycled_crushed_aggregates.pdf

[65] A. Di Maria, J. Eyckmans, and K. Van Acker, "Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making," *Waste Manag.,* vol. 75, pp. 3–21, 2018, https://doi.org/10.1016/j.wasman.2018.01.028.

[66] J. Xiao, Z. Cheng, Z. Zhou, and C. Wang, "Structural engineering applications of recycled aggregate concrete: Seismic performance, guidelines, projects and demonstrations," *Case Stud. Constr. Mater.,* vol. 17, 2022, Art. no. e01520, https://doi.org/10.1016/j.cscm.2022.e01520.

[67] R. V. Silva, J. de Brito, and R. K. Dhir, "Availability and processing of recycled aggregates within the construction and demolition supply chain: A review," *J. Clean. Prod.,* vol. 143, pp. 598–614, 2017, https://doi.org/10.1016/j.jclepro.2016.12.070.

[68] J. Penman *et al.,* Eds., "Waste," in *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories,* Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2000. Accessed: Dec. 19, 2021. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/2018/03/5_Waste-1.pdf

[69] A. Levasseur, P. Lesage, M. Margni, and R. Samson, "Biogenic carbon and temporary storage addressed with dynamic life cycle assessment," *J. Ind. Ecol.,* vol. 17, no. 1, pp. 117–128, 2013, https://doi.org/10.1111/j.1530-9290.2012.00503.x.

[70] B. P. Weidema *et al.,* Overview and methodology: Data quality guideline for the ecoinvent database version 3," Swiss Centre for Life Cycle Inventories, St. Gallen, Switzerland, 2013. [Online]. Available: https://lca-net.com/files/Overview_and_methodology.pdf

[71] Y. Zhang, X. Liu, R. Xiao, and Z. Yuan, "Life cycle assessment of cotton t-shirts in China," *Int. J. Life Cycle Assess.,* vol. 20, pp. 994–1004, 2015, https://doi.org/10.1007/s11367-015-0889-4.

[72] A. Q. Jakhrani, A. R. H. Rigit, A.-K. Othman, S. R. Samo, and S. A. Kamboh, "Estimation of carbon footprints from diesel generator emissions," in *2012 International Conference on Green and Ubiquitous Technology,* Jul 7–8, 2012, pp. 78–81, https://doi.org/10.1109/GUT.2012.6344193.

[73] P. T. Anastas and J. B. Zimmerman, "Peer reviewed: Design through the 12 principles of green engineering," *Environ. Sci. Technol.*, vol. 37, no. 5, pp. 94A–101A, 2003, https://doi.org/10.1021/es032373g.

[74] A. Atasu, C. Dumas, and L. N. Van Wassenhove, "The circular business model," *Harvard Business Review,* Jul.–Aug. 2021. [Online]. Available: https://hbr.org/2021/07/the-circular-business-model

[75] S. Pandey, "Wood waste utilization and associated product development from under-utilized low-quality wood and its prospects in Nepal," *SN Appl. Sci.*, vol. 4, p. 168, 2022, https://doi.org/10.1007/s42452-022-05061-5.

[76] A. T. Balasbaneh, W. Sher, and M. H. Wan Ibrahim, "Life cycle assessment and economic analysis of reusable formwork materials considering the circular economy," *Ain Shams Eng. J.,* vol. 15, no. 4, 2024, Art. no. 102585, https://doi.org/10.1016/j.asej.2023.102585.

[77] J. Gualandris, D. Lee, and R. Lin, "Policy-driven innovation in reverse supply chains for post-consumer plastic in packaging and electronic waste." Smart Prosperity Institute, Ottawa, ON, Canada, WP 21-09, Sep. 2021, [Online]. Available: https://institute.smartprosperity.ca/publications/reverse-supply-chains

[78] Environment and Climate Change Canada. "Developing recycled content and labelling rules for plastics." Accessed: May 31, 2024. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/reduce-plastic-waste/recycle-content.html

[79] A. Wicker. "The trendy second-hand clothing market is huge and still growing – yet nobody is turning a profit." BBC.com. Accessed: Jun. 4, 2024. [Online]. Available: https://www.bbc.com/worklife/article/20240301-international-second-hand-clothing-market-profitable

[80] Circular X. "Patagonia – Worn Wear program." Accessed: Jun. 4, 2024. [Online]. Available: https://www.circularx.eu/en/cases/34/patagonia-worn-wear-program

[81] B. P. Weidema, N. Frees, and A.-M. Nielsen, "Marginal production technologies for life cycle inventories," *Int. J. Life Cycle Assess.,* vol. 4, pp. 48–56, 1999, https://doi.org/10.1007/BF02979395.

[82] T. Ekvall, A. Azapagic, G. Finnveden, T. Rydberg, B. P. Weidema, and A. Zamagni, "Attributional and consequential LCA in the ILCD handbook," *Int. J. Life Cycle Assess.,* vol. 21, pp. 293–296, 2016, https://doi.org/10.1007/s11367-015-1026-0.

[83] M. U. Hossain, C. S. Poon, M. Y. K. Wong, and A. Khine, "Techno-environmental feasibility of wood waste derived fuel for cement production," *J. Clean. Prod.,* vol. 230, pp. 663–671, 2019, https://doi.org/10.1016/j.jclepro.2019.05.132.

[84] S. Paunonen, T. Kamppuri, L. Katajainen, C. Hohenthal, P. Heikkilä, and A. Harlin, "Environmental impact of cellulose carbamate fibres from chemically recycled cotton," *J. Clean. Prod.,* vol. 222, pp. 871–881, 2019, https://doi.org/10.1016/j.jclepro.2019.03.063.

[85] ShipTraffic.net. "Sea distance calculator." Accessed: Jan. 2, 2024. [Online]. Available: http://www.shiptraffic.net/2001/05/sea-distances-calculator.html

Appendix A

A.1 Common Information

This section describes common details, interview protocols, nomenclature, and data and assumptions for LCA, across all DMSs from the three sectors.

A.1.1 Interview Protocols

This section summarizes how the interviews were conducted. An internet search and other contacts combined with snowball sampling generated an initial list of organizations and experts deemed relevant for this research project. Overall, 100 organizations[17] were contacted, and interviews were conducted with 14 organizations from the textile sector and 27 organizations from the construction sector. Previous research provided the interview data for 10 organizations from the agrifood sector [5]. Interviews were semi-structured and guided by a prepared interview protocol guided, and each lasted about 30 to 60 minutes. All interviews were conducted via Zoom or Microsoft Teams and recorded when possible. Due to time constraints, some organizations provided information only via email instead of agreeing to an interview. During subsequent follow-ups, some interviewed organizations provided additional information and clarifications via email. The data for the agrifood sector were collected in the same way in previous research [5]. Primary information from the interviews was verified and supplemented with secondary sources, including literature and internal (public and private) documents mentioning the organization and the organization's website and reports.

A.1.2 Organization Coding

The real names of the organizations interviewed were anonymized and represented with a unique alphanumeric ID, which combined a sectoral prefix and two numerical digits. The following unique sectoral prefixes were used for each of the sectors: TXT for the textile sector, CON for the construction sector, and AGR for the agrifood sector. These sectoral prefixes were followed by two numerical digits. For example, the organizations from the textile sector were coded as TXT01, TXT02, and so on. The numerical component of these IDs was assigned largely at random and bears no correlation with the order in which the organizations were contacted or interviewed. It should be noted that some organizations gave consent for their real names to be disclosed in this report.

A.1.3 Common LCA Data and Assumptions

This section describes the data and assumptions that are common across all construction DMSs and associated circular pathways. The following assumptions were made to achieve uniformity and consistency across all DMSs and circular pathways without increasing modelling complexities.

Table A.1.1 summarizes the life cycle GHG emission intensity of several activities. The values are based on the selected processes from the ecoinvent database v3.9.1 (cut-off) [61].

[17] Including individual experts and consultants who were working independently or as a part of an organization.

For each operational stage, datasets were selected based on geographical relevance, and in some instances, modified slightly (such as altering electricity inputs) to enhance accuracy. In terms of geographical scope of unit processes, the ecoinvent database, while extensive, does not cover all geographies comprehensively. Therefore, unit processes (i.e., LCA datasets) were selected to best represent real-world scenarios. For example, datasets for Canada/US operations were chosen following this order of geographical preference:

- Canada/US > European region (RER) > global average (GLO) > rest of the world average (RoW) > India.

Further, a market unit process was preferred over stand-alone unit processes because a market unit process is a weighted average of all production mixes, thereby representing an average production better than an individual unit process.

Land distances, where relevant, were derived from information provided by organizations and verified using Google Maps driving distances. Personal or individual donations, typically transported by small trucks, vans, or cars, were represented in the ecoinvent database as "light, commercial vehicle, freight". Larger-scale land transport involving bulk discards used the largest available truck in the database.

Operational structures were coded to combine sectoral, DMS, and circular pathway identifiers. For example, cotton was coded as CT and polyester as PE. Circular pathways included reuse (RU), mechanical recycling (MR), chemical recycling (CR), incineration (IN), and landfilling (LF), so operational structures for reusing cotton discards were coded as TXT-RU-CT-A/B/C/D.

All non-US imports and exports from Canada were routed through the Port of Montreal and the Deendayal Port in Kandla, India. In cases where there were multiple ports in a country, an average distance was calculated. International shipping distances between ports were determined using an online nautical mile calculator, with the conversion of 1 nautical mile to 1.85 km [85].

All landfilling operational structures were considered as similar irrespective of country. No energy recovery was assumed. All transportation to a landfill or incinerator was done via municipal truck for the first 50 km and in a large truck for the remaining 50 to 200 km, based on previous research [5].

Any recovered materials, as well as the products made from these recovered materials, may differ from corresponding virgin materials or the products made from virgin materials in terms of quality, utility to end users, and end-of-life management. The study indirectly tried to capture some, if not all, of such differences in the quality of recovered materials by varying the quality of recovered materials relative to substituted virgin materials between 60 and 150% depending on the material. While not fully accurate, this approach addressed some of the quality differences between the recovered material and the virgin material, or the differences in the products made from these two types of materials.

Some material can be recovered multiple times in a sequence of recovery cycles. Such material cascading can amplify the environmental costs or benefits of a circular economy [52]. However, to limit the scope of the work, such cascading was excluded from this research.

Table A.1.1: Unit process greenhouse gas emission data based on the ecoinvent database.

Unit Process Name	Region	Functional Unit	Global Warming (kg CO_2e)
market for electricity, low voltage | electricity, low voltage | Cutoff, U	Ontario, Canada	1 kWh	0.07824
market for electricity, low voltage | electricity, low voltage | Cutoff, U	Quebec, Canada	1 kWh	0.02398
market group for electricity, low voltage | electricity, low voltage | Cutoff, U	Canada	1 kWh	0.19144
market group for electricity, low voltage | electricity, low voltage | Cutoff, U	US	1 kWh	0.45566
market for electricity, medium voltage | electricity, medium voltage | Cutoff, U	Ontario, Canada	1 kWh	0.07022
market for electricity, medium voltage | electricity, medium voltage | Cutoff, U	Quebec, Canada	1 kWh	0.0224
market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U	Canada	1 kWh	0.18047
market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U	US	1 kWh	0.44576
market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U	Quebec, Canada	1 MJ	0.06576
market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U	US	1 MJ	0.0285
market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U	Rest of world (RoW)	1 MJ	0.03449
market group for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U	Europe (RER)	1 MJ	0.05038
market for transport, freight, light commercial vehicle | transport, freight, light commercial vehicle | Cutoff, U	Europe (RER)	1 t·km	1.8304
market for transport, freight, lorry 3.5–7.5 metric ton, EURO6 | transport, freight, lorry 3.5–7.5 metric ton, EURO6 | Cutoff, U	Europe (RER)	1 t·km	0.50923
market for transport, freight, lorry 3.5–7.5 metric ton, EURO6 | transport, freight, lorry 3.5–7.5 metric ton, EURO6 | Cutoff, U	Rest of world (RoW)	1 t·km	0.53882
market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, U	Europe (RER)	1 t·km	0.09091
market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, U	Rest of world (RoW)	1 t·km	0.09323

Unit Process Name	Region	Functional Unit	Global Warming (kg CO_2e)
municipal waste collection service by 21 metric ton lorry | municipal waste collection service by 21 metric ton lorry | Cutoff, U	Europe (CH)	1 t·km	1.27054
municipal waste collection service by 21 metric ton lorry | municipal waste collection service by 21 metric ton lorry | Cutoff, U	Rest of world (RoW)	1 t·km	1.28341
market for diesel, burned in building machine | diesel, burned in building machine | Cutoff, U	Global	1 kg	3.93717555
market for transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U	Global	1 t·km	0.00946
market for transport, freight, sea, container ship with reefer, cooling | transport, freight, sea, container ship with reefer, cooling | Cutoff, U	Global	1 t·km	0.02064
market for transport, freight, sea, container ship with reefer, freezing | transport, freight, sea, container ship with reefer, freezing | Cutoff, U	Global	1 t·km	0.01788
market for electricity, medium voltage | electricity, medium voltage | Cutoff, U	Northern India	1 kWh	1.21351
market for electricity, medium voltage | electricity, medium voltage | Cutoff, U	Western India	1 kWh	1.36741
transport, freight train, electric | transport, freight train | Cutoff, U	India	1 t·km	0.04015
transport, freight train, diesel | transport, freight train | Cutoff, U	India	1 t·km	0.0217
market for transport, freight train | transport, freight train | Cutoff, U	US	1 t·km	0.05665
market for transport, freight train | transport, freight train | Cutoff, U	India	1 t·km	0.03359
textile production, cotton, circular knitting | textile, knit cotton | Cutoff, U	India	1 t	9268.14
textile production, cotton, circular knitting | textile, knit cotton | Cutoff, U	Rest of world (RoW)	1 t	7168
textile production, cotton, air jet loom weaving | textile, woven cotton | Cutoff, U	India	1 t	11061.34
textile production, cotton, air jet loom weaving | textile, woven cotton | Cutoff, U	Rest of world (RoW)	1 t	9441
batch dyeing, fibre, cotton | batch dyeing, fibre, cotton | Cutoff, U	India	1 t	3798.36

Unit Process Name	Region	Functional Unit	Global Warming (kg CO_2e)
batch dyeing, fibre, cotton | batch dyeing, fibre, cotton | Cutoff, U	Bangladesh	1 t	450
continuous dyeing, fibre, cotton | continuous dyeing, fibre, cotton | Cutoff, U	Global	1 t	3108.6
finishing, textile, knit cotton | finishing, textile, knit cotton | Cutoff, U	Global	1 t	1429.49
finishing, textile, woven cotton | finishing, textile, woven cotton | Cutoff, U	Global	1 t	579.79
fibre production, cotton, ginning | fibre, cotton | Cutoff, U	India	1 t	7084.79
fibre production, cotton, ginning | fibre, cotton | Cutoff, U	Rest of world (RoW)	1 t	2304.12
polyester fibre production, finished | fibre, polyester | Cutoff, U	India	1 t	3776.7
polyester fibre production, finished | fibre, polyester | Cutoff, U	Rest of world (RoW)	1 t	3779.06
market for electricity, medium voltage | electricity, medium voltage | Cutoff, U	Nordic	1 kWh	0.03417
market for electricity, medium voltage | electricity, medium voltage | Cutoff, U	Mexico	1 kWh	0.59078
treatment of municipal solid waste, sanitary landfill | municipal solid waste | Cutoff, U	Quebec, Canada	1 t	120.96
treatment of municipal solid waste, sanitary landfill | municipal solid waste | Cutoff, U	Global	1 t	118.99
treatment of municipal solid waste, sanitary landfill | municipal solid waste | Cutoff, U	Rest of world (RoW)	1 t	127.02
gravel production, crushed | gravel, crushed | Cutoff, U	Quebec, Canada	1 t	3.76
gravel and sand quarry operation | sand | Cutoff, U	Europe (CH)	1 t	2.17
tissue paper production | tissue paper | Cutoff, U	Europe	1 t	1450.72
tissue paper production | tissue paper | Cutoff, U	Rest of world (RoW)	1 t	1784.05
treatment of inert waste, sanitary landfill | inert waste | Cutoff, U	Europe (CH)	1 t	8.29

Unit Process Name	Region	Functional Unit	Global Warming (kg CO_2e)
treatment of inert waste, inert material landfill | inert waste, for final disposal | Cutoff, U	Europe (CH)	1 t	4.5
treatment of waste plastic, mixture, municipal incineration with fly ash extraction | waste plastic, mixture | Cutoff, U	Europe (CH)	1 t	2349.15
treatment of municipal solid waste, incineration | municipal solid waste | Cutoff, U	Ontario, Canada	1 t	508
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U	Europe	1 t	91.91
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U	Quebec, Canada	1 MJ	0.132
glued laminated timber production, average glue mix | residual wood, dry | Cutoff, U	Quebec, Canada	1 t	7.65774
wood chips production, softwood, at sawmill | wood chips, wet, measured as dry mass | Cutoff, U	Quebec, Canada	1 t	26.48
peat moss production, horticultural use | peat moss | Cutoff, U	Quebec, Canada	1 t	670
market for inorganic nitrogen fertiliser, as N | inorganic nitrogen fertiliser, as N | Cutoff, U	Canada	1 t	3820
market for inorganic potassium fertiliser, as K2O | inorganic potassium fertiliser, as K2O | Cutoff, U	Canada	1 t	760
market for inorganic phosphorus fertiliser, as P2O5 | inorganic phosphorus fertiliser, as P2O5 | Cutoff, U	Canada	1 t	2250

A.2 Interviews Information

A.2.1 Summary of Interviews: Textile Sector

Table A.2.1 summarizes the background details of the organizations from the textile sector that were interviewed for this report. The region lists the primary location of the organization or interviewee. In some cases, a broader region is provided instead of specific country in order to protect anonymity.

Additional details about the organizations' operations are presented in Section A.3.

Table A.2.1: Summary of Interviewed Textile Sector Organizations.

Organization ID	Function	Region	Key Points
TXT01 and TXT06	Charity/ Thrift stores	Canada	Well-known charity organizations engaged in collecting various used items, including textiles, which are then resold through their network of outlets. Textile items that remain unsold are further sold to graders or distributors for export purposes. TXT06 indicated the use of 3.5 to 7 t capacity freight trucks for logistics.
TXT02 and TXT07	Mechanical recycler	Chile and India	Mechanical recycling entities, functioning as shredders, processing a range of textiles, such as used clothing, towels, and bed sheets. TXT07 also receives discards from non-residential actors such as used uniforms or unsold inventory from retail stores. These recyclers are equipped to handle diverse materials like cotton, polyester, and polycotton, transforming them into various threads and products. Except for shredding and spinning, all operations (mainly sorting and grading) are done manually.
TXT03	Chemical recycler	Nordic	A specialized chemical recycler that focuses on processing cotton-based items, particularly denim jeans. This recycler is capable of converting these items into new fibres that they claim match the quality of virgin cotton fibres.
TXT04	Charity	Canada	A notable charity organization that mirrors the activities of TXT01, collecting used textiles and other items for resale, primarily to larger charities such as TXT01.
TXT05	Exporter/ Grader	Canada	An exporter of textile discards that aggregates these items from charities (such as TXT01/TXT06) and various partner organizations (such as those associated with TXT08). The collected textiles are then sorted, graded, and exported for global reuse, reaching countries including Canada, the US, and the UK. Additionally, some of the collected clothing is sold to chemical recyclers (such as TXT03) and mechanical recyclers (similar to TXT07).
TXT08	Facilitator	US	Facilitators specialize in purchasing textile discards from charity organizations, retaining only those made of 100% cotton for mechanical recycling. This facilitator collaborates with TXT05, coordinating the export of these items to India for detailed sorting and grading. The sorted and graded 100% cotton garments are re-exported to Mexico for further mechanical recycling processes.
TXT09	Technology provider	US	A tech company that designs and sells textile sorting technology and devices, including a handheld device/scanner that is capable of identifying and displaying the color and composition of any textile material.
TXT11	Technology provider	Norway	A tech company that designs and sells comprehensive textile sorting systems that comprise a conveyor belt, a sensor, and an air compressor, helping to streamline the sorting process.

Organization ID	Function	Region	Key Points
TXT12	Expert/ Consultant	Indonesia	A sustainability consultant that operates across various countries, who provided insights into the textile recycling industry. According to this consultant, most textile discards undergo downcycling. They also revealed that a mechanical recycling facility in Malaysia imports textile waste from Australia for sorting and shredding, with some of these items being further sold to India and other nations for reuse or downcycling.
TXT13	Chemical recycler	Australia	A chemical recycling company that processes a mix of cotton, polyester, and polycotton materials, handling both pre- and post-consumer textile waste globally. Their process involves shredding and sorting at various locations before the actual recycling takes place at their main facility. Here, mixed textile discards are segregated into cotton and polyester, each undergoing distinct recycling pathways.
TXT14	Chemical recycler	Finland	A chemical recycler that focuses on using 100% cellulosic pulp that is uncontaminated and bleached to white, sourced from various providers to create textile fibres comparable in quality to virgin fibres. While they can use different types of pulp, they prefer textile discards.

A.2.2 Summary of Interviews: Construction Sector

Table A.2.2 summarizes the background details of the organizations from the construction sector that were interviewed for this report. The region lists the primary location of the organization or interviewee.

Additional details about organizations' operations are presented in the subsequent sections.

Table A.2.2: Summary of Interviewed Construction Sector Organizations.

Organization ID	Function	Region	Key Points
CON01	Consultancy and performance testing lab	Ontario, Canada	Organization that tests concrete and other construction materials. It uses hollow polypropylene cylinders to create concrete blocks. Because the cylinders are contaminated after each use, they cannot be reused, and currently, both polypropylene and discarded concrete blocks are landfilled. It is pilot testing reusing or recycling the cylinders for the same application.
CON02	Consultant	Ontario, Canada	Consultant who has worked in the construction industry for years and provided insight on several issues. One is the mixing all DMSs into a common bin, reducing the potential for material recovery. While some transfer stations sort DMSs into different bins, most landfill it. **Wood:** The size of wood pieces is important. Small pieces are incinerated or landfilled, but large pieces have potential for circularity. Wood discards are mixed with other construction discards. Some clean wood is used as mulch or animal bedding, or artistic purposes. **Concrete:** It is used as backfill material or crushed in aggregates. Crushing is done either on-site or off-site. **Plastics:** No end market for plastic discards; mixing makes it harder to recover.

Organization ID	Function	Region	Key Points
CON03	Research and development	Quebec, Canada	Researcher who has conducted research in the construction sector.
CON04	Consultant	British Columbia, Canada	Independent consultant working as an architect. **Wood:** Unclean wood is contaminated with chemicals and other materials. Clean wood may only have nails. It can be reused as prefab blocks or burned as hog fuel. **Concrete:** After recovery of steel, concrete discards are processed either on-site or off-site into backfilling material or aggregates for non-structural applications. Landfilling is also common. **Plastics:** Several sources include vinyl flooring, windows, furniture, and pipes. Huge diversity and many discards are landfilled or burned. Organizations often avoid sharing information.
CON05	Construction contractor/ Process engineer	Quebec, Canada	Manufacturer of kitchen cabinets made from clean wood. Key discard materials include material off-cuts, production losses, and surplus inventory. About 10–15% of input wood is discarded during production. The cabinets have a lifespan of 10 years and are usually landfilled. They cannot be recycled due to the presence of contaminants such as glue and paint.
CON06	Senior sustainability manager in a real estate organization	Ontario, Canada	All discards from construction activities are mixed and hauled to a transfer station; some sorting and diversion occurs, otherwise all discards are landfilled. They prefer buying virgin wood because recovered wood is often unclean and contaminated.
CON07	Climate and sustainability specialist	Ontario, Canada	Construction and infrastructure service provider and project manager. Construction discards occupy significant space on-site, meaning that circularity requires additional cost. Many circularity practices depend on the client's requirements. Typical discards include metals, packaging, and cardboard. Without circularity requirement, most discards are co-mingled and hauled to a transfer station. **Wood:** Most treated wood is landfilled. **Concrete:** Concrete aggregates can only be used as a small proportion of overall aggregates in concrete production Canada. Some crushed concrete is used as backfill. **Plastics:** Most plastic discards are not recycled. Virgin plastics are cheaper.
CON08	Executive of a not-for-profit knowledge and research organization	Ontario, Canada	Recycled concrete aggregate is mainly used as road subbase material.
CON09	Coordinator	Ontario, Canada	Organization that does research on bioeconomy in Ontario. Only clean wood is reused; other wood is used as energy fuel or biochar that may substitute coke/coal in the steel industry, and it may also be used as soil amendment.

Organization ID	Function	Region	Key Points
CON10	Crushing operator	Ontario, Canada	Organization that provides crushing services for concrete and asphalt discards. It takes its equipment to locations, on-site (generation site) or off-site, for crushing. It uses a diesel generator to produce electricity to run machines.
CON11	Transfer station operator/Hauler	Ontario, Canada	Hauler that collects all types of discards and segregates them at its transfer station. **Wood:** Most wood discards are co-mingled with other discards. They segregate wood discards, which are then used as animal bedding, mulch, or fuel. Some wood is grinded to separate nails. **Concrete:** Highly contaminated concrete is landfilled, whereas almost clean or clean concrete is diverted for recycling.
CON12	Aggregate industry association	Ontario, Canada	Association that encourages concrete recycling among its members.
CON14	Biochar manufacturer	Ontario, Canada	Organization that uses wood discards from a variety of sources to produce biochar. The biochar is then used in steel industry as a substitute for coal.
CON15	Manufacturer of construction panels	British Columbia, Canada	Start-up company, conducting experiments and small-scale testing, that makes bio-composite panels using wood chips, lime, and pozzolan. Wood chips already have nails removed.
CON16	Manufacturer of construction materials	Ontario, Canada	Organization that manufactures numerous construction materials from construction discards. **Concrete:** After receiving concrete discards, it does a visual inspection and quality check and rejects discards with higher contamination (>1%). It then crushes discards into aggregates, which substitute virgin aggregates in 1:1 ratio. **Wood:** Clean and unclean wood is burned to meet thermal energy requirements for cement production. 1.5–2 t of wood substitutes 1 t of coal, which is imported from Virginia. **Plastics:** All types of plastics, except PVC, are burned to meet thermal energy requirements for cement production. 1 t of plastics substitutes 1 t of coal, which is imported from Virginia.
CON17	Civil infrastructure contractor	Ontario, Canada	Any concrete or asphalt discards are crushed at off-site locations and turned into aggregates.
CON18	Civil infrastructure contractor	Ontario, Canada	Organization with multiple divisions that uses construction discards. **Concrete:** Concrete and asphalt discards are recycled into aggregates. Due to on-site space constraints, off-site recycled is preferred. Concrete is broken down into smaller pieces to remove rebars before processing. All contaminated fraction is landfilled. **Wood:** Wood is sent to transfer station for energy recovery or other purposes. No wood is landfilled.

Organization ID	Function	Region	Key Points
CON19	Construction/ Sustainability consultancy	British Columbia, Canada	Consultancy for circular built environment. **Wood:** Based on its experience, most wood, clean or unclean, is downcycled. **Plastics:** PVC pipes and packaging are key sources of plastics discards. Some circular pathways are recycling and incinerating.
CON20	Processor of wood discards	British Columbia, Canada	Organization that collects wood from deconstruction organizations involved in recovering wood from large buildings. It avoids wood from the deconstruction of small houses due to diversity and smaller size pieces, leading to more nails and contamination. It manually removes nails and contaminated sections of clean wood but avoids processing wood contaminated with lead, concrete, and so on.
CON21	Crushing operator	Ontario, Canada	Organization that recycles concrete discards into aggregates. It takes its mobile equipment to different dedicated off-site locations. It allows for a maximum contamination of 1% and uses recycled aggregates for non-structural applications.
CON22	Haulers	Calgary, Alberta	Organization that collects discards from different construction sites. **Wood:** Clean wood is any wood other than plywood, and has no contamination, except for nails/metals. At transfer stations, clean wood discards may be repurposed for circularity, but unclean discards are landfilled or incinerated. **Concrete:** Large amount is diverted for circularity and only a small amount, which is contaminated, is landfilled. **Plastics:** All types of plastics are collected and manually sorted before sending to a transfer station. Some unrecyclable plastic is landfilled and some is recycled.
CON23	Research consultancy		Organization that conducts independent studies on circularity. It defines clean wood as wood that only contains nails/metals. Clean wood is reused among other things, whereas unclean wood is landfilled or burned.
CON24	Processor of wood discards	British Columbia, Canada	Organization that uses wood discards from deconstructed units such as film sets. They only process clean wood for health reasons. All nails/metals are manually removed. Manual labour does not use any energy. They claim the quality of their reclaimed wood is better than virgin wood because of more smoothing and processing.
CON25	Tech organization	California, US	Organization that is developing and deploying AI-based automatic nail-removal machines. It accepts clean wood, except plywood because it is a low-value product. Unclean wood creates hazardous conditions with all wood dust, so it is unacceptable.
CON26	Ready-mix concrete manufacturer and crushing operator	British Columbia, Canada	Organization that repurposes its fresh but unused or rejected concrete into aggregates or concrete blocks. It also crushes old concrete discards into aggregates.

A.3 Additional Data

A.3.1 Parameter Values

Table A.3.1 and Table A.3.2 summarize the data that was used for the simulation and regression analysis.

Table A.3.1: Data Used for Simulation of Different Circular Pathways of Different Discarded Material Streams.

Parameter	Remarks	Unit	Min.	Avg.	Max.
Energy Consumption					
Electricity – LowGHG-kWh	Emissions from producing low carbon electricity. Minimum value represents Quebec grid-mix, maximum represents Ontario grid-mix. GHG intensity of Nordic and British Columbia grid-mixes are covered within this range. Parameter was used for simulating all DMSs, except cotton and polyester mechanical recycling. 1 kWh was equal to 3.6 MJ for converting different types of energy consumption to a common unit for calculating GHG intensity.	kg CO_2e/kWh	0.024	0.053	0.082
Electricity – HighGHG-kWh	Emissions from producing high carbon electricity. Minimum value represents Mexico grid-mix, maximum represents India grid-mix. Parameter was used for simulating cotton and polyester mechanical recycling. 1 kWh was equal to 3.6 MJ for converting different types of energy consumption to a common unit for calculating GHG intensity.	kg CO_2e/kWh	0.59	0.9	1.21
Natural gas	Emissions from burning natural gas for heat. Minimum value represents the northeast US, maximum represents Quebec. The same values were used for all DMSs.	kg CO_2e/MJ	0.029	0.0475	0.066
Diesel Burning – kg	Emissions from burning natural gas for heat. Limited variations were noticed and the minimum and maximum values were identical. Values were similar for different countries and the same values were used for all DMSs. 1 kg was equal to 42.5 MJ for converting different types of energy consumption to a common unit for calculating GHG intensity.	kg CO_2e/kg	3.94	3.94	3.94
Transportation					
Light Commercial Vehicle	Limited variations were noticed across different countries, so minimum and maximum values were considered identical. Same values were used for all DMSs.	kg CO_2e/t·km	1.83	1.83	1.83
Small Truck	Limited variations were noticed across different countries, so minimum and maximum values were considered identical. Same values were used for all DMSs.	kg CO_2e/t·km	0.51	0.51	0.51
Large Truck	Limited variations were noticed across different countries, so minimum and maximum values were considered identical. Same values were used for all DMSs.	kg CO_2e/t·km	0.091	0.091	0.091
Rail Transport	Minimum value represents India, maximum represents the US midwest. Same values were used for all DMSs.	kg CO_2e/t·km	0.033	0.0445	0.056

Parameter	Remarks	Unit	Min.	Avg.	Max.
Transportation					
Sea Transport	Limited variations were noticed across different countries, so minimum and maximum values were considered identical. Same values were used for all DMSs.	kg CO_2e/t·km	0.01	0.01	0.01
Waste Collection Truck	Limited variations were noticed across different countries, so minimum and maximum values were considered identical. Same values were used for all DMSs.	kg CO_2e/t·km	1.27	1.27	1.27
Substitution					
Grain Production – Canada	Minimum value represents oats production, maximum represents rye production.	kg CO_2e/t	360	438	594
Carrot – Rest of World	Limited variations were noticed across different countries, so minimum and maximum values were considered identical. Same values were used for all DMSs.	kg CO_2e/t	82	82	82
Cotton Fiber	Minimum value represents rest of world, maximum represents India.	kg CO_2e/t	2304	4694.5	7085
Polyester Fiber	Limited variations were noticed across different countries, so minimum and maximum values were considered identical.	kg CO_2e/t	3778	3778	3778
Clothing Manufacturing	Minimum value represents an average of: (a) Bangladesh batch dyeing and global continuous dyeing; (b) global woven finishing and knit finishing; and (c) rest of world circular knitting and air jet loom weaving. Manufacturing occurred in Bangladesh using only electricity. Impacts of heat energy were ignored. Maximum value represents an average of: (a) India batch dyeing and global continuous dyeing; (b) global woven finishing and knit finishing; and (c) India circular knitting and air jet loom weaving. Manufacturing occurred in India using only electricity. Impacts of heat energy were ignored.	kg CO_2e/t	12 441	14 581	16 721
Peat Moss	Limited variations were noticed across different countries, so minimum and maximum values were considered identical.	kg CO_2e/t	670	670	670
Nitrogen Fertilizer, Inorganic (N)	Limited variations were noticed across different countries, so minimum and maximum values were considered identical.	kg CO_2e/t	3820	3820	3820
Phosphorus Fertilizer, Inorganic (P2O5)	Limited variations were noticed across different countries, so minimum and maximum values were considered identical.	kg CO_2e/t	2250	2250	2250
Potassium Fertilizer, Inorganic (K2O)	Limited variations were noticed across different countries, so the minimum and the maximum values were considered identical.	kg CO_2e/t	760	760	760

Parameter	Remarks	Unit	Min.	Avg.	Max.
Substitution					
Anaerobic Digestion Mix	Anaerobic digestion represents 1 t of agrifood DMSs managed via anaerobic digestion. Minimum value represents a case that substitutes 890 MJ of natural gas and 500 kWh of low carbon electricity. Maximum value represents a case that substitutes 2310 MJ of natural gas. In addition, 1 t of digestate is produced from 1 t of agrifood DMSs and it substitutes each of 2.74 kg (N); 1.31 kg (P2O5); 3.44 kg (K2O) fertilizers.	kg CO_2e/t	84.8037	105.2787	125.7537
Compost Mix	Composting represents 1 t of agrifood DMSs managed via composting. Minimum value represents a case that substitutes fertilizers. Maximum value represents a case that substitutes peat moss. In addition, 1 t of compost substitutes each of 6.55 kg (N); 6.925 kg (P2O5); 18.54 kg (K2O) fertilizers, or substitutes 0.285 t of peat moss, assuming 1 m3 of peat moss = 200 kg.	kg CO_2e/t	54.69265	122.821325	190.95
Wood Materials	Minimum value represents glued laminated timber, maximum represents chipped wood.	kg CO_2e/t	7.76	17.12	26.48
Waste Treatment – Sanitary Landfill	Limited variations were noticed across different countries, so minimum and maximum values were considered identical.	kg CO_2e/t	120	120	120
Aggregate Production	Minimum value represents sand production, maximum represents gravel production in Ontario.	kg CO_2e/t	2.17	3.185	4.2
Tissue Paper Production	Minimum value represents Europe, maximum represents rest of world.	kg CO_2e/t	1450	1617	1784
Heat from Coal Production	Limited variations were noticed across different countries, so minimum and maximum values were considered identical. Heat content of coal was 21 MJ/kg. 0.132 kg CO_2/MJ/kg value from ecoinvent database was multiplied by 21 000 to get the value in tonnes.	kg CO_2e/MJ/t	2772	2772	2772

Table A.3.2: Greenhouse Gas Intensities Used for Different Circular Pathways of Different Discarded Material Streams.

		Low Carbon Intensity (kg CO_2e/MJ)				High Carbon Intensity (kg CO_2e/MJ)				Transport GHG Intensity (kg CO_2e/t·km)			
Sector	**DMS-Pathway**	**Min.**	**Avg.**	**Max.**	**RC**	**Min.**	**Avg.**	**Max.**	**RC**	**Min.**	**Avg.**	**Max.**	**RC**
Agrifood	WG-UC	0.007	0.015	0.023	0.015	—	—	—	—	0.114	0.570	0.827	0.147
Agrifood	WG-AF	0.007	0.015	0.023	0.015	—	—	—	—	1.830	1.830	1.830	1.830
Agrifood	WG-AD	0.007	0.015	0.023	0.015	—	—	—	—	0.091	0.091	0.091	0.091
Agrifood	WG-CP	0.077	0.058	0.055	0.079	—	—	—	—	0.091	0.091	0.091	0.091
Agrifood	FR-UC	0.007	0.015	0.023	0.015	—	—		—	1.134	1.643	1.656	0.543
Agrifood	FR-AF	0.007	0.015	0.023	0.015	—	—	—	—	1.830	1.830	1.830	1.830
Agrifood	FR-AD	0.007	0.015	0.023	0.015	—	—	—	—	0.091	0.091	0.091	0.091
Agrifood	FR-CP	0.077	0.058	0.055	0.079	—	—	—	—	0.091	0.091	0.091	0.091
Textile	CT-RU	0.011	0.017	0.024	0.017	—	—	—	—	0.017	0.021	0.023	0.020
Textile	CT-CR	0.007	0.022	0.033	0.015	—	—	—	—	0.015	0.021	0.026	0.017
Textile	CT-MR					0.163	0.249	0.335	0.249	0.016	0.022	0.025	0.021
Textile	CT-DC	0.008	0.015	0.023	0.015	—	—	—	—	0.024	0.031	0.035	0.031
Textile	PE-RU	0.011	0.017	0.024	0.017	—	—	—	—	0.017	0.021	0.023	0.020
Textile	PE-CR	0.007	0.022	0.033	0.015	—	—	—	—	0.015	0.021	0.026	0.017
Textile	PE-MR					0.163	0.249	0.335	0.249	0.016	0.022	0.025	0.021
Textile	PE-DC	0.008	0.015	0.023	0.015	—	—	—	—	0.024	0.031	0.035	0.031
Construction	WD-RU	0.038	0.016	0.024	0.018	—	—	—	—	0.510	0.475	0.473	0.480
Construction	WD-MA	0.017	0.021	0.028	0.017	—	—	—	—	0.510	0.466	0.461	0.480
Construction	WD-ER	0.017	0.021	0.028	0.021	—	—	—	—	0.510	0.463	0.461	0.480
Construction	CC-RC	0.092	0.088	0.086	0.093	—	—	—	—	0.091	0.091	0.091	0.091
Construction	PT-RU	0.050	0.049	0.049	0.049	—	—	—	—	0.091	0.091	0.091	0.091
Construction	PT-MR	0.093	0.047	0.064	0.047	—	—	—	—	0.091	0.091	0.091	0.091

Note. RC = real case.

A.3.2 System Boundaries

Figure A.3.1: System boundaries for different operational structures of textile reuse. 'A', 'B', and 'C' indicate alternative operational structures for managing three textile DMSs via reusing. 'US' indicates the US side of operations, and the 'yellow' boxes connect the US part of the operational structures to the Canadian side of operations. TXT05 informed that India did not allow resale of imported used clothing and all textile items must be decommissioned. Therefore, while the operational structure 'B' may not represent India, it represents many international reuse operations in similar developing countries.textile reuse.

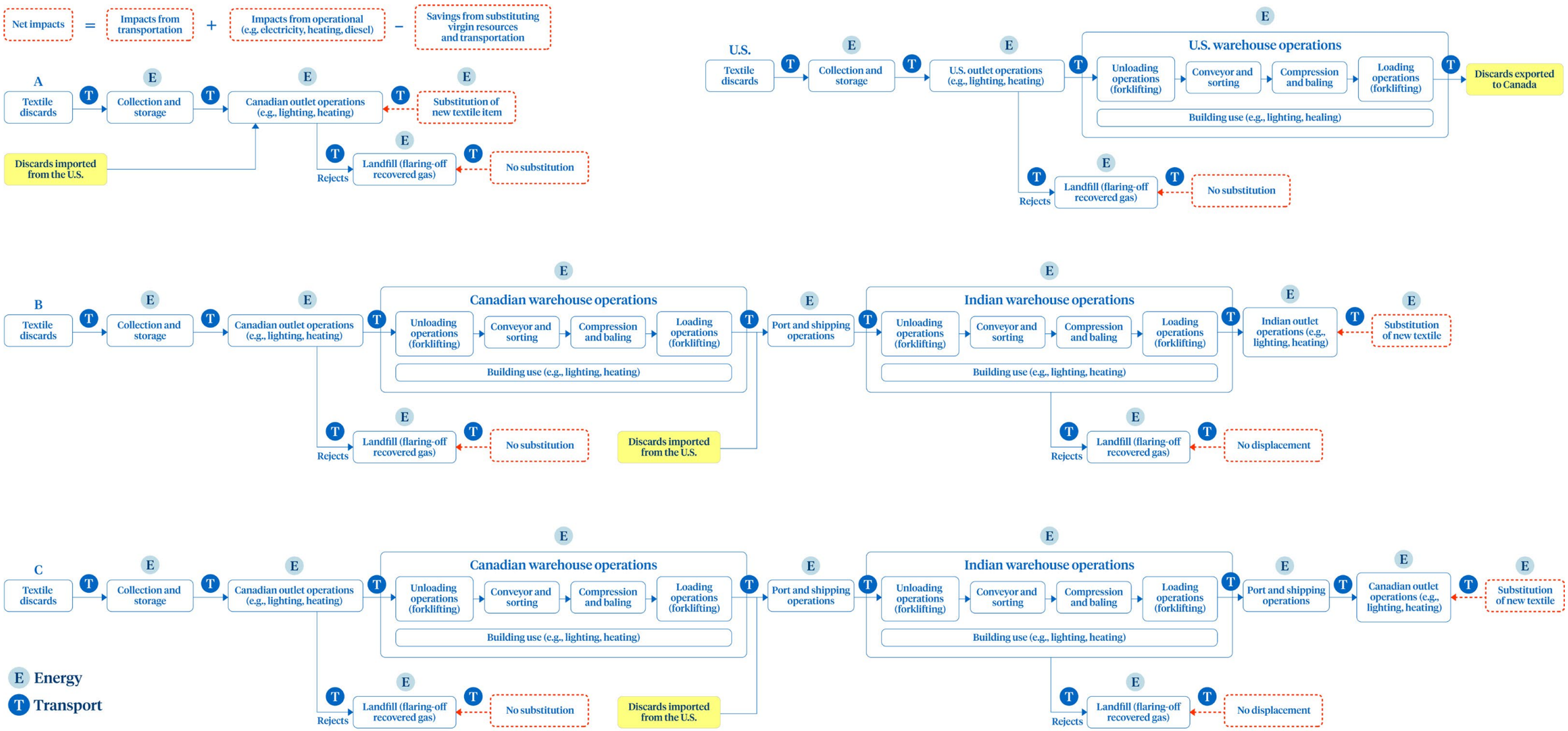


Figure A.3.2: System boundaries for different operational structures of chemical recycling of textile. 'A' and 'B' indicate alternative operational structures for managing three textile DMSs via chemical recycling. 'US' indicates the US side of operations, and the 'yellow' boxes connect the US part of the operational structures to the Canadian side of operations.

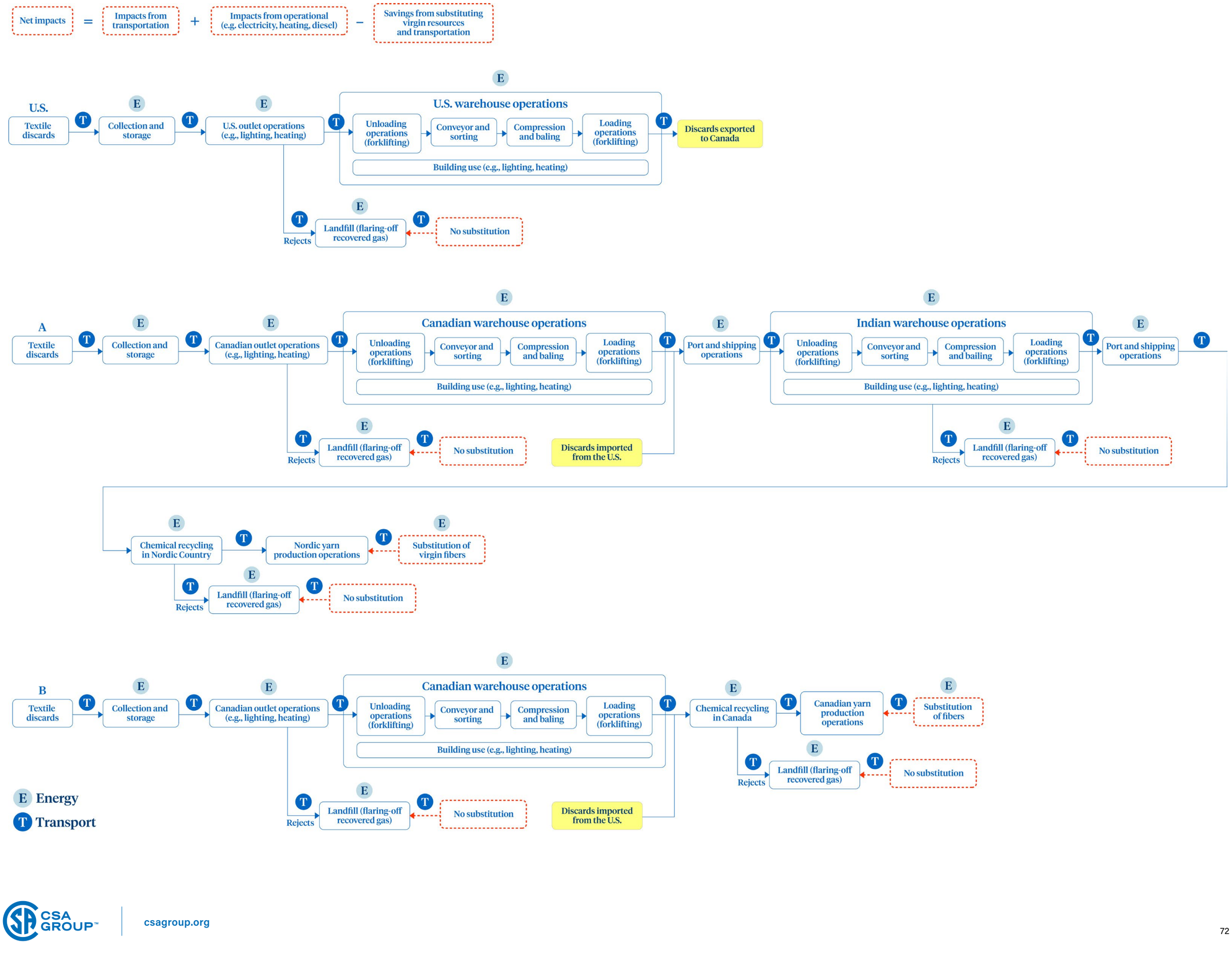


Figure A.3.3: System boundaries for different operational structures of mechanical recycling of textile. 'A', 'B', and 'C' indicate alternative operational structures for managing three textile DMSs via mechanical recycling. 'US' indicates the US side of operations, and the 'yellow' boxes connect the US part of the operational structures to the Canadian side of operations.

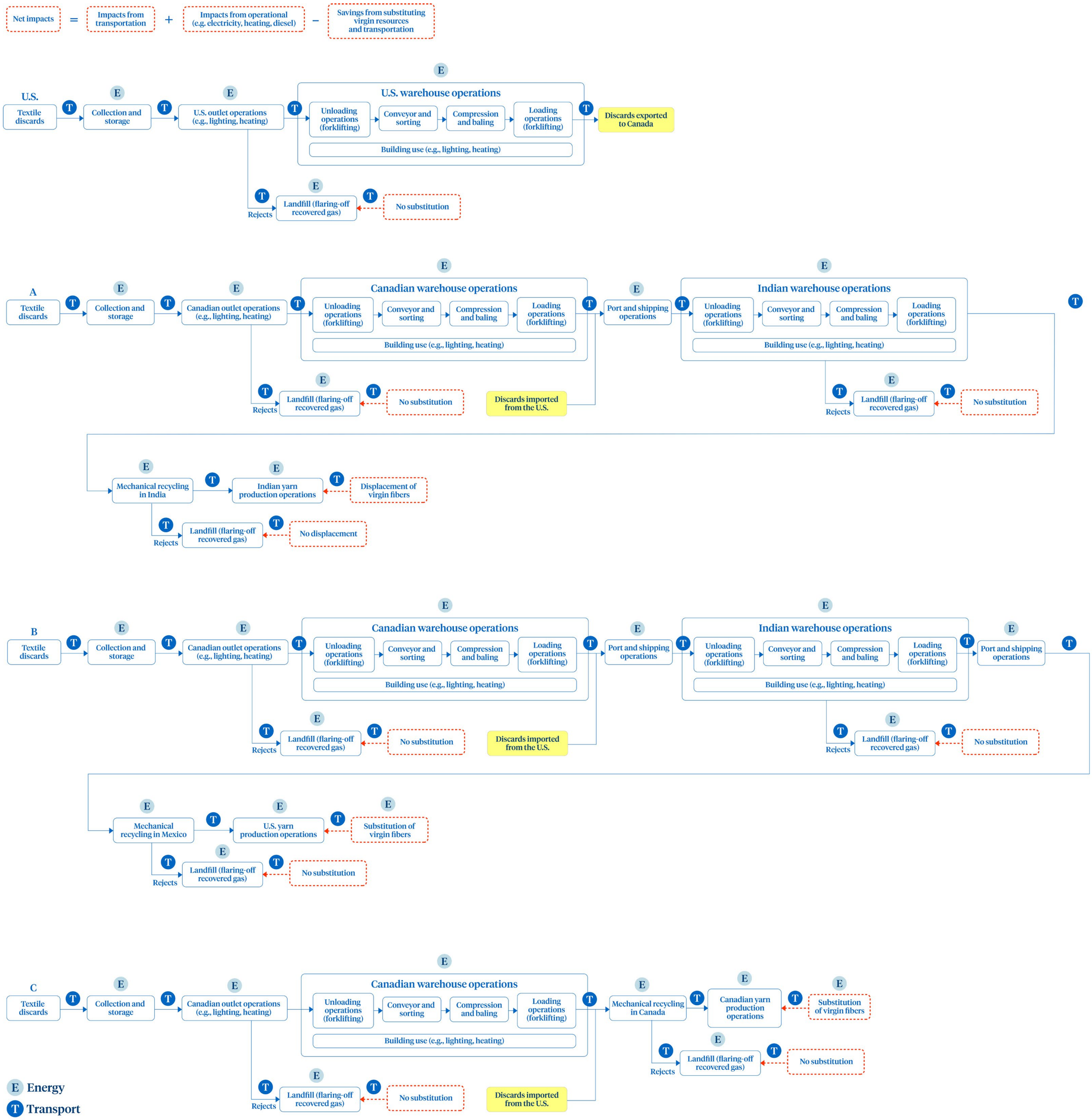
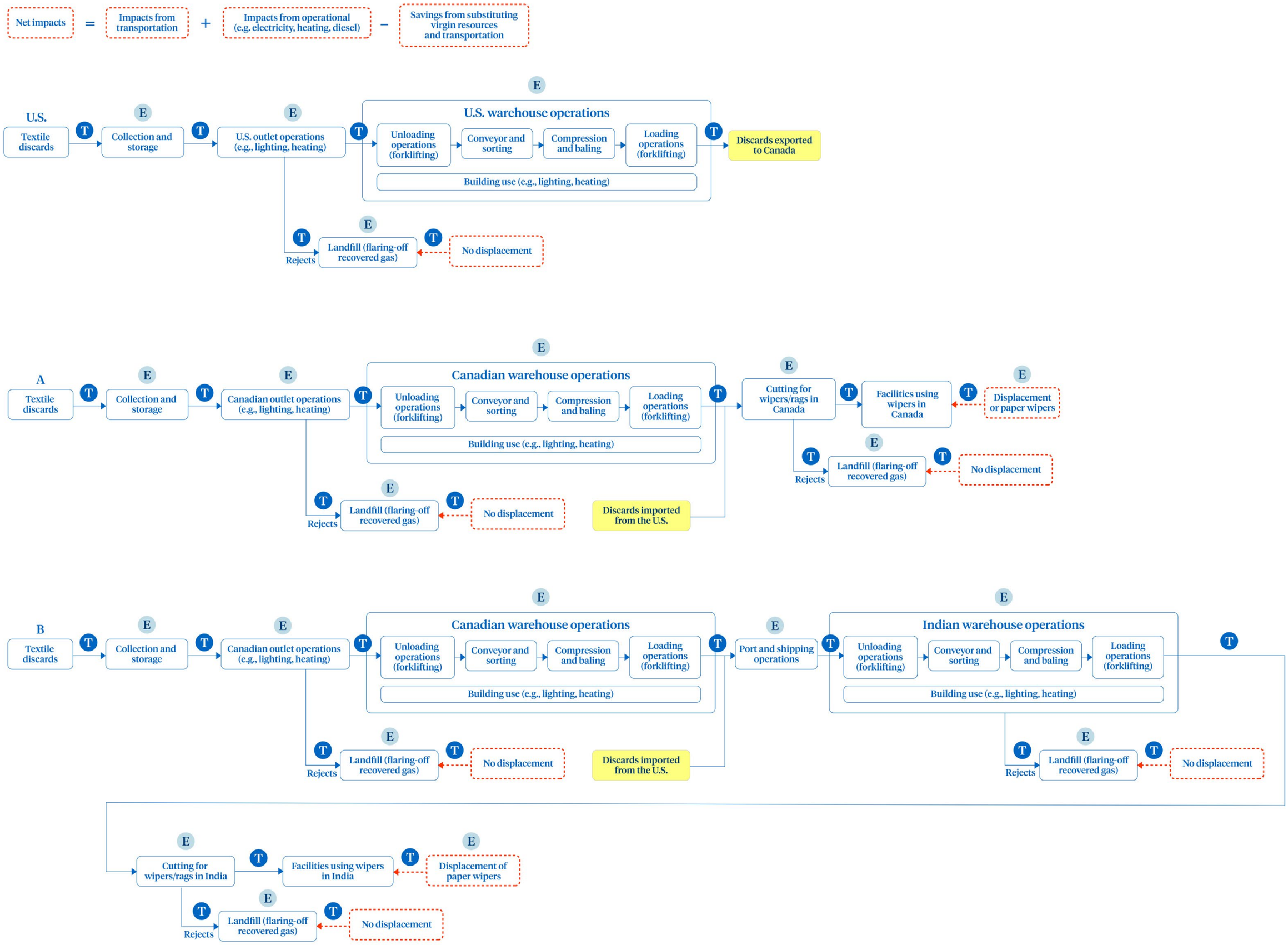


Figure A.3.4: System boundaries for different operational structures of downcycling of textile. 'A' and 'B' indicate alternative operational structures for managing cotton textile DMS via downcycling. 'US' indicates the US side of operations, and the 'yellow' boxes connect the US part of the operational structures to the Canadian side of operations.



CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

CSA GROUP™

© 2024 Canadian Standards Association. All Rights Reserved.