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Full length article

The convenience economy: Product flows and GHG emissions of returned apparel in the EU

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ABSTRACT

Each year, consumers return billions of new products to retailers. Despite growing concern over product destruction, post-return product flows are not well understood, and the full lifecycle environmental impacts of returns remain largely unknown. Building on a unique dataset covering over 630k returned apparel items in the EU, we map the flow of returned products under sustainable and conventional management practices, and quantify the full lifecycle impacts associated with returns using two illustrative apparel case studies. We find that 22%-44% of returned products never reach another consumer. Moreover, the GHG emissions associated with the production and distribution of unused returns can be 2–16 times higher than all post-return transport, packaging, and processing emissions combined. Our findings suggest that the environmental impacts eCommerce and specifically online apparel, may be systematically underestimated when returns are not accounted for, and highlight the urgent need to promote circular management practices that maximize use of returned products.

1. Introduction

Consumer returns (new products returned to sellers shortly after their purchase) are a pervasive aspect of retail, and eCommerce in particular. stimates suggest that annual consumer return management costs amount to €5.5b for Germany and £60b in the UK (Bamberg University, 2019; Garland, 2022; Parkin, 2020).

Consumer returns (hereafter referred to as ‘returns’), are a particularly thorny issue for eCommerce (Buldeo Rai et al., 2023; KPMG, 2017; Tian and Sarkis, 2021), where on average 20–30% of products are reportedly returned compared to only 10% of products sold through brick and mortar (Jack et al., 2019; Reagan, 2019; Velazquez and Chankov, 2019). Such high return rates result in part from the greater uncertainty inherent to online shopping as consumers cannot touch, feel, or try products before purchase (Abdulla et al., 2019; Nestler et al., 2021). In fashion – the leading eCommerce category with over $871 billion in sales in 2023 – uncertainty is further exacerbated by sizing inconsistencies across brands and countries (e.g., the use of different shoe sizing systems; Nestler et al., 2021). As a consequence, fashion has exceptionally high return rates, and some sources suggest that more than half of fashion items bought online are returned (Statista Research Department, 2023).

To ease purchase uncertainty, eCommerce sellers traditionally offer free, almost frictionless returns (Abdulla et al., 2019). Although a few large brands recently shortened the return window or started charging ‘restocking fees’, many still offer lenient return policies which allow consumers to ‘over -order’ knowing they can return any product that is not a perfect fit (Narvar, 2018; Orendorff, 2019). The practice of over-ordering (also referred to as bracketing) is further normalized by programs such as Amazon’s ‘Try before you buy’, which convey the message that returns have no negative repercussions (Abdulla et al., 2019; Janakiraman et al., 2016; Ketzenberg et al., 2020; Moore, 2016; Narvar, 2018). The share of fashion eCommerce has grown substantially, and given predictions that it will continue to be expanding (Cassetti, 2022) the challenges associated with high return rates are likely to only grow in scale.

While many consumers view return policies as a key factor in their purchase decisions (Orendorff, 2019) few seem to realize that returned items do not necessarily go back to the shelf (Optoro, 2023). Instead, retailers must first go through an expensive process of sorting, checking and often cleaning, repairing, and repackaging products. Since many returns can only be sold at a discount, some are discarded or destroyed without ever being used (Corkery, 2022; Frei, Jack, and Krzyzaniak, 2020; Roberts et al., 2023). Despite growing interest in the

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environmental impacts of (fast) fashion, research on the Greenhouse Gas (GHG) emissions associated with returns is scarce, and their full lifecycle impact remain poorly understood.

1.1. What happens to returned products

Returned products are by nature heterogeneous in quality, size, and seasonal compatibility. This leads to additional processing and logistical complexity compared to forward logistics (between factory gate and 1st consumer), and added costs that retiles are only now starting to consider (Zhang, 2023). According to industry reports, processing a return can cost retailers up to two-thirds of an item's original price (Salerno, and Maguire, 2022). The high costs of managing returns can be especially challenging in cheaper product categories, such as fast fashion, where one brand reportedly spent $530 million on returns from sales worth $500 million (Robertson et al., 2020). As a result, retailers often prefer to cut their losses, and donate, recycle, or simply dispose of returned products altogether (Constable, 2019; Corkery, 2022; Optoro, 2023; Reagan, 2019; Sanicola, 2017). In some cases, sellers issue the refund but let consumers keep the products to avoid the shipping costs (Cerullo, 2023; Reuter, 2024).

A recent report estimates that 4.3 billion kg of returned goods were landfilled in the US during 2022 (Optoro, 2023). This report and others suggest that the environmental impacts of returns extend well beyond post-return packaging and transport (Constable, 2019; Corkery, 2022; Sanicola, 2017). As such, they highlight the need to account for the squandered materials and energy invested in the production and distribution of returned products that ultimately go unused. The issue of returns is related to overstock (i.e., new, unsold products) which are common in fashion, an industry notorious for short product lifetimes and high environmental impacts (Nguyen et al., 2023; Niinimäki et al., 2020; Raz et al., 2013). The study of overstock fate is fairly limited and relevant in the context of our study as many returns eventually become overstock.

1.2. Environmental impacts of consumer returns

While returns in general are well studied (Abdulla et al., 2019; Frei, Jack, and Krzyzaniak, 2020; Su, 2009), surprisingly little work has examined their full lifecycle environmental impacts (Tian and Sarkis, 2021). Past work has explored the environmental impacts associated with Closed Loop Supply Chains (CLSC) and Reverse Logistics (RL) operations used to retrieve products from consumers (Abdulla et al., 2019; Frei, Jack, and Brown, 2020; Su, 2009). However, the RL literature mostly deals with used items at the end of their service life and not brand-new products. Other strands of literature center on issues such as the financial implications of product returns, return fraud, consumer behavior, and methods and technologies (e.g., virtual fitting rooms of alternative product photos) that could potentially reduce return rates (Chen et al., 2023; Ketzenberg et al., 2020; von Zahn et al., 2022).

A growing body of work examines the environmental impacts of eCommerce (Astashkina et al., 2019; Carling et al., 2015; Edwards et al., 2010; Jaller and Pahwa, 2020; Pålsson et al., 2017; Shahmohammadi et al., 2020; Wiese et al., 2012). With some notable exceptions (see for example Shahmohammadi, 2020), most studies find that eCommerce has lower environmental impacts than traditional shopping. eCommerce can reduce the need for energy and material intensive store fronts and lower the emissions associated with the last mile/km (i.e., the segment between consumer home and the post office/drop off location), although this depends on consumer behavior as well as the rate of failed or mistaken deliveries. For a comprehensive, recent review on the environmental impacts of eCommerce vs. brick and mortar see Buldeo Rai et al., 2023.

Notably however, most studies on the environmental impacts of eCommerce only consider impacts incurred between factory gate and 1st consumer (i.e., forward logistics, see Fig. 1) leaving returns outside of the system boundaries (Astashkina et al., 2019; Carling et al., 2015; Jaller and Pahwa, 2020; Shahmohammadi et al., 2020). Moreover, the studies which do consider returns typically adopt the simplification that all returned products are directly reintegrated into the sales funnel and therefore only include impacts associated with shipping items back to sellers (Buldeo Rai et al., 2023; Edwards et al., 2010; Pålsson et al., 2017; Wiese et al., 2012). This assumption however, stands in contrast to industry and media reports which indicate that many returns are not resold, but diverted to incineration, recycling, or landfills. As a result, the full lifecycle environmental impacts of product returns and eCommerce more broadly, remain poorly understood and are likely underestimated (Buldeo Rai et al., 2023; Pålsson et al., 2017).

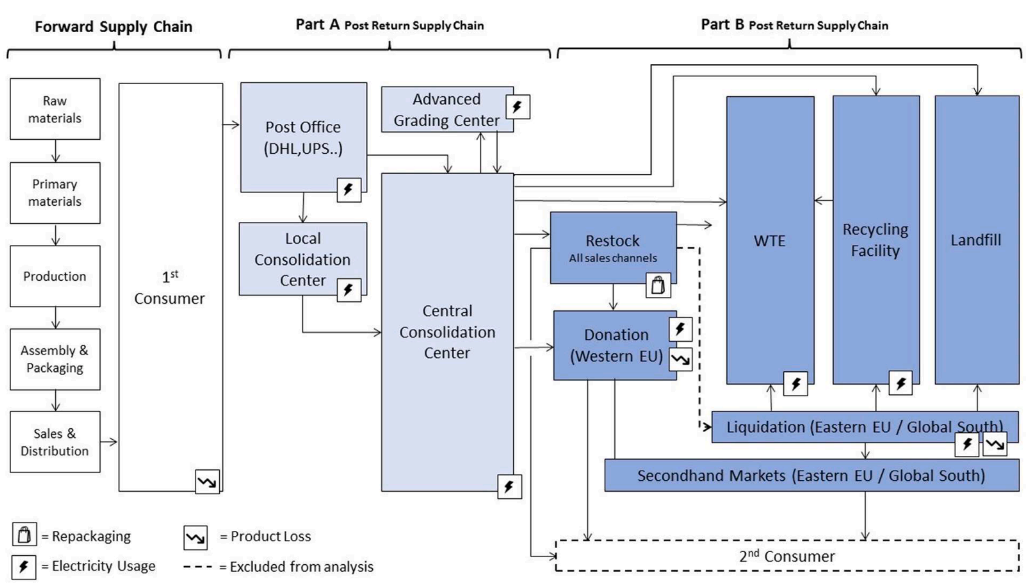

Fig. 1. System Boundaries Illustration. System boundaries of most research on returns to date (white); focus and system boundaries for current analysis (part A and part B of the post-return supply chain (in light blueand dark blue respectively). Dotted lines represent flows or stages that were considered beyond the scope of the current study. Icons represent stages that include repackaging, electricity usage and product loss. Note that in this work all retailer owned sale channels, including outlets, auctions and clearance, were considered as sale from restock.

This knowledge gap makes it challenging for policy makers, consumers, and advocacy groups to properly assess the full scope of environmental impacts associated with e-retail. In addition, current methods may limit retailers' ability to assess the potential environmental implications of different management practices, and overemphasize the importance of post-return transport or packaging for sustainable returns. Here we address this gap and examine the full lifecycle GHG emissions associated with apparel returns in the EU, building on a unique dataset provided by industry partners.

2. Material and methods

We used a multi-disciplinary approach to map the flows of returned products and assess the full lifecycle GHG emissions associated with the return of apparel in the EU. Building on a unique dataset, covering roughly 630k apparel items returned to large brands in the EU during 2021, we began by mapping the full post-return supply chain from the 1st consumer's home to product's final destination - a second consumer or end of life (i.e., recycling, incineration, landfill).

Next, to quantify post-return product flows and explore what affects the number of products diverted to end of life, we constructed two scenarios which reflect sustainable and conventional returns management practices. Where needed, we augmented the main dataset with empirical data on returned products grading (provided by a sustainability-oriented retailer included in the main dataset), academic and gray literature, and recent newspaper articles. To validate our assumptions and fill in reaming gaps, we conducted over a dozen interviews with industry experts in the EU and US (see SI 1 Section 1).

To illustrate the full lifecycle environmental impacts of apparel returns under each management scenario, we then assumed that all 630k returned products are either a cotton T-shirt or a ski jacket and used Life Cycle Assessment (LCA) to model the GHG emissions associated with each return management scenario. The T-shirt and ski jacket, were prevalent products in the main dataset and represent two of the most common raw materials in apparel (Ellen MacArthur Foundation, 2017). They were chosen as case studies to showcase how differences in material composition and product weight could affect the environmental impacts of apparel returns.

We estimated the GHG emissions associated with the production and distribution of each product (i.e., from cradle to 1st consumer, which we refer to as embodied emissions), as well as emissions associated with their recycling or incineration in Waste to Energy (WTE) facilities. We then estimated GHG associated with all post-return activities, including transport, processing, and packaging. Finally, we compared overall post-return emissions with the squandered embodied emissions invested in the production and distribution of returned products that were lost or reached end of life unused. A detailed description of each step is presented in the sections below.

2.1. Mapping the post-return supply chain

We began by mapping a typical EU post-return supply-chain, focusing on two parts:

1) Part A – post-return stages under the direct control of the retailer and/or its third-party reverse logistics contractor (e.g., consolidation centers, restock warehouses).
2) Part B – stages further down the supply chain beyond the control of the retailer or its subcontractors (e.g., donation outlets, recycling facilities).

Part A of the post-return supply chain was modeled based on the dataset, which included records for over 630k unique parcels containing clothing, shoes and accessories returned to several large retailers in the EU between April – December 2021. For each item, the dataset provided by ReBound Returns (www.reboundreturns.com) included a unique identifier as well as timestamps, and all facility locations, which we used to map the nodes along Part A of the post-return supply chain (from the returning consumer's postal code thought local and central return center etc.). Due to European General Data Protection regulations (GDPR), the dataset did not include details on specific product types nor their material composition.

Part B of the post-return supply chain was not covered in the main dataset. Therefore, we mainly relied on insights from previous academic work, gray literature, and industry reports to map out downstream stages such as donation outlets, recycling facilities, and incineration. To validate the product flows estimations, we conducted a series of semi-structured interviews with industry experts (for details see SI 1 Section 1). The reverse supply chain is much more complicated and includes various retailer sale channels as well as secondary markets for new unsold products. For simplification we focused on the main product flow stages.

2.2. Product flows by scenario

To explore the effects of different return management practices, we constructed two scenarios that reflect sustainable and conventional return management practices as detailed below (for more see SI 2).

2.2.1. Sustainable return management scenario

The sustainable return management practices scenario was modeled after the operations of a sustainability-oriented EU based retailer, included in the dataset. The retailer specializes in casual clothing, sports and outdoor sporting apparel. In efforts to increase product restock rates, the retailer sends all returns to an advanced grading facility, where trained personnel not only inspected products for quality, but can also apply minor repairs (e.g., removing a light stain or attaching a new tag). Based on the retailer's data, 90% of all returned products are restocked after advanced grading. Of the remaining products that are not restocked, we assume that 1 % are sent to incineration and the rest are evenly split between recycling and donations.

While returned products might be season-sensitive or in slightly used condition, in the sustainable scenario we conservatively assumed that restocked returns are equivalent to new products and thus just as likely to be sold. Hence, we assumed that 75% of restocked returns are resold (at full or discounted prices; Malka, 2023) while the rest, become overstock. Of these 3% are incinerated in co-generation waste to energy facilities (3%; Ellen MacArthur Foundation, 2017), while the rest are donated or sold off to liquidators. Whilw the allocation between donation and liquidation likely varies depending on seasonality and market prices, we found not data points to inform allocation at this stage. Given our interest in environmental (rather than economic) implications, we made a simplified assumption that all unsold products from restock are first donated (and could go on to liquidation from there). Finally, although our partners at ReBound Returns reported nearly no loss along Part A of the reverse logistics supply chain, to be conservative we applied a general loss factor of 1% (e.g., lost in warehouse or fell from a truck).

In part B of the supply chain, where products are no longer under the direct control of the retailer and flows were therefore less documented, the following assumptions were employed:

i. Donation (Western Europe) - Of all donated products, 25% are sold/given to secondary consumers in western Europe (Chiu, 2023; Doughton, 2021; Watson et al., 2016). Although some suggest that only 10% of donated items are resold in western/northern EU (Watson et al., 2016), others suggest 30% (Chiu, 2023). Since returns are in better condition than the typical used item, in line with experts interviews we chose a higher range value. As for the remaining products that were not resold/handed out by the charities (75% of donated), we assumed 5% are lost (general loss factor), and the rest (70%) are sent to EU liquidation

(Watson et al., 2016). Though some products are likely passed on directly to charities and liquidators in the global south, for simplicity we assume that these go through local EU liquidators first as this path would be more profitable for charities.

ii. Liquidation (Eastern Europe) –of all liquidated products, 50% go to secondhand markets in Eastern Europe (Watson et al., 2016; where a quarter are then resold, as assumed for Western Europe), 8% are sent to WTE, 3% are recycled locally and 34% are sold on to liquidators in the global south for resell or manual recycling (Watson et al., 2016). 5% of items sent to liquidation are lost along the way.

iii. Resell (Global South) – the fate of EU clothing exported to the global south is highly uncertain. We assumed 50% are sent directly to manual recycling facilities, 45% go to secondhand markets (Watson et al., 2016), and 5% are lost. Of all products sent to secondhand markets, we assume 40% are landfilled (Manieson and Ferrero-Regis, 2022), while 60 % are sold to secondary consumers.

End of life

iv. Recycling in the EU (Western & Eastern) – We assume 30% of items sent to recycling facilities cannot be mechanically recycled for technical reasons and are therefore sent to incineration. The rest (70% of items sent to recycling) are recycled into spinnable fibers and fluff. Following the best case technical feasibility scenarios presented in Duhoux et al. (2021), we assumed that 20% of T-shirts and 55% of mixed polyester ski jackets (by mass) are recycled into spinnable fiber and displace an equal amount of virgin fiber production. The rest become fluff- a common by-product whose use does not lead to avoided production. To simplify the calculation, we convert spinnable fiber and fluff mass into the respective number of products. Importantly, we use the best-case scenario as returns are mostly unused items which can be generally classified as pre-consumer textiles. Pre-consumer textiles tend to be cleaner and in better condition than post-consumer textiles and thus have higher recycling rates in practice (Huygens et al., 2023). Nonetheless, these assumptions should be considered conservative in terms of emissions magnitude as factors other than technical feasibility (e.g. contamination) are known to affect textile recycling (Huygens et al., 2023; Moazzem et al., 2021).

v. Incineration with energy recovery (WTE) –we conservatively assume that all discarded products in the EU are sent to incineration, where 50% are incinerated in practice while the remaining 50%, deemed unfit for incineration, are then sent to landfills (Huygens et al., 2023). In addition, we assume that the heat and electricity generated in the incineration process lead to avoided production of electricity and heat in a natural gas co-generation plant, with a thermal content efficiency conversion rate of 40% for heat and 15% for electricity (Huygens et al., 2023).

vi. Landfill- landfill processing emissions for natural fibers (cotton T-shirt) and synthetic fibers (ski-jacket) are adapted from Moazzem et al. (2021). Given large uncertinties and variance between facilities, textile degredation as well as processes such as landfill gas capture are considered beyond the socpe of this analysis.

vii. Recycling (Global South) – we assumed all products that reach recycling in Global South are manually recycled (i.e., downcycled into rags; Watson et al., 2016).

viii. Loss- As the end of life management of lost products remains unknown, these emissions are considered beyond the scope of the current analysis. However, results assuming all lost items are landfilled are presented in the SI to confirm they do not meaningfully affect our findings (see SI- Table 6 and 7).

2.1.2. Conventional returns management scenario

The same assumptions used in the sustainable management scenario were applied to the conventional management scenario, with three important exceptions. First, advanced grading (and specifically light cleaning or repair) is not a common practice in management of apparel returns since it is costly and time consuming for retailers. Therefore, we assumed that under conventional management practices returned products only undergo basic inspection in consolidation centers. Second, absent cleaning and light repair capabilities, we assume that only 70% of returned products are restocked (vs. 90% in the sustainable scenario). Cassetti (2022) indicated that, on average, 74% of returns in Belgium are restocked and resold. Considering that this average includes sustainable brands, we view 70 % as a conservative assumption. Third, we assumed that due to issues such as collection and seasonal compatibility, returned products would have lower resell rates than new items. Hence, under conventional management practices, we assume that only 50% of returned items (vs. 75% in the sustainable scenario) are sold after restock (Tait, 2023;KPMG, 2017). For more details on flow assumptions please see SI 2.

2.3. GHG emissions estimate

Due to privacy concerns, the specific composition of returned items included in the main dataset was unavailable. Therefor, to illustrate the environmental impacts of product returns under sustainable and conventional return management practices, we built on the results of the product flow analysis (Fig. 2) and calculate associated emissions under a simplistic assumption that all 630k returned products are either a 250 *g* 100% cotton T-shirt or an 815 *g* mixed polyester ski jacket. These specific items were chosen for several reasons. First, they were two common products included in our main dataset. Second, they allowed us to explore how differences in product weight and material composition could potentially affect overall emissions under the two management scenarios, as well as the balance between embodied and post-return emissions. Variance in product flows (e.g., return rates or resell rates) based on product type, color, or materials was considered beyond the scope of the current study (see more under limitations).

We report on CO_2-eq emissions (GWP100), using the ReCiPe Midpoint V1.13(H) life cycle impact assessment method (Huijbregts et al., 2017). Unless stated differently, our data source is ecoinvent 3.8 with the cut-off APOS model. The mean as well as the 5th and 95th percentiles of CO_2-eq emissions for both embodied and post-return were calculated using python-based Monte Carlo, where we randomly sampled the GHG emissions factors for electricity, packaging, EoL management, and transport from their respective distributions, and multiplied them by the corresponding unit counts, mass, or mass-distance for each stage.. We then summed up all emissions, and repeated this procedure 10^5 times. A detailed account of preliminary stages used to estimate emissions in each stage and overall is provided below.

2.3.1. Total post-return ghg emissions

Total post-return GHG emissions per scenario (s) and product (p) are given in Eq. (1):

$$E_{post-return}(s,p) = E_{trasnport}(s,p) + E_{processing}(s) + \ E_{packaging}(s,p) + \ E_{EoL}(s,p) \tag{1}$$

Where $E_{post-return}$ is the total GHG emissions associated with the post-return supply chain under returns management scenario (s) per product (p); $E_{transport}$ is the GHG emissions associated with transport post-return (from 1st consumer to final destination); $E_{proccesing}$ is the GHG emissions associated with the electricity used for processing along the reverse supply chain (sorting, inspecting, and grading); $E_{packaging}$ represents GHG emissions associated with re-packaging products that are restocked; and E_{EoL} is net GHG emissions associated with EoL treatment of products sent to recycling or incineration in WTE facilities.

An overview of of post-return GHG emissions factors per stage is presented in Table 1 and additional details are available details are

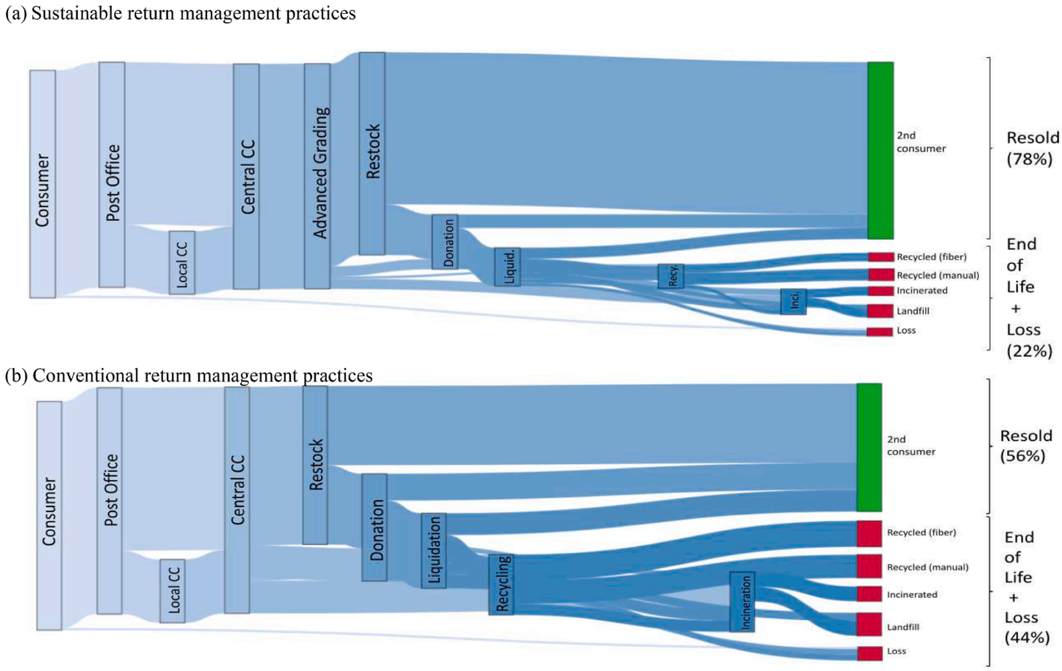

Fig. 2. Simplified product flows by scenario. The width of the flow is proportional to the share of products that pass through the different post-return pathways. Panel (a) Sustainable return management practices. Under this scenario all products are sent to advanced grading after which 90% return to stock where 75% are resold. Panel (b) Conventional return management practices. Under this scenario no products are sent to advanced grading**.** 70% of products go back to stock where 50% are then sold.

available in SI Table 2.

2.3.2. *Transport*

The GHG emissions of transport ($E_{transport}$) is given in the following Eq. (2):

$$E_{transport}(s,p) = \sum_{segment,\ i=1}^{20} D_i \times E_{kg\times km,\ i} \times N_i(s) \ \times W(p) \tag{2}$$

Where $E_{transport}$ is the GHG emissions associated with transport in the post-return supply chain under returns management scenario (s) per product (p); D is the distance travelled by returned products per segment (i); $E_{kg\times km}$ is the GHG emissions associated with segment i's respective transport mode (kg × km); N_i is the number of returned products transported per segment (i) under each scenario (s); and W is the weight per unit of product (p).

We mapped 20 unique travel segments distances (D) between post-return stages. Where possible, segment distances were based on locations noted in the main dataset from our industry partners. For locations beyond the supply chain stages included in the dataset (e.g., donation and liquidation) we built on existing literature or generated region-specific estimates via the Google Maps API (for details see SI 1 segment 3). We then assumed that each segment was normally distributed with a SD of 10% of the mean distance.

Each segment was assigned a specific CO_2-eq intensity ($E_{kg\times km}$), based on mode of transport. The emission intensities and their respective distributions per kg × km were modeled using a weighted average constructed according to the relative prevalence of each transport mode in the respective EU fleet (See Table 1).

For the 1st mile (from consumer to logistics carrier), we assumed that 90% of returned products are dropped off by consumers (e.g., at a post office, locker boxes) via car (70%) or on foot/bike (30%; Buldeo Rai, 2019). For the remaining 10% we assume a van collected products from consumers' homes. Thes assumptions were validated by ReBound Returns but may vary in other geographies where collection from home might be more common. For carbon emissions from passenger cars, the weight of transported products per vehicle is generally considered negligible. Therefore emissions were derived based on distance driven alone. As most consumers do not drive their car solely to return items, total car emissions were divided by 4 to account for multiple purpose trips (see Table 1;Feichtinger and Gronalt, 2021), under the assumption that each returned parcel contains a single product.

Past the 1st mile, all road transport was assumed to be carried out via truck, with the exception of the segment between the local post office and local or central consolidation centers, where products were partially transported via van (based on our industry partners' insights, see SI 2).

For international shipping to the Global South, we assumed travel by truck to the nearest port in Eastern Europe, sea freight via container ship, and an additional truck ride from destination port to sorting facilities (see SI 1 Section 3). We did not model the distribution of GHG emissions for the container ship as an internal sensitivity analysis showed that this has little impact on results. Similarly, we used the European truck CO_2-eq emission intensity for all truck segments, including those in the Global South.

2.3.3. *Processing*

Calculation of GHG emission associated with processing ($E_{processing}$) is given in Eq. (3):

$$E_{processing}(s) = \sum_{segment,\ i=1}^{20} E_{electricity,i} \times N_i(s) \tag{3}$$

Where $E_{electricity}$ stands for the GHG emissions associated with the processing electricity under returns management scenario (s) per product in each segment (i.e., stage) i, and N_i - for the number of returned products processed per stage.

We estimated electricity consumption for relevant post-return stages (i.e., sorting, grading, donations, liquidation) based on information provided by our industry partners (per product, and per facility). We assume a product undergoes processing at the post office, either the local or the main consolidation center, and at advanced grading, donation, recycling, incineration, and liquidation facilities (see Fig 1). As our

Table 1
GHG emission factors per stage.

	Process	Unit	kg CO_2-eq (GWP 100)	Source	Comments
Embodied Emissions	T-shirt Production & Distribution	250 *g* T-shirt	3.040800 (SD = 5%)	ecoinvent v3.8	100% cotton T-shirt (bleached, knitted cotton, shirt produced in Bangladesh), includes unit packaging (5 *g* virgin plastic polybag) and transport from factory to 1st EU consumer.
	Ski Jacket Production & Distribution	815 *g* Jacket	17.919355 (SD = 5%)	Goffetti et al., 2020 ecoinvent v3.8	Mixed polyester ski jacket (produced in Japan), Includes unit packaging (10 *g* virgin plastic polybag) and transport from factory to 1st EU consumer.
Electricity Usage	Consolidation Center Handling in Europe	per garment	0.003670 (SD = 5%)	Industry Expert Interviews ecoinvent v3.8	Industry partner insight. General electricity, low voltage (RER, APOS, U)
Transport Mode	Truck	kgXkm	0.000105 (Distribution based on weighted average)	ecoinvent v3.8	Weighted average of all Euro6 trucks based on their relative proportion in the average European transport fleet The truck fleets in our industry partners' network include mostly Euro6 trucks. Unspecified Vehicle EURO6 vehicle mix, 85% Truck Utilization. Unspecified freight, lorry (RER, APOS, U)
	Van	kgXkm	0.001846 (Distribution based on weighted average)	ecoinvent v3.8	Light Commercial Vehicle (RER, APOS, U)
	Private Car	kgXkm	0.083587 (Distribution based on weighted average)	ecoinvent v3.8	Weighted average of all passenger cars (Euro3–5) according to their proportion in the average European passenger car fleet Passenger car (RER, APOS, U), To allocate emissions from one ride across multiple activities, can emissions were divided by four (Feichtinger and Gronalt, 2021).
	Ship	kgXkm	0.000009	ecoinvent v3.8	Container ship, weighted average {(GLO, APOS, U)
Packaging	T-shirt Virgin Polybag Production	5 g	0.014528 (SD = 5%)	ecoinvent v3.8	Based on low density polyethylene production (GLO).
	Ski Jacket Virgin Polybag Production	10 g	0.029056 (SD = 5%)	ecoinvent v3.8	
EoL	Cotton Recycling (Net emissions)	A single T-shirt	−0.375642 (SD = 5%)	Duhoux et al., 2021 ecoinvent v3.8	Mechanical Recycling, assuming garments are recycled into 20% spinnable fibers, 5% metals (Steel/Alu/Copper), 3% dust, 73% fluff/filling (PET/PP/cotton/cellulose). CO_2-eq intensity is for net emissions after credit for avoided virgin fiber production (−0.423757 kg CO_2-eq) and recycling process emissions (0.048115 kg CO_2-eq).
	Cotton Incineration (Net emissions)	A single T-shirt	0.387476 (SD = 5%)	Bodin, 2016; Huygens et al., 2023; Hogg, 2023	Cotton municipal incineration (excluding shipping to facility) with thermal and electric energy recovery (efficiency conversion of 40% and 15% respectively). CO_2-eq intensity is for net emissions accounting for incineration process (0.375642 kg CO_2-eq) and avoided electricity and heat production from natural gas in the EU.
	Natural textile Landfill processing	1 kg natural fiber	0.00281 (SD = 5%)	Moazzem et al., 2021	Textile processing only. Excludes transport to landfill, textile decomposition, or landfill gas capture.
	Polyester Recycling (Net emissions)	A single Jacket	−1.935905 (SD = 5%)	Duhoux et al., 2021	Mechanical Recycling, assuming garments are recycled to 55% spinnable fibers, 5% metals (Steel/Alu/Copper), 3% dust, 37% fluff/filling (PET/PP/cotton/cellulose). CO_2-eq intensity is for net emissions after considering avoided production (−2.092760 kg CO_2-eq) and recycling process emissions (0.156855 kg CO_2-eq).
	Polyester Incineration (Net emissions)	A single Jacket	1.773903 (SD = 5%)	Bodin, 2016; Huygens et al., 2023; Hogg, 2023	Polyethylene terephthalate municipal incineration (excluding shipping to facility) with thermal and electric energy recovery (efficiency conversion of 40% and 15% respectively). CO_2-eq intensity is for net emissions accounting for incineration process (1.865317 kg CO_2-eq) and avoided electricity and heat production from natural gas in the EU.
	Synthetic textile Landfill processing	1 kg, synthetic textile	0.00158 (SD = 5%)	Adapted from Moazzem et al., 2021	Textile processing only. Excludes transport to landfill, textile decomposition, or landfill gas capture.

model is Eurocentric, we considered electricity consumption outside of the EU beyond the scope of this work. Emissions per kWh are based on average EU electricity mix and are assumed to be normally distributed with a SD of 5% of the mean (ecoinvent 3.8 EU market mix). Note that transport from point of sale/donation to second consumer is considered an integral part of the next buyer's purchase and thus beyond the system boundaries of this analysis.

2.3.4. Packaging

Calculation of GHG emission associated with packaging ($E_{packaging}$) is given in Eq. (4):

$$E_{packaging}(s,p) = E_{polybag}(p) \times N(s) \tag{4}$$

Where $E_{polybag}$ stands for GHG emissions associated with the production of one virgin PET polybag (size varies by product *(p)*) and N_i refers to the number of returned products that are restocked per scenario (*s*).

Building on previous work and our industry partners' insights, we assumed a high rate of products need to be repackaged before returning to stock (Velazquez and Chankov, 2019). Hence,we assumed all returns are repackaged before they are restocked, while products diverted to all other pathways are not. The GHG emissions of packaging ($E_{packaging}$) represent emissions associated with packaging production, with T-shirts repackaged in a 5 *g* virgin PET polybag, and the larger ski jackets in a 10 *g* polybag. Emission per gram of packaging are assumed to be normally distributed with a SD of 5% of the mean. Packaging beyond polybags, for example - cardboard boxes, or plastic used to wrap pallets were excluded from the analysis.

2.3.5. End of life – incineration in waste to energy facilities and recycling

Calculation of GHG emission associated with EoL treatments (E_{EoL}) is given in Eq. (5):

$$E_{EoL}(s,p) = E_{WTE}(p) \times N_i(s) \times W(p) + E_{recycling}(p) \times N_i(s) \times W(p) \tag{5}$$

Where E_{WTE} is the net GHG emissions associated with product (p)'s incineration; $E_{recycling}$ is the net GHG emissions associated with product (p)'s mechanical recycling in the EU; N_i is the total number of returned products sent to incineration/recycling under each management scenario (s), and W is the mass of each product (p).

Net GHG emissions for incineration and recycling were derived using LCA based on garments' material composition, whereby T-shirt consisted of 100% cotton and ski jackets of mixed Polyethylene terephthalate (see Table 1). For incineration, we assumed that all products are burnt in energy recovery facilities, and that the heat and electricity generated in the incineration process lead to avoided production of electricity and heat in a natural gas co-generation plant, with a thermal content efficiency conversion rate of 40% for heat and 15% for electricity (Huygens et al., 2023). Note however, that this assumption might be overly optimistic and may not apply in other geographies where energy recovery facilities are less common or efficient.

Recycling within the EU was modeled based on a 2021 European Commission report (Duhoux et al., 2021). Since returned products are typically unused, they are less likely to suffer from contamination or wear which can lower recycling yields of spinnable fiber (Huygens et al., 2023). Hence, we model recycling according to the best-case scenario assuming 20% spinnable fiber yield (Duhoux et al., 2021). Importantly, we consider this a conservative assumption that may underestimate emissions since recycling rates are likely lower in practice as factors other than technical feasibility also come into play. For both incineration and recycling, GHG emissions per product were assumed to be normally distributed with a SD of 5% of the mean. EoL pathways beyond the EU were considered beyond the scope of this analysis.

Emissions associated with EoL of lost products are considered beyond the scope of the current study. However, to explore whether they could meaningfully affect results we reran the model assuming that all lost products are sent to landfills (see section 5 in the SI).

2.3.6. Embodied emissions- cradle to 1st consumer

Embodied GHG emissions per product, from cradle to 1st consumer, were calculated using LCA. T-shirts, are assumed to be a 250 g white shirt made of 100% cotton (produced in Bangladesh). Ski jackets, are assumed to be an 815 g jacket made from a polyester blend (produced in Japan). The system boundaries of the LCA included product's original packaging (5 g virgin polybag for T-shirt, 10 g virgin polybag for the ski jacket) and shipping to the first EU consumer. Transport during the production phase was excluded from the analysis. In both cases, we assumed that the GHG emissions per product were normally distributed with a SD equal to 5% of the mean (see SI 1 Section 4 for more).

3. Results

3.1. Post-return product flows

Examining post-return product flows, returns management practices meaningfully affect the share of products that are ultimately discarded. We find that 78% of returned items reach a secondary consumer when sustainable management practices are employed (Fig. 2a). The remaining 22% end up in recycling (9%), landfills (6%), incineration (4%), or are lost along the way (e.g., 'fell off a truck'; 4%). In contrast, under conventional management practices only 56% of returned items reach a secondary consumer. The rest, ends up in recycling (21%), landfills (10%), incineration (6%), and 6% are lost along the way (Fig. 2b). These findings align with available industry estimates (Moore, 2016).

3.2. Post-return logistics and processing GHG emissions

As Fig. 3 illustrates, we find that on average, transport is the major contributor to post-return emissions responsible for 79%−89% of GHG emissions (before accounting for avoided emissions). The 1st mile emerges as a hotspot, responsible for 28%−58% of post-return emissions, while transport in total accounts for 79%−89% of post-return emissions. These results are well aligned with past work (see for example, Buldeo Rai et al., 2023). Notably, emissions from processing and packaging are negligible (2%−3% each on average), while incineration is a net GHG emitter responsible for 4%−16% of post return emissions, even when avoided electricity and heat production are accounted for.

For T-shirts, net GHG emissions associated with post-return transport, processing, packaging, and EoL (including credits for avoided emissions), are roughly 231t of CO_2-eq (with a 5th and 95th percentile interval of [202, 266t CO_2-eq]) under sustainable management practices, and 201t of CO_2-eq [174, 230t CO_2-eq] under conventional management practices. For the heavier ski jacket, net post-return emissions amount to 425t of CO_2-eq [364, 517t CO_2-eq] under sustainable management practices, and 304t of CO_2-eq [256, 374t CO_2-eq], under conventional management practices.

3.3. Embodied GHG emissions

When considering emissions from a full lifecycle perspective, we find that on average, embodied emissions associated with the production and distribution of products that once returned ultimately go unused can be 2–16 times those of all post-return supply chain emissions combined (Fig. 4). Under the sustainable management practices, embodied emissions of discarded and lost products amount to 426t CO_2-eq [391, 461t CO_2-eq] for T-shirts, and 2511t CO_2-eq [2304, 2717t CO_2-eq] for ski jackets. Under conventional management practices, where a larger share of products is ultimately discarded, embodied emissions amount to roughly 844t CO_2-eq [775, 914t CO_2-eq] for T-shirts, and 4976t CO_2-eq [4570, 5382t CO_2-eq] for ski jackets.

4. Discussion and conclusions

Although the sheer scale of product returns should give anyone interested in sustainable consumption pause, the full lifecycle environmental impacts associated with new product returns remain largely unknown (Abdulla et al., 2019; Constable, 2019; Corkery, 2022; KPMG, 2017; Reagan, 2019; Sanicola, 2017; Tian and Sarkis, 2021; Zhang, 2023). Here, we focus on apparel – the largest eCommerce product category – notoriously known for its high return rates (Kemp, 2023; Orendorff, 2019; Shopify, 2022). Apparel is in high demand in Europe, especially Western Europe, with significant amounts of annual exports and destruction of clothing (Ökopol, 2021; Watson et al., 2016). We map returned product flows from 1st consumer to their destination under different return management practices and use two products as case studies to illustrate the full lifecycle GHG emissions associated with returns. To the best of our knowledge, this work presents one of the first data driven attempts to assess the impacts of returns from a full lifecycle perspective.

Our results suggest that even when sustainable management practices are employed, roughly one out of four returned products are discarded. According to our industry partners, this model, based on data from a large sustainably oriented apparel brand in the EU represents the most sustainable companies (roughly of the total apparel landscape). Under the more common, conventional management practices almost half of returns (44%) never make it to the hands of another consumer.

4.1. Full life cycle environmental impacts

Thus far, attention has mostly centered on how to curb post-return

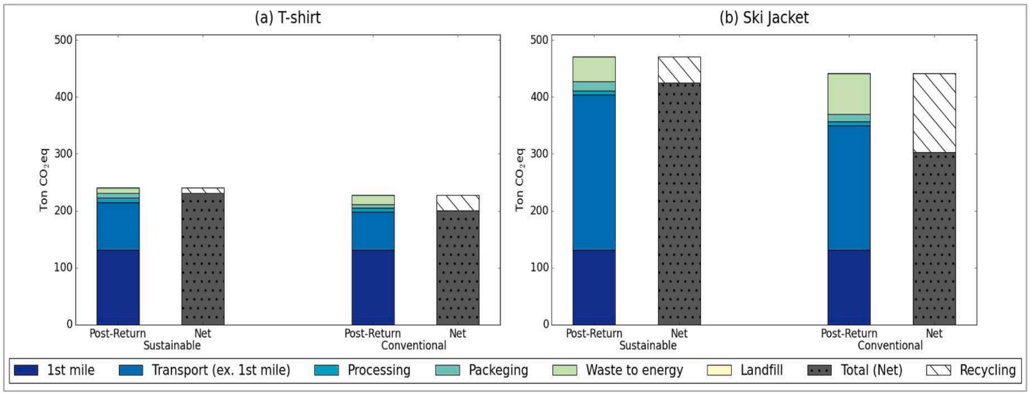

Fig. 3. Post-return supply chain GHG emissions by product and return management scenario. Metric tons of GHG emissions associated with the return of 630k T-shirts (Panel a) or ski jackets (Panel b), under sustainable and conventional returns management practices. Post-return (left, colored stacked bars) present overall post-return supply chain emissions by stage. Net (right) present avoided emissions from textile recycling (white dashed) and net post-return emissions (Dark gray with dots) accounting for recycling.

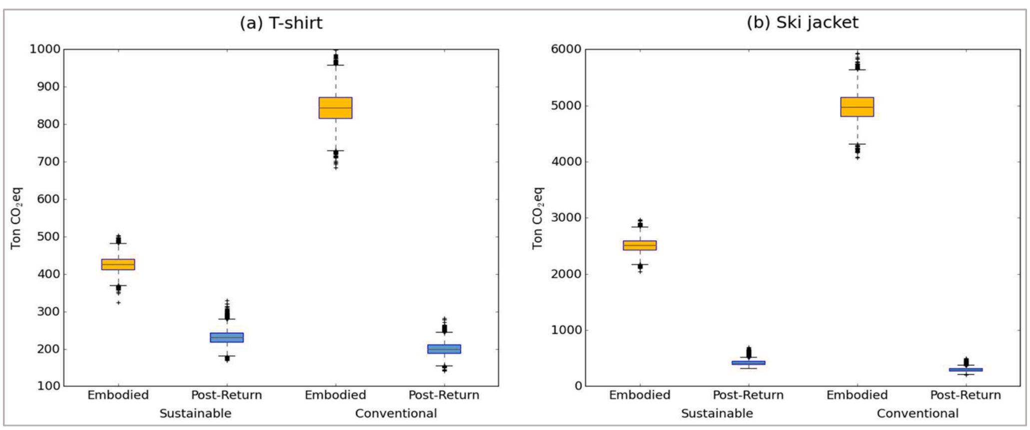

Fig. 4. Embodied vs. post-return supply chain GHG emissions by product and scenario.
Embodied GHG emissions associated with the production and distribution of discarded or lost retuned products (Embodied, in yellow), vs. emissions from all post-return supply chain stages combined, including transport, processing, packaging, incineration and recycling (in blue). Boxes present median (solid line) and the interquartile range,. Note differences in scales between Panel a (T-shirt) and Panel b (Ski jacket).

transport related emissions, and particularly the carbon intensive 1st mile (Buldeo Rai et al., 2023; Edwards et al., 2010; Pålsson et al., 2017; Wiese et al., 2012). While our results support the notion that transport is the major source of GHG emissions post-return and should definelty be optimized, our analysis reveals that from a full lifecycle perspective, transport emissions are likely substantially lower and even marginal. In the case of the heavier ski jacket, embodied emissions associated with the production and distribution of returned items that ultimately remain unused, can be as much as 16 times those of all post-return supply chain emissions combined, including transport, processing, packaging and EoL management.

In both product case studies, post-return transport emissions are higher under sustainable (vs. conventional) management practices due to the added transport and processing during stages such as advanced grading. Critically, these stages can increase the number of restocked products, lower the squandering of embodied emissions, and thus result in lower net emissions overall.

Our findings have two main implications. First, they suggest that GHG emissions of retail, and specifically eCommerce where return rates are exceptionally high, are likely systematically underestimated, and demonstrate how important it is to examine retail and returns from a full lifecycle perspective. Second, our findings illustrate that returns create a unique form of overstock – products in brand new or lightly used condition that retailers either lack the ability or find costly to resell. This highlights the urgent need for more research and practical tools that can help inform and optimize return management practices to minimize environmental impacts (Frei, Jack, and Krzyzaniak, 2020). Similar to end-of-life circularity efforts, policy measures should target consumer returns management to ensure fewer new products go to end-of-life without ever being used.

4.2. Management of returned products

The misalignment between economic and environmental costs is one of the fundamental drivers of the wider discussion about the environmental burdens of fast fashion, overproduction as a business model, product destruction, as well as policy makers' attempts to curtail the destruction of unsold goods (European Commission, 2023; Niinimäki et al., 2020). Most products are returned because of bad fit or buyer's remorse, while only a small share (~10% according to the sustainable retailer's data) are in such poor condition that they cannot be mended in advanced grading facilities (Ji et al., 2018; Orendorff, 2019). Yet while they are new, unused products, many returns are not restocked because it is cheaper (and simpler) for retailers to discard or liquidate returned products than pay for post-return transport, sorting, processing etc. (Bamberg University, 2019). Moreover, limited seasonal or collection compatibility (e.g., Christmas sweaters returned in February) can affect the likelihood that a returned item would be sold at full price (if it can be sold at all).

Given pending regulation on product destruction (Dehoux, 2024), and the emphasis on circularity, one commonly discussed strategy among retailers is to ask consumers to keep returns (Cerullo, 2023; Reuter, 2024) or donate them directly to local charities (Narvar and Cycleon, 2022). These steps would eliminate the need to ship items back to sellers and thus save retailers money and emissions. However, due to the ever-growing volumes of donated clothes, many donated items are not reused reused in practice (Chiu, 2023; Doughton, 2021). To be able to manage the high volumes of eCommerce returns, reuse actors need to improve their handling capacity and incorporate tools such as digitalized inventory management systems (Roberts et. al, 2023).

Currently however, secondary markets are saturated, which means that donations may shift rather than solve the issue of surplus cheap clothing (Manieson and Ferrero-Regis, 2022). Our research suggests that only 4%−30% of items donated go up for sale in local thrift shops. Since most returned products are practically new items in good condition, we assume that 25% of donated items reach a second consumer. This assumption, however, might be optimistic as experts noted in interviews that while products' condition significantly affects the likelihood of an item reaching the store front (i.e., pass the donation sorting processes), brand name is often a better predictor for secondhand market demand than "newness" (Makov et al., 2018). As such, current redistribution networks might not be as effective at prolonging the service life of inexpensive apparel returns.

Our findings suggest that advanced grading and light repair capabilities, can substantially increase restock rates and reduce the number of new products that are discarded. Although such circular economy practices may require additional energy, labor, and materials, they are more sustainable from a full systems perspective, as they increase restock rates, extend product lifetimes, and improve overall energy and material efficiency. Yet unlike post-return transport, where shorter, more efficient routes can save retailers money while reducing emissions, circular economy practices impose additional costs on retailers. This issue is particularly challenging for fast fashion where the price of new products is often lower than the $5–20 it can cost to transport, sort, mend, and repackage a single small item (Bamberg University, 2019; Orendorff, 2019; Tait, 2023). Hence, the low retail value of new clothing items may discourage investments in circular management practices. Zhang et al. (2023) suggest that outsourcing the management of returns to specialized firms could lower costs and offer greater opportunities for resale or sustainable EoL management. In addition, adopting an omni-channel approach, allowing consumers to return items bought online in stores could enable improved inventory management and cut operational costs while driving more in store traffic (Nageswaran et al., 2020; Roberts et al. (2023) argue that well-established redistribution networks should be formed, and suggest a variety of policies that lower the costs of managing returns, including reduced VAT, digital tools, and tax on returned items.

As the economic costs of returns become more apparent, some suggest that retailers can reduce returns at the purchase stage. For example, providing consumers with better product descriptions, advanced imaging (e.g. 360 °), more accurate and detailed consumer reviews, sizing guides, and virtual reality tools, could help consumers avoid purchases that are subsequently returned (Dehoux et al., 2024; Zhang et al., 2023; Roberts et al., 2023; Sahoo et al., 2018; Yang and Xiong, 2019). Others, suggest that tweaking return policies, making return windows shorter, charging consumers for returns, or 'nudging' consumers so they return fewer items could help curtail the environmental and economic costs associated with consumer returns (Dehoux et al., 2024; Kapner, 2023; von Zahn et al., 2022) . However, many retailers fear potential backlash in sales and consumer loyalty (Abdulla et al., 2019; Chen, 2023). Further research should explore strategies that facilitate synergy between economic and environmental performance in managing returns, and how these may differ across products types and price categories. Of particular interest might be slow fashion and 'just on time' inventory management systems as these may increase actual use of returned products.

4.3. Limitations

This work has several limitations. First, our dataset and the modeling assumptions used to estimate product flows and transport distances are representative of large retailers in Western Europe. Future work should explore smaller retailers as well as additional geographies to examine potential differences in return management practices and reverse supply chain structure and distances. For example, road transport in the US tends to be more carbon intensive than in the EU due to different fleet compositions. Thecarbon intensity of trucks for example, is 32% higher in the US compared with the EU (see SI 1 section 6 for details). In our model this would mean that transport emissions from an equivalent US post-return supply chain would be roughly 15% higher.

Second, our results are sensitive to assumptions regarding restock rates, the share of items sold after restocking, and the share of donated items that are indeed reused. For example, in the conventional scenario we assumed that resell rates of returned goods are lower than new stock given issues such as seasonal compatibility, limited availability of sizes and colors etc. (Tait, 2023). However, resell rates likely vary by product size, type, category, and color (e.g., a basic white T-shirt vs. thermal magenta T-shirt). While we employ conservative estimates throughout, future work should explore a wider variety of apparel items and incorporate product specific return rates and flow estimates. Future work should also explore if and how return policy conditions (e.g., full refund, partial refund, store credit etc.) as well as an omnichannel approach affect flows and full lifecycle emissions.

Given the large flow of returns going to charities, more work is needed to ascertain the actual reuse potential of donated apparel products and shed light on the factors that increase the likelihood of a donated item to reach a second consumer. Finally, the economics of product returns likely affect management practices more than environmental impacts (Dehoux, 2024). More work is needed to examine environmental and economic tradeoffs in returns' management and how they may differ across product types, price categories, and geographic locations.

4.4. Conclusion

Although many returns are functional items that could potentially be used by a second consumer, our findings suggest that currently, post return flows are often not optimized to increase such flows. We demonstrate that the embodied emissions associated with the production and distribution of products that, once returned, never reach a second consumer far surpass emissions resulting from all post-return supply chain (transport, packaging, and processing). Hence, our work highlights the imperative to incorporate returns into environmental evaluations of the retail sector and adopt sustainable return management practices that enable product life extension.

CRediT authorship contribution statement

Rotem Roichman: Writing – original draft, Writing – review & editing, Formal analysis, Software, Validation. **Benjamin Sprecher:** Writing – review & editing, Software, Funding acquisition, Formal analysis. **Vered Blass:** Writing – review & editing, Funding acquisition. **Tamar Meshulam:** Writing – review & editing, Validation, Software, Formal analysis. **Tamar Makov:** Conceptualization, Data curation, Formal analysis, Software, Validation, Writing – review & editing, Writing – original draft, Funding acquisition.

Declaration of competing interest

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The proprietary dataset used in this research was generously provided to the research team by ReBound Returns (www.reboundreturns.com). Due to privacy concerns the data cannot be openly shared but is available from the authors upon reasonable request and with the permission of ReBound Returns.

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Supplementary materials

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