

The Environmental Impacts of Clothing **Evidence from United States and Three European Countries**

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The environmental impacts of clothing: Evidence from United States and three European countries

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Abstract

Because of the near doubling of clothing purchased and the shift toward fast fashion in recent decades, clothing induces increasingly significant global environmental impacts throughout its entire life cycle. To measure the environmental impacts of clothing across the major life cycle phases of production, purchase, transportation, usage, and disposal, we apply life cycle assessment (LCA) to detailed survey data on jeans and t-shirt consumption by 4,591 consumers across four countries: Germany, Poland, Sweden, and the United States. The results reveal that, except for jeans in the United States, the production phase is consistently responsible for the largest share of the environmental impacts associated with clothing. Nevertheless, the use phase, which includes washing and drying, also induces sizable environmental impacts, especially when laundering is frequent and, as in Poland and the United States, the associated electricity consumption comes from carbon-intensive energy sources. Taken together, our results suggest that future efforts to reduce the environmental impacts of clothing must comprehensively address the production, acquisition, and use of clothing through not only technological and efficiency improvements but changes in both purchasing and usage behavior.

Keywords: Clothing, Environmental impacts, Consumer behavior, Clothing consumption and production, Life cycle assessment.

1. Introduction

Although clothing production and consumption are significant sources of environmental degradation and greenhouse gas (GHG) emissions (Choudhury, 2014; Wood et al., 2018), the magnitude of clothing-induced environmental impacts globally is currently under debate, partly due to high uncertainty (Wicker, 2020). For example, conclusions from the white and grey literature of clothing production and consumption being responsible for 8-10% of global GHG emissions (Quantis, 2018; UNEP, 2018), appear incompatible with authoritative assessments of the global drivers of GHG emissions (Friedlingstein et al., 2019; IPCC, 2018). Rather, these conclusions probably reflect the limited resolution and quality of existing data on clothing-induced environmental impacts. Yet despite pertinent data issues, some robust research does suggest a contribution nearer 2-3% of global GHG emissions (Hertwich and Peters, 2009; Peters et al., 2021) and 4-5% of the GHG emissions allocated to European households (Ivanova et al., 2017; Steen-Olsen et al., 2016; Wood et al., 2018). Similar uncertainty encircles the scale of other environmental impacts such as land-use change, freshwater depletion, and ecotoxicological damage, which most related research attributes to manufacturing and production phases that require large inputs of water, energy, and chemicals (Choudhury, 2014; Niinimäki et al., 2020; Roos et al., 2017, 2016). For instance, one comprehensive report from the Ellen MacArthur Foundation (2017) attributed 20% of global industrial water pollution to the clothing industry. However, based in part on low quality sources – some already retracted – the validity of this statistic is highly questionable (Wicker, 2020).

Nonetheless, even if the global environmental impacts linked to clothing are less severe than sometimes postulated, clothing remains an important domain for mitigating climate change, freshwater depletion, biodiversity loss, and general ecosystem degradation (Choudhury, 2014; Hertwich and Peters, 2009; Koslowski et al., 2020; Niinimäki et al., 2020;

Peters et al., 2021). The production of cotton, for example, a widely used but land-intensive clothing material, directly competes with arable land for food production, urbanization, conservation and restoration of ecosystems, and the diffusion of negative emission technologies (Creutzig, 2019; IPCC, 2019). Clothing production is also associated with local environmental, social, and economic impacts that go well beyond the scope of this paper (see for example Ertekin and Atik, 2015; and Kant, 2012 for a discussion).

In addition, whereas the negative environmental effects of clothing production remain uncertain, those of clothing consumption are largely unknown. Currently, only limited evidence exists on consumer purchasing patterns and motivations or on their usage and disposal of clothes (Gwozdz et al., 2017; Laitala and Klepp, 2020). This paucity of social scientific research is surprising given the importance of clothing in many cultures, the complex psychological processes involved in its purchase and selection, and the fundamental transformation of clothing culture toward fast fashion (Byun and Sternquist, 2012; Gupta et al., 2019; O'Cass, 2000). In fact, the relevance and need for research on clothing consumption has only increased with the near doubling of clothing sales over the past two decades (Ellen MacArthur Foundation, 2017; Niinimäki et al., 2020), which has been augmented by the growing market dominance of fast-fashion companies such as H&M and Forever 21. Most notably, fast-fashion companies have been instrumental in shortening the service life of clothing by offering low-priced apparel in rapidly increasing collection cycles in which new trends quickly supersede old (Barnes and Lea-Greenwood, 2006; Ertekin and Atik, 2015). This faster turnover, together with lower prices, has been instrumental in stimulating symbolic obsolescence and lowering practical service life, resulting in larger per capita sales and hence greater environmental impacts (Ellen MacArthur Foundation, 2017; Niinimäki et al., 2020). The observed increase in clothing consumption, the changing clothing market, and

the paucity of knowledge about consumption patterns firmly underscore the necessity to better understand its environmental impacts.

Because the clothing consumption phases of purchase, use, and disposal remain understudied and poorly documented, attempts to estimate environmental impacts throughout the clothing life cycle have either been restricted to "cradle to gate" analyses or those based on highly generalized assumptions about consumer behavior during the use and disposal phases (Cotton Incorporated, 2012; Niinimäki et al., 2020; Roos et al., 2017, 2016). For example, while acknowledging the significance of the use phase, a recent review of the environmental impacts of fast fashion only superficially treated the use phase and predominantly referenced studies that relied on stylized behavioral assumptions (Niinimäki et al., 2020). The studies that do include the post-purchase life cycle phases clearly suggest that the use phase (wearing, storing, maintaining, washing, and drying) is a key contributor to the overall energy consumption and GHG emissions associated with clothing (Cullen and Allwood, 2009; Roos et al., 2016; Wood et al., 2018). However, because washing and drying are closely connected to the energy grid, energy efficiency of appliances, load efficiency, and use frequency, the impacts induced during the use phase vary considerably depending on consumer behavior, household equipment, and geographic location (i.e., energy source) (Kennedy, 2017; Stamminger and Schmitz, 2016). Such variability highlights the tendency of existing environmental impact studies to either grossly overgeneralize behavior during the post-purchase phases or fail to account for all possible variables. They thus insufficiently inform researchers, policymakers, industry, and other stakeholders about where to intervene in the clothing life cycle to reduce the associated environmental impacts most effectively.

The aim of this study, therefore, is to generate more accurate and detailed data on the environmental impacts of clothing production and consumption in Germany, Poland, Sweden, and the United States. These countries are chosen to capture the heterogeneity of

clothing markets and consumption patterns in Western countries: Germany is one of the largest clothing markets in Europe; Poland is a representative of Eastern Europe and thus a post-communist regime with a clothing market less dominated by fast fashion; Sweden has an increasingly sustainability-oriented clothing market; and the United States is the world's largest clothing market while being culturally and politically distinct from continental Europe. In analyzing the environmental impacts of clothing across the four countries, we make the following threefold contribution:

- The development of a detailed framework for assessing consumers' clothing purchase, use, and disposal patterns and resultant environmental impacts by the application of life cycle assessment (LCA) to corresponding consumer survey data from four countries. This methodology permits assessment of annual clothing-induced environmental impacts throughout the entire life cycle, thereby addressing the limitations of earlier research, including generalized assumptions about consumer behavior.
- 2) Dissection of the variability in clothing consumption-induced impacts between the four countries to enable differentiation of the contribution to environmental impacts of geographically different consumer behaviors and infrastructures (e.g., energy supply, waste management systems).
- 3) The provision of important insights for developing tailored and effective interventions to mitigate the environmental impacts of clothing by identifying them within each life cycle phase, thereby revealing the contribution of consumer behavior to the observed impacts across the four countries. The analysis will also identify the potentially most impact reducing intervention points throughout the life cycle, providing useful guidance not only for researchers but also policymakers, fashion industry actors, and other relevant stakeholders.

2. Methods

To assess the environmental impacts of clothing consumption, we use the Ecoinvent database, as life cycle inventory for the entire clothing life cycle (i.e., from raw material extraction through production, use, and end-of-life), to perform a life cycle analysis (LCA) of individual self-reported consumer behavior data for all consumption phases. In doing so, we focus on jeans and t-shirts, two product categories familiar to the majority of consumers in the four countries surveyed (Roos et al., 2017), ensuring more accurate recall and reporting of clothing consumption behavior in the individual survey data. Because the better defined the analytical unit (i.e., jeans and t-shirts), the more relevant the conclusions, this focus also enables detailed analyses of behavior's interconnectedness with environmental impacts throughout the clothing life cycle while maintaining sufficient generalizability to render the results useful. Put simply, it successfully balances the inherent tradeoff between high specificity (i.e., a particular clothing product) and high generality (i.e., the impact of clothing overall).

2.1. Consumer survey data

To assess consumer clothing consumption patterns, we use relevant data from a comprehensive online survey conducted in Germany, Poland, Sweden, and the United States (US) (Gwozdz et al., 2017). Originally developed in English, the survey questionnaire was subsequently translated into German, Polish, and Swedish by ISO17100 certified translators and administered in all countries by the market research company *Qualtrics*. To ensure data quality and eliminate careless responses, the questionnaire contained multiple measures, including instructed items (e.g., "Please select strongly agree") (DeSimone et al., 2015). Because of its length, the survey consisted of two parts administered at two to four-week

intervals between October 2016 and January 2017. This current analysis employs data related to the consumption phases of purchase, use, and disposal, based on which we develop an average country-specific consumer profile.

2.1.1. Sample

To ensure representativeness, *Qualtrics* recruited adult participants (aged 18-65) from each of the four countries based on age, sex, educational and regional distribution, incentivizing participation with points redeemable for various products (e.g., gift cards). The final sample (inclusion criteria: participation in both Part I and Part II) included 4,591 participants with the following country breakdown: Germany (n = 1,170), Poland (n = 1,105), Sweden (n = 1,176), and the US (n = 1,140). The mean age is 42.2 (SD = 13.6), with 56.7% being female (see Supplementary Material for country-specific sociodemographics).

2.1.2. Measurements

Having identified no preexisting tested survey measurements for consumer self-reports of purchase, use, and disposal behaviors for jeans and t-shirts, we worked as an interdisciplinary team to develop new measurements based on both the information needed to conduct LCA and similar measures described in the literature. After pretesting our newly developed measures, we included each measure twice in the questionnaire, referring once to jeans and once to t-shirts (see Supplementary Material for item details).

For the *purchase phase*, we first determined a consumer's stock at any given point in time by asking the number of jeans and t-shirts owned and the time those items are usually kept before being discarded on a five-point scale of 1 "less than 6 months", 2 "less than a year", 3 "1-2 years", 4 "3-4 years", and 5 "5 years or more". After using the midpoints of each time category to calculate the amount of time a piece of clothing remained in a

consumer's stock, we calculated the annual restocking of jeans and t-shirts per consumer given the assumption of a constant stock. This calculation is relevant for the environmental impacts occurring during production (see 2.2.2.).

For the *use phase*, to capture washing and drying behavior specifically, we asked how many times participants wore their jeans and t-shirts on average before washing (number of wears), washing temperature (from 20°C to 60°C), use of detergents (yes/no), and use of dryer (yes/no). We used these responses to calculate the number of washes and dries, as well as the corresponding numbers of full wash and dry cycles (see 2.2.2.).

Lastly, for the *disposal phase*, we asked participants whether they discarded their clothes by giving them a second life (e.g., donating, recycling, flea-market), downcycling (e.g., as rags), or putting them in the trash. Respondents could distribute 100% across the three options.

2.2. Life cycle assessment

To determine the environmental impacts from jeans and t-shirt provisioning, we use the Ecoinvent lifecycle inventory (Wernet et al., 2016) to conduct two life cycle assessments (International Organization for Standardization, 2006) encompassing all phases from raw material extraction through end-of-life. For all process inventories, we use location specific Ecoinvent inventories to the extent possible. Where not possible, we select the most appropriate regions. We thereby provide a detailed breakdown of the environmental impacts induced during the production, use, and disposal phases, as well as the relative differences between them. For both assessments, we employ OpenLCA (GreenDelta, 2019) with all environmental impacts characterized using the ReCiPe 2016 method (Huijbregts et al., 2017). To dissect the environmental impacts of consumer behavior (purchase, use, and disposal) and context (i.e., carbon intensity of the underlying energy grid), we adopt the interpretation

methods of endpoint modeling; single midpoint indicator comparisons (e.g., carbon footprint); monetization (Pizzol et al., 2015); and ArgCW-LCA (Sohn et al., 2020), a novel form of multiple criteria decision analysis (MCDA).

2.2.1. Scope and system boundaries

In assessing the environmental impacts of jeans and t-shirts over the entire clothing life cycle (see Fig. 1), we use a functional unit (FU) of jeans or t-shirt provisioning that includes production, purchasing, transportation, use, and disposal for *one consumer* over *one year* in one region from either Germany, Poland, Sweden, or the US. When a disposed clothing item is made available for a second life (see 2.1.2), we allocate all production-induced environmental impacts to primary production and all impacts associated with the first to second life transition to the second life (see **Fig.** *I*).



Fig. 1. System boundaries of the product system modeled for the LCA of jeans and t-shirt provisioning

2.2.2. Annual provisioning inventory

After using the survey data to build a base inventory of consumer purchasing, use, and disposal behavior (see 2.1.), we develop an inventory of the functional unit for jeans and t-shirts specifically (Table 1, see Fig. 1 for system boundaries), which includes restock (i.e., number of items purchased in a given time period), use behavior (washing and drying), and disposal (second life, downcycling, or trash). We calculate this latter based on Kalbar et al.'s (2016) concept of personal metabolism, a holistic method for understanding individual consumer consumption patterns and their associated material flows. In performing the LCA, we make two main assumptions: (i) an average pair of jeans (t-shirt) weighs 1 kg (200 g) and (ii) transport during production involves a 16-32 metric ton lorry (truck) traversing 200 km of land plus transoceanic shipment from Thailand. Based on these two assumptions and the consumption data, we populate the remainder of the inventory using the Ecoinvent database (Wernet et al., 2016).

	Germany	Poland	Sweden	United States	All	
		Jeans				
Restock*	1.74	1.52	1.31	1.80	1.59	
Full wash cycles ^{**}	5.19	4.40	3.32	11.45	6.09	
Full dry cycles ^{***}	1.34	0.71	0.74	12.43	3.80	
Second life [*]	1.20	0.93	0.77	1.20	1.02	
Downcycle*	0.27	0.26	0.17	0.24	0.23	
Landfill [*]	0.27	0.33	0.38	0.37	0.34	
T-shirts						
Restock [*]	5.92	6.33	4.48	4.92	5.41	
Full wash cycles ^{**}	3.74	3.29	3.12	4.61	3.69	
Full dry cycles ^{***}	1.06	0.55	0.85	5.07	1.88	
Second life [*]	3.56	3.10	1.92	2.79	2.84	
Downcycle*	1.47	2.23	1.22	1.20	1.53	
Landfill [*]	0.89	1.00	1.35	0.93	1.04	

Table 1. Inventory of consumption patterns for jeans and t-shirt

Note: A t-shirt is assumed to weigh 0.2 kg and be worn 260 times per year. *in number of t-shirts per year, **in number of full cycles per year assuming an 8 kg capacity machine with 80% utilization, ***in number of full cycles per year assuming a 6 kg capacity machine with 80% utilization.

For the *production phase*, we use the Ecoinvent (Wernet et al., 2016) knit finished cotton process applied in its original form for t-shirts but with an energy consumption

modification, adding 0.195kwh of electricity consumption, for jeans that better aligns the process with jeans production based on the description of jeans production by Islam (2016). To accommodate for the amount of purchased clothing items, we use a simple residence time calculation dividing the number of clothing items possessed by the time clothing items were kept assuming a steady stock state (see 2.1.2) in which each consumer maintains the self-reported number of clothing items owned by purchasing and discarding, on average, an equal number of items. This calculation yields an average consumer clothing restock rate of 1.6 jeans and 5.4 t-shirts per consumer per year across all countries.

For the *use phase*, which includes washing and drying, we assume that the average consumer uses an 8 kg capacity washing machine and a 6 kg capacity dryer at 80% capacity. We further assume that all consumers wear jeans and t-shirts from their stock as primary clothing for 5 wears per week equaling 260 wears per year. We thus calculate the number of washes by dividing 260 wears per year by the number of wears before washing, resulting in an average across the four countries surveyed of about 39 pairs of jeans and 118 t-shirts washed per year. For an 8 kg washing machine used at 80% capacity, the result is an average of 6.1 washing cycles for jeans and 3.7 washing cycles for t-shirts per year across all four countries. Similar calculations for the number of dries yields cross-country averages of 18.3 pairs of jeans and 45.2 t-shirts, which for a 6 kg dryer used at 80% capacity means an average of 3.8 drying cycles for jeans and 1.9 for t-shirts per year.

To estimate the environmental impacts of washing, we use the self-reported data on temperature (response categories from 20 °C – 60 °C) and detergent usage (yes/no). The reference washing machine is a front-loader that uses 75 liters of water per 8 kg load (see Table 22), and the detergent, with an assumed dosage of 2.25 dl, is based on a Procter & Gamble laundry soap (Saouter and Van Hoof, 2002). Although the detergent inventory of ingredients lists 15 chemicals, no production data are available for three of these components

(FWA DAS-1, Antifoam S1.2-3522, and Protease) that represent 2.1% of the total volume, so we model these latter as undefined chemicals without impacts. Due to total volume and chemical type, it is considered unlikely that their omission affects the results. For the reference dryer, we assume 0.95 kilowatt-hours of electricity consumption per kilogram of dried cotton, with energy consumption modeled using the most current Ecoinvent energy market data, which take into account energy trading (i.e., energy imports and exports).

	Germany	Poland	Sweden	United States	All			
One-load washing machine								
Detergent use (dl)	2.17	2.16	2.2	2.17	2.18			
Wash water temp ($^{\circ}C$)	39.35	40.77	41.86	33.25	38.81			
Washer energy consumption (kWh)	2.51	2.64	2.74	1.97	2.46			
One-load dryer								
Dryer energy consumption (kWh)	4.56	4.56	4.56	4.56	4.56			
N	1 0 0 5 11 6 1 .	1 1 100	1 1 1 1 1	1 1.1				

Table 2. Inventory for a single load of jeans in an 8 kg washing machine and a 6 kg dryer

Note: Assumes 75 l of water use per cycle, 2.25 dl of detergent, and a $14^{\circ}C$ water supply; kWh = kilowatt-hours of electricity

Lastly, for the *disposal phase*, we divide the restocking rate from the purchase phase (i.e., number of disposed jeans or t-shirts assuming a steady stock) by the reported ratios across the three disposal channels (second life, downcycling, and trash; see Table 1). For the fraction of disposed clothing items trashed, we assume landfilling via municipal waste collection by a 21-ton lorry (truck) traveling an average distance of 80 km., although national differences such as Sweden's incineration of a significant portion of waste for energy recovery may render this assumption inaccurate. However, as the overall impact of collection and disposal (ca. 0.1%) is unlikely to contribute meaningfully to the conclusions, greater inventory precision is unwarranted.

2.2.3. Interpretation methods

In discussing our findings, we not only report all assessed environmental impacts from clothing consumption using midpoint (i.e., single environmental impact) indicators but also employ multiple interpretation methods to compare the relative differences in provisioninggenerated outcomes. Through such multiplicity, we avoid the biasing of our conclusions by dominating factors in any one interpretive approach.

First, to simplify our results presentation and enable comparison with findings from other climate-impact studies, we focus on a single score environmental impact indicator, GHG emissions (alternatively known as GWP, global warming potential). Because this sole focus may increase the risk of burden shifting (Laurent et al., 2012), we also provide results for 17 additional environmental impact categories in the Supplementary Material. We further mitigate this burden shifting risk by adopting a moneuzed environmental impact interpretation method (Ögmundarson et al., 2020; Pizzol et al., 2015; Weidema, 2009) that accounts for all environmental damage through conversion to a corresponding loss of economic value. In addition to shedding light on the potential for burden shifting by comparing relative monetized impacts with single GHG scores, this method also offers insights into the relation between both the internalized and external costs associated with clothing consumption. Nonetheless, because monetarization is susceptible to uncertainty in the normalization of impacts (i.e., conversion of disparate impacts to damage with like units) (Kalbar et al., 2016b, 2012; Kalbar and Das, 2020; Sohn et al., 2017), the absolute values should be used with caution.

To compensate for the monetization method's susceptibility to uncertainty, we additionally employ the more holistic interpretation method of ArgCW-LCA (Sohn et al., 2020), which uses multiple attribute decision assessment to aggregate all midpoint impacts to a single performance rating. By paralleling the preference order and magnitude, ArgCW-

LCA serves as a sensitivity analysis ensuring that the relations identified using the monetization approach are not dominated – and thus biased – by the uncertainty in the normalization factors used. More specifically, by permitting direct observation of each midpoint impact's contribution to the single-score conclusion and allowing the use of multiple weighting factors in the analysis, it enables assessment of the sensitivity to normalization factors.

3. Results

We report our results in four sections, beginning with the environmental impacts of jeans and t-shirts via production (including transport), use, and disposal as indicated by GHG emissions. To facilitate comparison with other studies, we first report these emissions for one single pair of jeans and one t-shirt and then for the jeans and t-shirts consumed by one consumer in one year as the functional unit. The latter statistics highlight the importance of clothing consumption behavior and its implications for the associated environmental impacts. The second section scrutinizes the robustness of these results as derived using first the single impact assessment method and then the monetized environmental impact interpretation and ArgCW-LCA methods. The third section then explores the relative importance of consumer transport to clothing consumption's overall environmental impact, which, although sometimes highlighted as a major contributor, is often neglected in the research (Roos et al., 2016). To do so, we simulate the outcome of special trips made for clothing purchases only and their implications for environmental damage. Lastly, the final section addresses how behavior and context (i.e., national energy grids) determine the importance of the use phase as a contributor to the overall environmental impacts.

3.1. Environmental impacts of jeans and t-shirts per year and consumer

As outlined above, we first report the GHG emissions of single action impacts – that is, from one action (e.g., washing or drying) for one pair of jeans or one t-shirt (see Table 3) – and then those from jeans and t-shirt consumption by one consumer per year (one FU) across all consumption phases. To avoid any risk of burden shifting from this focus on GHG emissions, we supplement these results with those for 17 other environmental impact categories, which are detailed in the Supplementary Material. As Table 3 shows, for GHG emissions associated with single actions within the life cycle of one pair of jeans and one tshirt, production induces 28.1 kg CO₂-eq./pair and 5.6 kg CO₂-eq./shirt, respectively, across all countries, while transportation from producer to respective markets only has a negligible impact (0.2 and 0.04 kg CO₂-eq./item).

	Germany	Poland	Sweden	United States	All		
Jeans							
Production	28.10	28.11	28.11	28.05	28.08		
Washing	0.36	0.51	0.11	0.32	0.32		
Drying	0.77	1.19	0.04	0.61	0.65		
Disposal	0.10	0.11	0.10	0.11	0.11		
T-shirts							
Production	5.62	5.62	5.61	5.61	5.62		
Washing	0.07	0.10	0.02	0.06	0.07		
Drying	0.15	0.23	0.00	0.12	0.13		
Disposal	0.00	0.00	0.00	0.00	0.00		

Table 3. Single action impact of one pair of jeans or one t-shirt in kg CO₂-eq./clothing item per consumption action and country and on average for all countries

Note: Production includes transportation from producer to respective markets; disposal includes both waste collection and treatment.

When the unit of analysis is the jeans and t-shirt FU, however, the picture changes greatly. As Fig. 2 shows, GHG emissions for both jeans and t-shirt provisioning differ markedly between the four countries, with the t-shirt FU across all four consumption phases inducing the largest per consumer impact of 52 kg CO₂-eq./FU in the US, followed closely by 50 kg CO₂-eq./FU in Poland, and 46 kg CO₂-eq./FU in Germany. Provisioning t-shirts for Swedish consumers, in contrast, has approximately half the environmental impacts (28 kg

 CO_2 -eq./FU) of provisioning them for US consumers, while the impacts of the production phase, including transportation, ranges between 25 kg CO_2 -eq./FU for Sweden and 36 kg CO_2 -eq./FU for Poland. Despite drying having twice the impact of washing per action as is typical in countries other than Sweden (where the energy grid's lower carbon intensity lessens the impacts); in Poland and Germany, drying is responsible for much lower environmental impacts per FU than washing (Table 4).



production (incl. transport) = use = disposal

Fig. 2. Contribution of all life cycle phases to the GHG emissions from jeans and t-shirt provisioning in kg CO2-eq./FU by consumer and year

Overall, even though the environmental impacts from production per item are the same for all four countries except for very minor variances in transportation-induced effects, the between-country variability in production-induced impacts mirrors the greater restock rate. That is, the variation results from a shorter service life or greater number of items owned and the resultant higher purchasing rate. For t-shirts, the highest restock rates occur in Poland and Germany, while for jeans, restock rates are highest in Germany and the US (see Table 1). The disposal phase, in contrast, including municipal waste collection and landfilling, contributes a rather small share (at or below 0.1 kg CO₂-eq./FU) to the total GHG emissions in all countries.

The large discrepancy in t-shirt related GHG emissions between the US and Sweden, at 25 kg CO₂-eq./FU and 2.5 kg CO₂-eq./FU, respectively (see also Table 4), results mainly from the use phase. That is, whereas drying accounts for the bulk of use-phase GHG emissions in the US – specifically, 15 of the 25 kg CO₂-eq./FU – washing plays a relatively larger part in the other countries (e.g., 2.3 of 2.5 kg CO₂-eq./FU in Sweden). This discrepancy is attributable first to significant intercountry differences in use behavior (e.g., drying frequency; see Table 1) and second to differences in household electricity supplies (i.e., the carbon intensity of regional energy grids). To illustrate the latter, one dryer load induces approximately 3.0 kg CO₂-eq in the US but only 0.2 kg CO₂-eq. in Sweden.

Table 4. Contribution of the use phase to GHC emissions from jeans and t-shirt provisioning in kg CO₂-eq./FU by country

	Germany	Poland	Sweden	United States	All		
Jeans							
Washing	11.9	14.4	2.5	23.8	13.1		
Drying	5.0	4.0	0.2	36.8	11.5		
Total use	16.9	18.4	2.7	60.6	24.6		
T-shirts							
Washing	8.6	10.8	2.3	9.6	7.8		
Drying	3.9	3.1	0.2	15.0	5.6		
Total use	12.5	13.9	2.5	24.6	13.4		

These behavioral and contextual differences become even more apparent for jeans where provisioning to US consumers induces 111 kg CO_2 -eq./FU, almost three times the GHG emissions induced for Swedish consumers (40 kg CO_2 -eq./FU) and nearly double that for German (66 CO_2 -eq./FU) and Polish consumers (61 CO_2 -eq./FU). Again, the largest GHG emissions discrepancy results from the use phase, ranging from 2.7 kg CO_2 -eq./FU in Sweden to 60.6 kg CO_2 -eq./FU in the US.

To avoid biasing our conclusions, we supply sensitivity analyses drawing upon damage monetization and ArgCW-LCA methods (as described in 2.2.3). Across both interpretation methods, jeans and t-shirts provisioning consistently produce the greatest GHG emissions in the US, affirming our results above. Using the monetization method, Fig. 3 shows that US consumers would have to pay an additional price of \$39.37 and \$18.20 per jeans and t-shirt, respectively, to offset currently unaccounted for environmental damage. This greatly exceeds the additional price of \$26.87 and \$12.50, respectively, Swedish consumers would have to pay. Using the ArgCW-LCA methodology, we find that the US exhibits an idealness indicator of 0 for jeans (range: 0-1), indicating the worst performance across all midpoint impact categories, and an idealness ranking for t-shirts of 0.038 with the second lowest of 0.242 for Poland (Fig. 4). This confirms what can be inferred from a qualitative inspection of the individual midpoint impacts: the variation between the midpoints of the 18 individual environmental impact dimensions is very limited (Fig. S1 and S2).



Fig. 3. Monetized damages and GHG emission impacts from jeans and t-shirt provisioning in FU across countries.



Fig. 4. ArgCW-LCA performance indication of jeans and t-shirt provisioning in Germany, Poland, Sweden, and US. Performance indication factor of 1 is most ideal.

3.2. Purchase phase: Significance of consumer transportation

Because some research also points to clothing purchase-associated transportation as a potentially significant contributor to the environmental impacts of clothing (Roos et al., 2016), we also perform a sensitivity analysis to estimate the additional GHG emissions from such transport. Whereas for the previous analysis (see 3.1), we assume that clothing is purchased in conjunction with other daily tasks and accounts for only a trivially small share of the transportation impact (meaning no control for it in the calculations), we now consider a scenario in which consumers make a special trip via motor vehicle to purchase a pair of jeans or t-shirt.

Assuming a trip of 5 km (10 km both ways) for each clothing item purchased or restocked, a consumer making a special trip to purchase each pair of jeans for a year (one FU) induces a significant increase of about 5 kg CO₂-eq./FU in total GHG emissions across all countries (see Fig. 5). Overall, GHG emissions for both jeans and t-shirts for the average consumer increase by around 8% and 40%, respectively, from the addition of special trips for purchasing, relative to the impact of the jeans or t-shirt FU over the entire life cycle. Admittedly, the reported average purchase of 1.6 jeans and 5.4 t-shirts per year causes the

one extra trip per purchase to have a significantly greater impact for t-shirts than jeans. Nonetheless, each extra trip for either still increases GHG emissions on average by 8% and 5%, respectively, relative to the functional unit.



Fig. 5. Environmental impact of consumer transport. Consumers driving to a destination 5 km away to purchase each restocked clothing item by jeans FU and t-shirt FU for each country.

One aspect that our analysis cannot address, despite the potentially significant impact on GHG emissions of different traveling behaviors, is the assumedly different propensities among consumers in the four countries to make such additional trips, which may vary depending on transportation infrastructure, location, and clothing store distribution. Hence, although our analyses of the relative impacts based on the FU indicate significant intercountry differences in the importance of consumer personal transportation for total impacts, we derive absolute differences strictly from variation in the purchase rate.

3.3. Use phase: Behavior and context

Having previously assumed, based on their primary role in the consumer wardrobe, that jeans and t-shirts are worn about 5 times per week or 260 times per year, we now consider whether this assumption may be skewing our results. For example, whereas the original assumption implies a 54% contribution to total GHG emissions from the use phase in the US, when we calculate the GHG emissions for 0 to 365 days of wear per year, all else being equal, this contribution varies from 0% to 76% (see Fig. 6). The percentages by country reported in Fig. 6 represent washing and drying rates relative to number of wears with the potential variance in total number of annual washes and dries based on consumers' reported clothing use behavior. Hence, a steeper line indicates a larger use phase contribution per item wear from the impacts of washing and drying. As might be expected from earlier findings, the steepest lines refer to US consumers and the flattest to Swedish consumers, with German and Polish consumers somewhere in between. This indicates that the greatest sensitivity to use phase behavior is found in the US, while the least sensitivity is found in Sweden.

Because the clothing worn instead of jeans and t-shirts also needs washing and perhaps drying, reducing the number of jeans and t-shirt days would not necessarily change GHG emissions (or other environmental impacts) induced by provisioning clothing in a direct way. However, the number of wears before washing (see Table 5) – which varies from 3.5 (1.8) in the US to 12.2 (2.6) in Sweden for jeans (t-shirts) – could be a point of differentiation. Hence, GHG emissions could be reduced on an individual level by increasing the number of wears before washing to decrease the number of annual full washing cycles. Reducing the importance of use phase behavior changes on a national or regional level, however, would require lowering the carbon intensity of energy grids.



Fig. 6. Contribution to total GHG emissions induced by jeans servicing from use by number of days worn per year.

Table 5. Number of wears before	ore washing by country
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	Germany	Poland	Sweden	United States	All
Jeans	7.8	9.2	12.2	3.5	8.2
T-shirt	2.2	2.5	2.6	1.8	2.3

To explore the roles of both these strategies (i.e., the contributions of behavior and context), we place a Swedish consumer with their wearing, washing, and drying behavior into the US context with a typical US energy grid. As Fig. 7 shows, whereas this Swedish consumer induces 39.6 kg CO₂-eq./FU for jeans and 27.8 kg CO₂-eq./FU per t-shirt FU in Sweden, their GHG emissions in the US increase to 45.6 kg CO₂-eq./FU and 34.1 kg CO₂-eq./FU, respectively, around a 10% rise. In monetary terms, the identical washing and drying behavior for jeans imposes a cost of \$12.50 in Sweden but \$14.30 in the US. Nonetheless, compared to the environmental impacts from the average US consumer, that from the Swedish consumer's use phase behavior in the US is almost 65% less, representing a

significant reduction in GHG emissions. This scenario clearly illustrates that, depending on context, behavior can have a tremendous influence on the environmental impacts of clothing, so changing consumer washing and drying behaviors should be a clear priority when seeking to reduce such consequences.

Lastly, in a final analysis, we explore the potential impact of temporal changes in the energy grid and washing machine efficiency, both of which can significantly influence the environmental impacts of jeans and t-shirt provisioning. In general, the analytic results (see Fig. S5 in Supplementary Material) indicate that although improvements in the energy grid and washing machine efficiency can effectively lower the environmental impacts of clothing, these improvements satiate and must be complemented by changes in consumer behavior.



Fig. 7. Impact of Swedish use phase behavior under US energy conditions, with the environmental impact shown per FU.

4. Discussion

Because the environmental impacts of clothing provision have received limited scientific attention, substantial uncertainty persists about their scale and primary drivers (Wicker, 2020). To address this gap, this current study uses a combination of consumer survey data for four countries with life cycle analysis of consumer purchasing, use, and

disposal patterns to provide a detailed assessment of the environmental impacts of jeans and t-shirt provisioning throughout their entire life cycle. We first find substantial heterogeneity in clothing-induced environmental impacts across countries, although with the greatest impacts observed for US consumers. While our study may be the most detailed assessment across the entire clothing life cycle, the identification of US consumers as global outliers aligns well with carbon footprinting studies examining global consumption patterns (Hertwich and Peters, 2009; Hubacek et al., 2017; Ivanova et al., 2016).

A second important observation is that clothing production consistently emerges as the primary contributor to the environmental impacts of jeans and t-shirt provisioning, except for jeans in the US. In fact, because the transport from production and manufacturing facilities to clothing markets only has negligible environmental impacts, any country differences documented result almost entirely from variations in purchasing frequency or restock rate. Whereas Swedish consumers, on average, report the lowest purchasing frequency for both jeans and t-shirts, US and Polish consumers are responsible for the highest production-induced impacts from jeans and t-shirts, respectively.

Our third observation is that the contribution of the use phase and its related behaviors to the total environmental impacts of jeans and t-shirt provision varies from a minor share (in Sweden) to nearly or over half (in the US). We further show that the greater importance of the use phase in the US is driven both by more carbon-intensive energy grids (relative to Germany and Sweden) and more frequent washing and drying. The latter primarily explains the considerably greater US consumer impact from the use phase. In fact, by hypothetically transferring the washing and drying patterns of Swedish consumers to the US context, we observe that these behaviors induce a 64% lower impact than those of the average US consumer, thereby highlighting the significance of washing and drying behavior in countries with carbon-intensive energy grids.

Lastly, we identify several environmental externalities linked to jeans and t-shirt life cycles that are not currently reflected in their pricing. Whereas this unaccounted for cost may not seem overly significant at the individual level, when applied to all jeans sold annually and scaled up to a national level like the \$110 billion US jeans market (Statistica, 2019), it matters considerably. This clearly suggests a need for better accounting of the environmental externalities linked to clothing production and consumption.

4.1. Implications for studying the environmental impacts of clothing

The present study has important implications for the analysis of clothing-induced environmental impacts. Because existing research has predominantly focused on documenting the environmental impacts induced during the manufacturing and production phases and to a lesser extent the disposal phase (Ellen MacArthur Foundation, 2017; Niinimäki et al., 2020), the contribution of the use phase to the overall environmental impacts of clothing remain poorly understood. In the present study, we aimed to offer more finegrained insights into how consumers use and maintain clothing through a detailed consumer survey. Our findings show notable intercountry differences in the environmental significance of the use phase determined by variation in washing and drying behavior and the carbonintensity of energy grids. Moreover, we show that environmental impacts induced during the use phase are far from negligible and may even, as in the case of jeans in the US, represent the main contributor to GHG emissions. This is particularly relevant for the implementation of future LCAs in the context of clothing, where a stylized theoretical use phase has often been used as a proxy for self-reported (or ideally actual) behavioral data in the determination of the environmental impacts of clothing. This variation indicates that the sensitivity to differences in the use phase may significantly alter the results of most clothing impact assessments and thus warrant greater attention in the future.

Since our analysis was aggregated to the country level, greater variability and nuance may emerge from disaggregated analyses focusing on individual differences in purchasing and use-phase behavior. Here, alternative methods that offer greater precision than our crosssectional survey – for example, wardrobe analysis, experience sampling, or clothes tagging – may prove even more effective in generating detailed behavioral evidence. Nevertheless, the present results clearly underscore that the use phase should not be overlooked when analyzing the environmental impacts of clothing.

4.2. Practical implications for reducing the environmental impacts of clothing

The dominance of production in driving the environmental impacts of clothing underscores its significance for mitigation (Niinimäki et al., 2020). However, limiting these impacts require both per item damage reduction and decreased purchasing frequency. Yet despite recent progress in lowering production-induced environmental impacts by increasingly replacing cotton, wool, and polyester with alternatives like viscose and lyocell, these latter also come with unique sets of production, use, and environmental challenges (Ellen MacArthur Foundation, 2017; Laitala et al., 2018). Moreover, even though the problems presented by alternatives are often less serious than those from traditional fabrics, their use currently constitutes only a small niche in the global clothing market (Ellen MacArthur Foundation, 2017). Nonetheless, not only are noteworthy research and innovation activities attempting to bridge and minimize these environmental challenges, but recycling materials from discarded clothing is also becoming increasingly common, even among large corporations (e.g., Adidas, Nike, and Patagonia). Unfortunately, the effectiveness of recycled fabrics in lowering environmental impacts remains uncertain and may depend on whether recycling is chemical or mechanical (Niinimäki et al., 2020; Sandin and Peters, 2018).

At the same time, although alternative and recycled fabrics show some promise, particularly when complemented by initiatives to reduce energy grid-associated carbon intensity and minimize usage, these supply-side initiatives cannot stand alone (Creutzig et al., 2016). They must be pursued alongside initiatives that tackle the growing absolute and per capita demand for clothing. Addressing these problems involves reducing overall clothing consumption and shifting consumers toward alternative business models that promote greater longevity, such as clothing libraries, subscription-based rentals, in-store repair services, swapping markets, and online reselling platforms (Armstrong et al., 2015; Hvass, 2015; Joanes et al., 2020; Nielsen and Gwozdz, 2018; Pedersen and Netter, 2015; Zamani et al., 2017). Achieving these objectives will require not only initiatives to reduce demand (for an extensive discussion, see Creutzig et al., 2016; Marteau, 2017; Nielsen et al., 2021), but also an accelerated diffusion of alternative business models that ensure greater availability and popularity (Day et al., 2020) while combating consumer (mis)perceptions of secondhand or recycled clothing (Diddi and Yan, 2019). Such efforts to reduce demand may adopt pricebased initiatives like carbon pricing (Carattini et al., 2019; Klenert et al., 2018; Meckling et al., 2015), which can also help capture the environmental externalities not currently reflected in clothing prices. We do, however, note that the feasibility of carbon pricing implementation is low in many jurisdictions (Carattini et al., 2019; Creutzig, 2019; Nielsen et al., 2020), implying a need for other less politically sensitive initiatives to effectively reduce clothing demand as well.

During the transition toward more sustainable production methods, in which the reduction and shifting of demand are paramount, policymakers and practitioners should leverage other mitigation opportunities. As our analysis shows, changing use phase behavior can be as important as production phase alternatives for lowering environmental impacts, particularly in countries with carbon-intensive energy grids, widespread use of dryers, and a

consumer propensity to frequent laundering. If the environmental impacts of the use phase are to be mitigated, then consumers must prolong wear time to reduce washing frequency and avoid or reduce dryer usage. At the same time, because many consumers may not be using the newest, most energy-efficient appliances, initiatives to encourage them to update their appliances to efficient models when replacement is necessary (Dietz et al., 2009; Roy, 1994) could also significantly reduce environmental impacts (see our sensitivity analysis in Supplementary Material).

4.3. Limitations

Despite its numerous strengths, our study is still subject to certain limitations, which can nonetheless open useful avenues for future research. Most notably, as is common in LCA, our analysis makes several assumptions that despite our use of a sensitivity analysis to minimize their potential effects on our conclusions, might still have skewed our results. In addition, our strict focus on jeans and t-shirts prevents assessment of the full environmental impacts of clothing by limiting the findings to household consumers and not bulk buyers such as public institutions or private companies and organizations. It thus cannot accurately measure the relative importance of clothing production and consumption for mitigating climate change and other environmental impacts relative to other consumer products or behavioral domains (e.g., transportation, food, or electronic equipment). Also pertinent is our reliance on self-reported purchasing, use, and disposal behaviors, which, although more accurate than stylized behavioral assumptions, are subject to several potential biases, including memory bias (e.g., inaccurate reporting of purchase amounts or usage frequencies) and social desirability bias (e.g., deliberate underreporting of purchases or binning). Unfortunately, we cannot estimate the precise prevalence of these biases in our data and/or their possible variations between countries. Finally, our study is constrained to four Western

countries where clothing markets and energy infrastructure are distinct from those in lowerincome countries. Although we captured considerable variability in purchasing and use-phase behavior, even greater variability may be expected when studying clothing consumption elsewhere, especially in countries with fundamentally different purchasing patterns, washing practices, and dryer ownership.

5. Conclusion

This study provides a detailed assessment of the environmental impacts induced throughout the entire life cycle of jeans and t-shirts across four countries. Unlike previous studies which have mostly relied on stylized behavioral assumptions, the present study use self-reported consumer behavior to offer more fine-grained analyses of the environmental impacts from clothing purchasing and usage. We find that production consistently emerges as the main contributor to the environmental impacts induced by jeans and t-shirt provisioning across the four countries with the exception of jeans provisioning in the US. However, the use phase induces far from negligible environmental impacts, which depending on washing and drying frequency and the carbon intensity of the associated energy consumption may even exceed those induced from clothing production. Finally, we show that current clothing prices insufficiently account for the environmental damage created, thereby highlighting the need for policy intervention to address and better account for such damage. We hope this study can serve as a useful foundation for future research and spark greater research interest in clothing production and consumption across the sciences.

Declaration of Competing Interest

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

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References

- Armstrong, C.M., Niinimäki, K., Kujala, S., Karell, E., Lang, C., 2015. Sustainable productservice systems for clothing: Exploring consumer perceptions of consumption alternatives in Finland. J. Clean. Prod. 97, 30–39. https://doi.org/10.1016/j.jclepro.2014.01.046
- Barnes, L., Lea-Greenwood, G., 2006. Fast fashioning the supply chain: shaping the research agenda. J. Fash. Mark. Manag. 10, 259–271.
- Byun, S.-E., Sternquist, B., 2012. Here today, gone tomorrow: Consumer reactions to perceived limited availability. J. Mark. Theory Pract. 20, 223–234.
- Carattini, S., Kallbekken, S., Orlov, A., 2019. How to win public support for a global carbon tax. Nature 565, 289–291. https://doi.org/10.1038/d41586-019-00124-x
- Choudhury, A.K.R., 2014. Environmental impacts of the textile industry and its assessment through life cycle assessment, in: Roadmap to Sustainable Textiles and Clothing. Springer, pp. 1–39.
- Cotton Incorporated, 2012. Life Cycle Assessment of Cotton Fiber & Fabric. Cary, USA.
- Creutzig, F., 2019. Perspective the mitigation trinity: Coordinating policies to escalate climate mitigation. One Earth 1, 76–85. https://doi.org/10.1016/j.oneear.2019.08.007
- Creutzig, F., Fernandez, B., Haberl, H., Khosla, R., Mulugetta, Y., Seto, K.C., 2016. Beyond technology: Demand-side solutions for climate change mitigation. Annu. Rev. Environ. Resour. 41, 173–198. https://doi.org/10.1146/annurev-environ-110615-085428
- Cullen, J.M., Allwood, J.M., 2009. The role of washing machines in life cycle assessment studies the dangers of using lca for prioritization. J. Ind. Ecol. 13, 27–37. https://doi.org/10.1111/j.1530-9290.2009.00107.x
- Day, S., Godsell, J., Masi, D., Zhang, W., 2020. Predicting consumer adoption of branded subscription services: A prospect theory perspective. Bus. Strateg. Environ. 29, 1310–

1330.

- DeSimone, J.A., Harms, P.D., DeSimone, A.J., 2015. Best practice recommendations for data screening. J. Organ. Behav. 36, 171–181.
- Diddi, S., Yan, R.-N., 2019. Consumer perceptions related to clothing repair and community mending events: A circular economy perspective. Sustainability 11, 5306.
- Dietz, T., Gardner, G.T., Gilligan, J., Stern, P.C., Vandenbergh, M.P., 2009. Household actions can provide a behavioral wedge to rapidly reduce U.S. carbon emissions. Proc. Natl. Acad. Sci. 106, 18452–18456.
- Ellen MacArthur Foundation, 2017. A New Textiles Economy: Redesigning Fashion's Future.
- Ertekin, Z.O., Atik, D., 2015. Sustainable Markets: Motivating Factors, Barriers, and Remedies for Mobilization of Slow Fashion. J. Macromarketing 35, 53–69. https://doi.org/10.1177/0276146714535932
- Friedlingstein, P., Jones, M., O'sullivan, M., Andrew, R., Hauck, J., Peters, G., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., 2019. Global carbon budget 2019. Earth Syst. Sci. Data 11, 1783–1838.
- GreenDelta, 2019. OpenLCA.
- Gupta, S., Gwozdz, W., Gentry, J., 2019. The Role of Style Versus Fashion Orientation on Sustainable Apparel Consumption. J. Macromarketing 39, 188–207. https://doi.org/10.1177/0276146719835283
- Gwozdz, W., Nielsen, K.S., Müller, T., 2017. An environmental perspective on clothing consumption: Consumer segments and their behavioral patterns. Sustainability 9, 762. https://doi.org/10.3390/su9050762
- Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: A global, trade-linked analysis. Environ. Sci. Technol. 43, 6414–6420. https://doi.org/10.1021/es803496a

- Hubacek, K., Baiocchi, G., Feng, K., Muñoz Castillo, R., Sun, L., Xue, J., 2017. Global carbon inequality. Energy, Ecol. Environ. 2, 361–369. https://doi.org/10.1007/s40974-017-0072-9
- Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F.M., Stam, G., Verones, F., Vieira,
 M.D.M., Zijp, M., van Zelm, R., 2017. ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y
- Hvass, K.K., 2015. Business Model Innovation through Second Hand Retailing A Fashion Industry Case. J. Corp. Citizsh. 57, 11–32.

https://doi.org/10.9774/GLEAF.5001.2015.ma.00005

International Organization for Standardization, 2006. ISO 14040:2006.

- IPCC, 2019. Summary for Policymakers, in: Shukla, P.R., Skea, J., Buendia, E.C., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., Diemen, R. van, Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Pereira, J.P., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J. (Eds.), Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems.
- IPCC, 2018. Summary for Policymakers. Special Report: Global Warming of 1.5°C., in: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat

of Climate Change. World Meteorological Organization, Geneva, Switzerland.

- Islam, I., 2016. Energy Consumption Determinants For Apparel Sewing Operations: An Approach To Environmental Sustainability. Manhattan, Kansas.
- Ivanova, D., Stadler, K., Steen-Olsen, K., Wood, R., Vita, G., Tukker, A., Hertwich, E.G., 2016. Environmental impact assessment of household consumption. J. Ind. Ecol. 20, 526–536. https://doi.org/10.1111/jiec.12371
- Ivanova, D., Vita, G., Steen-Olsen, K., Stadler, K., Melo, P.C., Wood, R., Hertwich, E.G., 2017. Mapping the carbon footprint of EU regions. Environ. Res. Lett. 12, 054013. https://doi.org/10.1088/1748-9326/aa6da9
- Joanes, T., Gwozdz, W., Klöckner, C.A., 2020. Reducing personal clothing consumption: A cross-cultural validation of the comprehensive action determination model. J. Environ. Psychol. 101396. https://doi.org/10.1016/j.jenvp.2020.101396
- Kalbar, P.P., Birkved, M., Kabins, S., Nygaard, S.E., 2016a. Personal Metabolism (PM) coupled with Life Cycle Assessment (LCA) model: Danish Case Study. Environ. Int. 91, 168–179. https://doi.org/10.1016/j.envint.2016.02.032
- Kalbar, P.P., Birkved, M., Nygaard, S.E., Hauschild, M., 2016b. Weighting and Aggregation in Life Cycle Assessment: Do Present Aggregated Single Scores Provide Correct Decision Support? J. Ind. Ecol. 21, 1591–1600. https://doi.org/10.1111/jiec.12520
- Kalbar, P.P., Das, D., 2020. Advancing life cycle sustainability assessment using multiple criteria, Life Cycle Sustainability Assessment for Decision-Making. https://doi.org/10.1016/B978-0-12-818355-7.00010-5
- Kalbar, P.P., Karmakar, S., Asolekar, S.R., 2012. Technology assessment for wastewater treatment using multiple-attribute decision-making. Technol. Soc. 34, 295–302. https://doi.org/10.1016/j.techsoc.2012.10.001

Kant, R., 2012. Textile dyeing industry an environmental hazard. Nat. Sci. 4, 22–26.

Kennedy, C., 2017. Boycott products from states with dirty energy. Nature 551, 294–295.

- Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., Stern, N., 2018. Making carbon pricing work for citizens. Nat. Clim. Chang. 8, 669–677. https://doi.org/10.1038/s41558-018-0201-2
- Koslowski, M., Moran, D.D., Tisserant, A., 2020. Quantifying Europe's biodiversity footprints and the role of urbanization and income. Glob. Sustain. 3, 1–12.
- Laitala, K., Klepp, I.G., 2020. What affects garment lifespans? International clothing practices based on a wardrobe survey in China, Germany, Japan, the UK, and the USA. Sustainability 12, 9151.
- Laitala, K., Klepp, I.G., Henry, B., 2018. Does use matter? Comparison of environmental impacts of clothing based on fiber type. Sustainability 10, 2524.
- Laurent, A., Olsen, S.I., Hauschild, M.Z., 2012. Limitations of carbon footprint as indicator of environmental sustainability. Environ. Sci. Technol. 46, 4100–4108. https://doi.org/10.1021/es204163f
- Marteau, T.M., 2017. Towards environmentally sustainable human behaviour: Targeting non-conscious and conscious processes for effective and acceptable policies. Philos. Trans.R. Soc. A Math. Phys. Eng. Sci. 375, 20160371. https://doi.org/10.1098/rsta.2016.0371
- Meckling, J., Kelsey, N., Biber, E., Zysman, J., 2015. Winning coalitions for climate policy. Science. 349, 1170–1171. https://doi.org/10.1126/science.aab1336
- Nielsen, K.S., Clayton, S., Stern, P.C., Dietz, T., Capstick, S., Whitmarsh, L., 2021. How psychology can help limit climate change. Am. Psychol. 76, 130–144. https://doi.org/10.1037/amp0000624
- Nielsen, K.S., Gwozdz, W., 2018. Report on geographic differences in acceptance of alternative business models.

Nielsen, K.S., Stern, P.C., Dietz, T., Gilligan, J.M., van Vuuren, D.P., Figueroa, M.J., Folke,

C., Gwozdz, W., Ivanova, D., Reisch, L.A., Vandenbergh, M.P., Wolske, K.S., Wood,

R., 2020. Improving climate change mitigation analysis: A framework for examining feasibility. One Earth 3, 325–336. https://doi.org/10.1016/j.oneear.2020.08.007

- Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T., Gwilt, A., 2020. The environmental price of fast fashion. Nat. Rev. Earth Environ. 1, 189–200. https://doi.org/10.1038/s43017-020-0039-9
- O'Cass, A., 2000. An assessment of consumers product, purchase decision, advertising and consumption involvement in fashion clothing. J. Econ. Psychol. 21, 545–576.
- Ögmundarson, Ó., Herrgård, M.J., Forster, J., Hauschild, M.Z., Fantke, P., 2020. Addressing environmental sustainability of biochemicals. Nat. Sustain. 3, 167–174. https://doi.org/10.1038/s41893-019-0442-8
- Pedersen, E.R.G., Netter, S., 2015. Collaborative consumption: Business model opportunities and barriers for fashion libraries. J. Fash. Mark. Manag. 19, 258–273. https://doi.org/10.1108/JFMM-05-2013-0073
- Peters, G., Li, M., Lenzen, M., 2021. The need to decelerate fast fashion in a hot climate a global sustainability perspective on the garment industry. J. Clean. Prod. 295, 126390. https://doi.org/10.1016/j.jclepro.2021.126390
- Pizzol, M., Weidema, B., Brandão, M., Osset, P., 2015. Monetary valuation in Life Cycle Assessment: A review. J. Clean. Prod. 86, 170–179. https://doi.org/10.1016/j.jclepro.2014.08.007
- Quantis, 2018. Measuring Fashion: Insights from the Environmental Impact of the Global Apparel and Footwear Industries.
- Roos, S., Sandin, G., Zamani, B., Peters, G., Svanström, M., 2017. Will Clothing Be Sustainable? Clarifying Sustainable Fashion, in: Muthu, S.. (Ed.), Textiles and Clothing Sustainability. Springer, Singapore, pp. 1–45.

Roos, S., Zamani, B., Sandin, G., Peters, G.M., 2016. A life cycle assessment (LCA)-based approach to guiding an industry sector towards sustainability: the case of the Swedish apparel sector. J. Clean. Prod. 133, 691–700. https://doi.org/10.1016/j.jclepro.2016.05.146

Roy, R., 1994. The evolution of ecodesign. Technovation 14, 422–423.

- Sandin, G., Peters, G.M., 2018. Environmental impact of textile reuse and recycling A review. J. Clean. Prod. 184, 353–365. https://doi.org/10.1016/j.jclepro.2018.02.266
- Saouter, E., Van Hoof, G., 2002. A database for the life-cycle assessment of Procter & Gamble laundry detergents. Int. J. Life Cycle Assess. 7, 103–114. https://doi.org/10.1007/BF02978854
- Sohn, J., Bisquert, P., Buche, P., Hecham, A., Kalbar, P.P., Goldstein, B., Birkved, M.,
 Olsen, S.I., 2020. Argumentation Corrected Context Weighting-LCA: a Practical
 Method of Including Stakeholder Perspectives in Multi-Criteria Decision Support for
 Life Cycle Assessment. Sustainability 12, 2170.
- Sohn, J.L., Kalbar, P.P., Birkved, M., 2017. Life cycle based dynamic assessment coupled with multiple criteria decision analysis: A case study of determining an optimal building insulation level. J. Clean. Prod. 162, 449–457. https://doi.org/10.1016/j.jclepro.2017.06.058
- Stamminger, R., Schmitz, A., 2016. Washing machines in Europe–detailed assessment of consumption and performance. Tenside Surfactants Deterg. 53, 70–86.

Statistica, 2019. Size of the jeans wear market worldwide from 2018 to 2023.

- Steen-Olsen, K., Wood, R., Hertwich, E.G., 2016. The carbon footprint of Norwegian household consumption 1999–2012. J. Ind. Ecol. 20, 582–592.
- UNEP, 2018. Putting the brakes on fast fashion [WWW Document]. URL https://www.unenvironment.org/news-and-stories/story/putting-brakes-fast-fashion

- Weidema, B.P., 2009. Using the budget constraint to monetarise impact assessment results. Ecol. Econ. 68, 1591–1598. https://doi.org/10.1016/j.ecolecon.2008.01.019
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): Overview and methodology. Int. J. Life Cycle Assess. 3, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8
- Wicker, A., 2020. Fashion has a misinformation problem. That's bad for the environment. Vox.
- Wood, R., Moran, D., Stadler, K., Ivanova, D., Steen-Olsen, K., Tisserant, A., Hertwich,
 E.G., 2018. Prioritizing Consumption-Based Carbon Policy Based on the Evaluation of
 Mitigation Potential Using Input-Output Methods. J. Ind. Ecol. 22, 540–552.
 https://doi.org/10.1111/jiec.12702
- Zamani, B., Sandin, G., Peters, G.M., 2017. Life cycle assessment of clothing libraries: can collaborative consumption reduce the environmental impact of fast fashion? J. Clean. Prod. 162, 1368–1375. https://doi.org/10.1016/j.jclepro.2017.06.128