Sustainable Production and Consumption 58 (2025) 396–411

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Reducing environmental pressure through a more circular consumption of clothes☆

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ARTICLE INFO

Editor: Prof. K Tsagarakis

Keywords:
Apparel
Pro-environmental behaviour
Sustainable consumption
Circular economy
Environmental pressure

ABSTRACT

Clothing production and consumption contribute to various environmental problems, such as climate change and environmental pollution. With the expected growth in demand, these negative effects will only increase. Consumers making sustainable choices in the acquisition, use and disposal of garments can play a critical role in the reduction of such environmental pressures. This study, taking a circular economy perspective, assesses to what extent the adoption of circular consumer behaviour in the Netherlands could reduce environmental pressures related to clothing and which behavioural changes are most effective in doing so.

In our analysis we incorporated 14 types of behaviours, all based on a framework for consumer options related to the circular economy. To provide a realistic estimation of the environmental reduction potential of these behaviours, we not only calculated the theoretical environmental reduction potential of each behaviour but also considered behavioural plasticity (i.e., the share of consumers that do not yet engage in a behaviour but would be willing to do so) and interactions between behaviours. The theoretical reduction potential was calculated with a combination of input-output- and process analysis, and the behavioural plasticity was based on survey data of a study among Dutch consumers.

Our results show that a more circular consumption of clothing in the Netherlands could reduce approximately 11–19 % of greenhouse gas emissions and approximately 3–29 % of land use related to clothing. Buying fewer new clothes, and choosing more durable garments, garments made from more environmentally-friendly and from recycled materials are behaviours that have the highest reduction potential when behavioural plasticity is considered. Renting clothes, buying second-hand, repairing, and changes in washing and drying behaviour have a lower reduction potential.

1. Introduction

In 2015, the United Nations member states agreed on the 'Sustainable Development Goals' (SDGs) to limit environmental degradation and sustain the livelihoods of future generations, by – among other means – ensuring sustainable consumption and production patterns (SDG 12, UN, 2024). Transitioning to a circular economy can contribute to this goal through societal shifts and the introduction of business models and policy measures that promote sustainable lifestyles, limit resource use, and reduce waste (Chatham House, 2024). In this article, we focus on clothing, a specific subset of current consumption and production patterns that contributes to several environmental problems and could contribute to SDG 12 if made more circular. Driven by, among other things, a decline in textile prices (EEA, 2019; Koszewska, 2018) and garment quality (Sitra, 2022) in the past decades, global fibre production (of which more than half is used in clothes) has more than doubled between 2000 and 2023, reaching an all-time high of 124 million tonnes (Textile Exchange, 2024). This development comes with increasing environmental costs. Currently, the fashion industry is estimated to cause between 2 % (Sadowski et al., 2021) and 6.7 % (Quantis, 2018a, 2018b) of global greenhouse gas (GHG) emissions, to use around 2.5 % of global arable land for the production of (cotton) fibres (UNEP, 2020), and to contribute to 7 % of water scarcity in arid regions (Weinzettel and Pfister, 2019) due to large amounts of water mainly used for cotton cultivation and textile bleaching, dyeing, printing and finishing (Niinimäki et al., 2020). Furthermore, fertilisers, pesticides

☆ This article is part of a Special issue entitled: 'Circular Economy 2024' published in Sustainable Production and Consumption.

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https://doi.org/10.1016/j.spc.2025.07.007
Received 18 February 2025; Received in revised form 8 July 2025; Accepted 16 July 2025
Available online 21 July 2025
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and a variety of hazardous chemicals are released during textile production, leading to environmental pollution and human health impacts (Sitra, 2022; UNEP, 2020; Niinimäki et al., 2020). These negative effects are expected to exacerbate in the coming years (EMF, 2017; Sadowski et al., 2021; UNEP, 2023), particularly due to expected growth in demand for clothing in emerging markets, such as in Asia and Africa (EMF, 2017).

1.1. Objectives of this study

To reduce the environmental problems related to production and consumption of clothes, changes are needed in numerous parts of the value chain, including in the design, production, promotion, and consumption of clothes (UNEP, 2020). Consumers play a critical role here, as they make the decisions about the quantity and quality of clothes they purchase, how and how long they use the clothes and what they do with them afterwards. For the development of measures targeting clothing consumption, it is critical to understand which behavioural changes (such as buying less clothes, buying clothes made of recycled instead of virgin materials or reducing washing temperatures) can be most effective in mitigating negative environmental pressures. Several studies have assessed the environmental reduction potential of such behavioural changes; however, they do not consider that some behaviour changes might be taken up by a larger group of consumers than others (see Section 2). We argue that the share of the population that can be expected to adopt a given behaviour is a relevant aspect to consider in order to provide a realistic estimation of the environmental reduction potential. Furthermore, previous studies have assessed the environmental reduction potential for various behavioural changes separately but not considered the interactions between them. If less garments are being bought, for example, this also reduces the reduction potential that can be achieved through clothes made of recycled materials. The objective of this study is to provide a realistic estimation of the environmental reduction potential of behavioural changes of consumers related to clothing, considering both expected adoption rates and behavioural interactions.

1.2. Scope of this study

We use the Netherlands as a case for our study. The Dutch consume relatively high amounts of clothing; they are in seventh position in the EU when it comes to annual spending on apparel in 2015 (Eurostat, 2024, most recent data, controlled for the differences of price levels between countries). On average, they each buy 46 new garments annually and have 173 pieces of clothing in their wardrobe. More than a fourth of these clothes have not been worn in the past year, and less than 1 % is second-hand (Maldini et al., 2017). To reduce the environmental pressures related to the current clothing consumption, the Dutch government has announced its vision of a circular textiles value chain in 2050 and set concrete targets to achieve that (encompassing the stimulation of circular business models, the use of entirely sustainable materials in textiles, lifetime prolongation, and reduction of textile waste) (Ministry of Infrastructure and Water Management, 2023). This illustrates that there is a potential for environmental mitigation related to clothing, and the Netherlands therefore provides a suitable context for this study.

Our study encompasses environmental pressures related to the whole life cycle of clothes, from the production of fibres to the waste processing stage. This also includes the use phase of clothing, namely the electricity used for laundering and drying of clothes as well as the washing detergent. We decided to exclude consumer transport to and from the retail location, as the environmental pressures vary highly between modes of transport and the degree to which the purchase of clothes is considered the purpose of the trip. The scope of this study is limited to two indicators of environmental pressure: GHG emissions and land use (LU). GHG emissions are the main driver of climate change, and changes in LU the main driver of biodiversity loss (Jaureguiberry et al., 2022; Newbold et al., 2015). The combination of GHG emissions and LU forms a good set of indicators for assessing the environmental mitigation potential of garments because of the limited overlap between the two, as goods and services that require a lot of land often require few fossil resources and thus emit relatively few GHG emissions and vice versa (Steinmann et al., 2016). This study encompasses clothes for adults and excludes clothes for babies and children as well as shoes and accessories.

2. Literature review

Various studies assessed the environmental impacts related to the production and use of garments (see SI 1.a for an overview). The highest shares of GHG emissions and LU in the life cycle of a garment are generated in the stages of material production and manufacturing. Transport, wholesale and retail, washing and drying, and waste processing generally contribute less to the total emissions and LU. In line with these findings, studies show that consumer choices affecting the production stage of clothes (e.g., rental, buying clothes made of alternative materials or prolonging garment lifetimes) are generally associated with higher reductions in GHG emissions and LU than behaviours related to washing and drying (e.g., reducing washing frequency and temperature) or the disposal stage (e.g., handing in garments for recycling) (SI 1.b).

The importance of the washing and drying stage of the total garment life cycle (in terms of GHG emissions) varies strongly between studies, mainly due to differences in functional units, system boundaries and washing parameters (e.g., laundry frequency, washing temperature, share of laundry that is machine-dried, energy use for the washing machine and dryer, and emissions intensity for electricity) (Luo et al., 2023). Reasons for these differences might be that the parameters vary strongly between different countries and over time. For example, the use of dryers is more widespread in the USA than in Europe (Cabeza et al., 2018), the share of renewable energy has grown over the years and varies substantially between countries (Ritchie et al., 2020), and energy efficiency of appliances on the market has increased in recent years (Sohn et al., 2021).

2.1. Research gaps

Previous studies have assessed the environmental reduction potential of sustainable clothing behaviour under the assumption that each behaviour would be adopted by all consumers. They do not take into account the extent to which each behaviour can be expected to be taken up by the population (e.g., Horn et al., 2023; Schmutz et al., 2021; Sandin et al., 2019) or do so only for a limited set of behaviours and largely based on assumptions (Wiprächtiger et al., 2022). Sustainable behaviour may mitigate negative environmental effects in theory; however, this mitigation potential is only realised in practice if consumers are actually willing to change their behaviour. The proportion of people that could be induced to change their behaviour under a particular set of policies, opportunities and constraints is referred to as ‘behavioural plasticity’ (Dietz, 2023). Research has shown that many types of sustainable behaviour with a rather large reduction potential in theory have a limited behavioural plasticity (such as behaviour related to lowering consumption levels and saving energy), either because most people have already adopted the behaviour or because they are not willing to adopt it (Koch et al., 2024). This means that the environmental benefit of these behaviours is likely much lower in practice. At the same time, consumer behaviour with a relatively small reduction potential in theory but a relatively high behavioural plasticity (such as purchasing environmentally-friendly product alternatives and prolonging product lifetimes) might contribute to a considerable reduction in environmental pressures, because many people are likely to adopt the behaviour. Behavioural plasticity is therefore a relevant aspect to provide realistic estimates of the environmental mitigation potential

expected from sustainable behaviour changes. An environmental assessment integrating empirical data on behaviour plasticity is still lacking in the existing literature around sustainable clothing consumption.

An additional gap in previous research is that the environmental effects have not been assessed for combinations of behavioural changes, but just for individual behavioural changes. The latter approach allows for comparison between behaviour changes to identify the ones with the highest (theoretical) environmental reduction potential. However, the additional step to estimate the total environmental benefit resulting from multiple behavioural changes is missing. Due to interactions between different behaviour, their total environmental reduction potential is smaller than the sum of the environmental reduction potential of individual behavioural changes. For example, if less garments are being bought, the reduction potential that can be achieved through clothes made of recycled materials is reduced.

2.2. Research question

Our main research question based on the observed research gaps is: ***To what extent can changes in consumer behaviour reduce current environmental pressures related to clothing when considering behavioural plasticity and interactions between behaviours?*** In our study, the resulting environmental reduction potential, which considers behavioural plasticity, is referred to as the '*reasonably achievable reduction potential*' (RARP), in contrast to the '*theoretical reduction potential*' (TRP, see Table 1). We do not only estimate of the environmental reduction potential of individual behavioural changes but also of the total mitigation potential that could be achieved through a more sustainable clothing consumption in the Netherlands. To do so, we develop and apply an approach to combine the environmental effects from individual behaviour changes considering interactions between them.

3. Methods

Table 1 gives an overview of the key terms used in this study and their definitions. In Fig. 1, we provide an overview of the methodological steps taken and data used to address our research question. We take the current environmental pressures related to clothing consumption of adults in the Netherlands as a starting point (step 1 in Fig. 1) to calculate the TRP of each behaviour change (step 2). This is done by comparing the environmental pressure of different types of circular behaviour (e.g., buying second-hand or renting clothes) to the environmental pressure of the current standard (purchasing new clothes). By multiplying the TRP of each behaviour change with the share of Dutch consumers that would be willing to adopt the circular behaviour (i.e., behaviour plasticity), we get an estimation of the total annual RARP for each behaviour change (step 3). We assess the behavioural plasticity based on survey data from an earlier study (Koch et al., 2024) about consumers' current uptake of the different clothing behaviours and consumers' willingness to engage in them. To calculate the total RARP of a more circular clothing consumption for the Netherlands as a whole, given all consumers would adopt the circular behaviours they are willing to do, we account for interactions between the different behaviours (step 4). These 4 steps are explained in more detail in the following Sections 3.1–3.4.

3.1. The current environmental pressures of Dutch clothing consumption (step 1)

We calculated the total environmental pressures related to clothing consumption of households in the Netherlands (*EP*) through the following Eq. (1):

$$EP = HN^{*}\Sigma_j\, e_j{}^{*}i_j \quad (1)$$

HN is the number of households in the Netherlands,
e_j is the household expenditure of a given expenditure category j

Table 1
Key terms and definitions used in this study.

Term	Abbreviation	Definition	Unit of measurement
Circular consumer behaviour	–	The individual acts performed by people to satisfy their needs in various areas of life, in which they acquire, use and dispose of goods and services that contribute to the principles of a circular economy: narrow, slow down, close, and substitute resource flows (Koch et al., 2024, based on Geiger et al., 2018; Hanemaaijer et al., 2023; Bocken et al., 2016).	–
Greenhouse gas emissions	GHG emissions	Greenhouse gas emissions (CO_2, CH_4, N_2O, NO_x, SO_2, NH_3, CFK-12 equivalents, CO, NMVOs, PM10) generated over the different life cycle stages of a garment (production, transport, wholesale/ retail, washing/drying, and disposal).	kg CO_2 equivalents
Land use	LU	Land used over the different life cycle stages of a garment (production, transport, wholesale/ retail, washing/drying, and disposal).	m^2
Theoretical reduction potential	TRP	The environmental benefits that result from a consumer adopting a given circular behaviour.	kg CO_2 equivalents and m^2 per year
Behavioural plasticity	BP	The proportion of people that could be induced to change their behaviour under a particular set of policies, opportunities and constraints (Dietz, 2023). In this study, behavioural plasticity is defined as the proportion of people who do currently not engage in a given circular behaviour but would be willing to do so if circular goods and services were more easily accessible and not more expensive than currently common non-circular alternatives (based on Koch et al., 2024).	% of the population
Reasonably achievable reduction potential	RARP	The environmental benefits that result from consumers adopting a given circular behaviour, encompassing behavioural plasticity. The term 'reasonably achievable reduction potential' is based on earlier research by Dietz et al. (2009) who used a similar approach to estimate the carbon emissions reduction potential from energy	kg CO_2 equivalents and m^2 per year

(*continued on next page*)

Table 1 (*continued*)

Term	Abbreviation	Definition	Unit of measurement
		saving behaviour of American households and described it as 'reasonably achievable emissions reduction'.	
Total reasonably achievable reduction potential	Total RARP	The environmental benefits that result from consumers adopting multiple circular behaviours, encompassing behavioural plasticity and interactions between behaviours.	kg CO_2 equivalents and m^2 per year
Maximum achievable reduction potential	–	The environmental benefits that could be attained if not only the willing consumers adopted a given circular behaviour but also the ones who are currently not willing to do so.	kg CO_2 equivalents and m^2 per year

related to clothing consumption, and

i_j is the environmental intensity of that same expenditure category j.

3.1.1. Household expenditure

The starting point is the annual household expenditure related to clothing. The expenditure data is derived from Statistics Netherlands for the year 2017 (as provided by Benders et al., 2021, based on 2015 values from CBS, 2017a that are converted to 2017 using consumer price indices). We selected the following expenditure categories:

i. Men's and women's clothes
ii. Clothes repair and rental
iii. Laundry and dry-cleaning services
iv. Laundry detergent
v. Electricity use (washing, drying, and ironing)

Given our scope of clothes for adults, we corrected the expenditures for each category by excluding the share related to children (based on the national age distribution, CBS, 2024a) and the share related to household textiles (50 % of households' laundry, Groot-Marcus and Scherhorn, 1994). For category v, the share of energy use related to washing, drying and ironing of adults' clothes was calculated (based on the EVA-model by Vethman, 2019 and own assumptions, see SI 2.a). The expenditures related to the washing machine and dryer themselves are not included in our calculation.

3.1.2. Environmental intensity

Next, we multiplied the annual household expenditure of each category with its 'environmental intensity' (i.e., GHG emissions and LU per Euro spent). This results in the annual environmental impact per category for an average Dutch household. The environmental intensity of each category is the result of the environmental impact of a unit of the product or service divided by its consumer price. The environmental intensities for the categories ii-v were taken from the 'Environmental Analysis Program' (EAP, version 4.5, Benders et al., 2021; see Section 3.2.1), and for category i, we calculated the environmental intensity ourselves. We did so by assessing the environmental impact and price of five different versions (new, second-hand, environmentally-friendly, durable, and recycled, following the method described in Section 3.2) of a piece of clothing (average of a pullover, shirt, and trousers) and weighing these versions based on the current uptake share of each option (using survey data from Koch et al., 2024) (see SI 2.b).

To obtain the total annual GHG emissions and LU of all Dutch households related to clothing, we summed up the environmental impact of all five categories and multiplied the result by the number of households in the Netherlands (data for 2017; CBS, 2024b).

3.2. Theoretical reduction potential (TRP) per behaviour (step 2)

The TRP describes the environmental pressures that could be avoided if a person engaged in a certain circular clothing behaviour instead of the currently common, non-circular behaviour ('*default*', e.g., buying a second-hand garment instead of a new one), not considering behavioural plasticity (Koch et al., 2024). The annual TRP of a given behaviour can be calculated as follows (Eq. (2)):

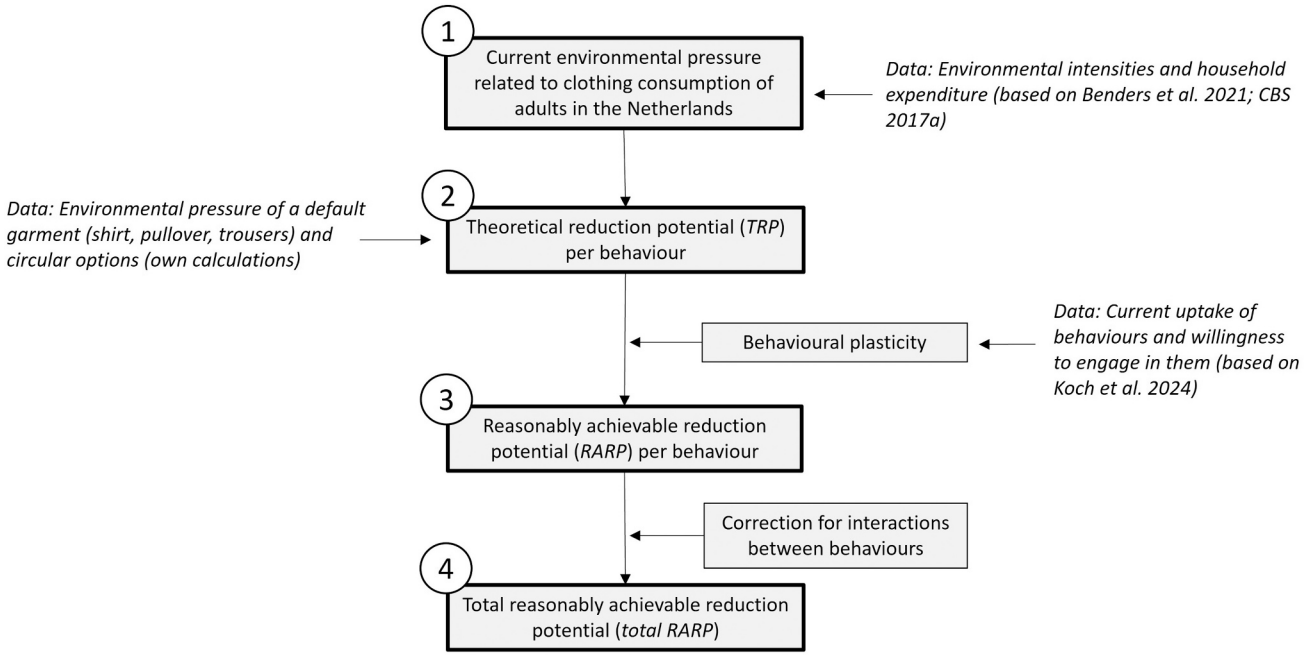

Fig. 1. A schematic illustration of the methodological steps and data used in this study.

$$TRP = X^*m^*i \quad (2)$$

X is the annual environmental pressure of a person who does not engage in the behaviour in question,

m is the reduction percentage that behaviour can achieve,

i is the intensity in which this behaviour is expected to be carried out.

X was calculated by using the average annual environmental pressure per adult person related to clothing (A) as a starting point. A is the result of the calculation in Section 3.1 per household, divided by the average number of adults per household in the Netherlands (for 2017, CBS, 2024c). We can describe A as the annual environmental pressure of the two groups who engage and do not engage in the behaviour (C and X), weighted by their proportion of the population. See Eq. (3):

$$A = (1-c)^*X + c^*C \quad (3)$$

c is the share of people who engage in the behaviour, and

C is the annual environmental pressure of a person who engages in the behaviour in question.

C can be described as $C = (1\text{-}m * i) * X$. Therefore, Eq. (3) can be replaced by Eq. (4):

$$A = (1-c)^*X + c^*(1-m^*i)^*X \quad (4)$$

This leads to Eq. (5) to calculate X:

$$X = A/(1-m^*i^*c) \quad (5)$$

We can thus calculate TRP based on A, m, i, and c, as shown in Eq. (6):

$$TRP = A^*m^*i/(1-m^*i^*c) \quad (6)$$

The uptake rate c is derived from Koch et al. (2024), see Table 3). To determine m, we calculated the GHG emissions and LU for the default for a pullover, shirt, and trousers (see Section 3.2.1) and for each circular behaviour alternative (see Section 3.2.2). The reduction achieved by a circular behaviour in comparison to the default is m. The behaviour intensity factor i describes the share of a person's garments a circular behaviour applies to. For most circular behaviours in our study, we used a behaviour intensity of 100 %. For a few behaviours, which seem hard for consumers to apply to *all* their clothes, we calculated the TRP with a lower behaviour intensity, meaning that each person would apply this behaviour to a certain share of their clothes (e.g., renting half of their clothes or reducing clothes purchases by half). An overview of the behaviour intensities used in this study can be found in SI 3.

3.2.1. Default

We selected a pullover, a shirt, and a pair of trousers for the calculations of the reduction percentage m as these three items represent widely used garments that cover top and bottom and are, moreover, suitable to calculate variations in main characteristics that affect the environmental footprint (such as types of materials, washing frequency, lifetime and price). The functional unit of this study is the purchase and use of one item over its total lifetime. The *default* is defined as purchasing a new garment, wearing, washing and drying it according to the Dutch average and throwing it away after the average lifetime. More details about the assumptions and sources used for the calculation can be found in SI 4.

The environmental pressures were calculated using a hybrid approach combining input-output analysis and process analysis, as shown in Fig. 2 (based on Bullard et al., 1978; Van Engelenburg et al., 1994; Wilting, 1996). The figure shows the assessed elements of the total life cycle of a garment. The environmental pressures related to the life cycle elements clothing fibres, transport, energy use in the use phase (washing and drying) and waste management are based on process analysis, using the database 'EcoInvent' and additional literature on recycled fibres. The pressures related to the production process of the garment and to wholesale/retail are based on input-output analysis.

We used EAP (version 4.5, see Benders et al., 2021) for the calculation of the total environmental footprint of a garment. EAP uses the consumer price of the garment as the starting point. The consumer price is reduced by the value-added tax (VAT, 21 %), trade margins (54.4 %, Benders et al., 2021, based on CBS, 2017b), and the prices of the clothing fibres. Based on input-output-tables, the resulting amount is split into production costs, capital goods (means of production such as buildings and machinery) and residual goods. 'Residual goods' encompass the remaining materials that are also part of the final product but are unknown or are of tiny quantities, as well as the products and services that are indirectly used during production, such as office equipment and building maintenance. The environmental pressures related to the fibre production, transport, direct energy use and waste management are added based on process analysis. A more detailed description of EAP can be found in Benders et al. (2001, 2012). All the life cycle elements depicted in Fig. 2 add up to the total environmental pressure of a garment. This total environmental pressure was divided by the average lifetime of a garment, resulting in the environmental pressure per piece per year.

3.2.2. Circular clothing behaviours

To identify sustainable consumer behaviours related to clothes, we used a framework on circular consumer behaviour presented in Koch et al. (2024). This framework combines strategies contributing to the circular economy (so-called "R-strategies") with consumption phases (i.e., acquiring, using and disposing). Each R-strategy contributes to a reduction in resource use and related environmental pressures through one of four circular economy principles: i) *narrow* resource flows (reduce

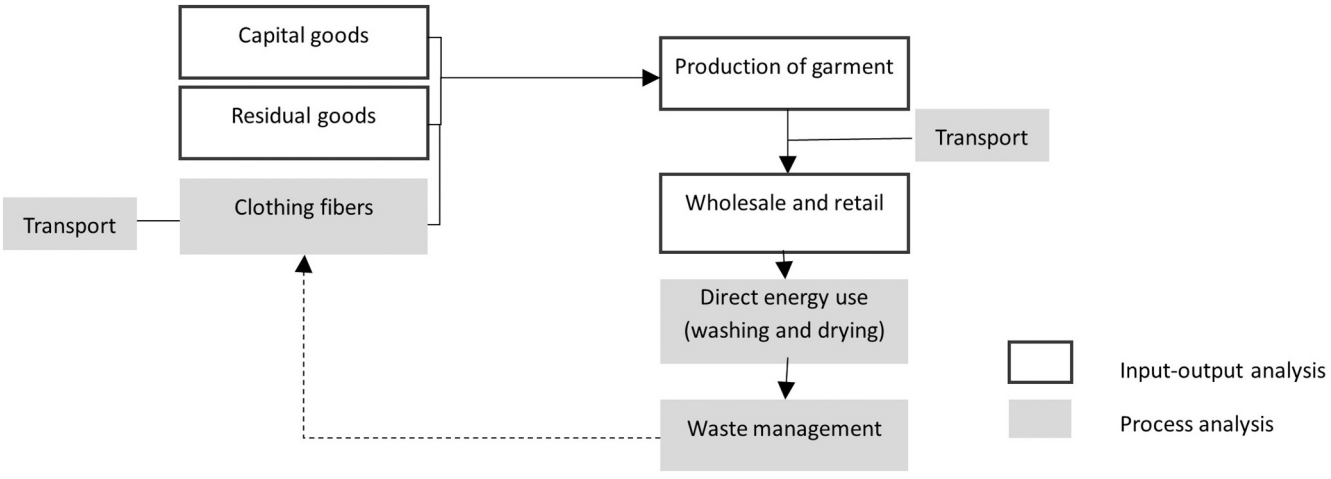

Fig. 2. Elements of the life cycle of clothes used for the analysis.

the use of materials and products), ii) *slow* down resource flows (extend product life so less new products are needed), iii) *close* resource loops (recycle products at the end of their life span so less new materials are needed), and iv) *substitute* resource flows (replace products with alternatives that are made of renewable materials or materials with less environmental impact) (Hanemaaijer et al., 2023, based on Bocken et al., 2016). Consumers can contribute to each principle through different behaviour during each of the three consumption phases of clothes (Table 2). For instance, consumers can contribute to narrowing resource flows by renting clothes instead of owning them or by refraining from new clothing purchases in the acquisition phase. This reduces the amount of clothes that need to be produced. Or they can contribute to closing resource loops by buying garments made from recycled fibres and handing damaged garments in for recycling. By applying the framework to clothing consumption, we identified 14 circular behaviours consumers can engage in.

To assess the TRP, we calculated the reduction percentage (*m*) of each circular behaviour compared to the default (for a shirt, a pullover, and a pair of trousers, separately) by altering the different variables in the calculation, such as material composition, product lifetime, washing frequency or washing temperature. For example, in the case of washing clothes at lower temperature, the washing temperature of a shirt, pullover and pair of trousers was reduced to 30 degrees while all other variables in the calculation stayed the same as in the default option. In the case of durable clothes, we increased the price of the garment and its lifetime but kept all other variables the same (see SI 5). The environmental pressures of each circular option compared to the environmental pressures of the default represents *m*. We used the average *m* of each circular option for a pullover, shirt, and pair of trousers for the calculation of the TRP.

Table 2
Circular consumers behaviours related to clothing.

CE principles	R-strategies	Consumption phases		
		Acquire	Use	Dispose of
Narrow	Refuse	–	–	–
	Rethink	(1) Rent clothes	–	–
	Reduce	(2) Buy fewer new clothes	(7) Wash clothes less often, (8) in an energy-efficient washing machine, (9) at a lower temperature, (10) in eco-mode, and (11) wash & dry sensitive clothes gently	–
Slow	Reuse	(3) Buy second-hand and (4) durable clothes	–	(13) Sell or donate clothes for reuse (e.g. via second-hand stores, clothes swap events or family and friends)
	Repair	–	(12) Get damaged clothes repaired	–
Close	Recycle	(5) Buy clothes made of recycled materials	–	(14) Hand in clothes for recycling (via clothing collection bins)
Substitute	–	(6) Buy clothes made of environmentally-friendly materials		

3.2.3. Main assumptions

In this section, we describe the main assumptions used in our calculations. More details about the assumptions and respective sources can be found in SI 4 (default garments), SI 5 (overview of circular behaviour alternatives), SI 6 (variations in material composition), and SI 7 (clothes rental).

3.2.3.1. Lifetime. To account for lifetime prolongation that results from certain consumer options, we calculated the TRP based on the *annual* environmental pressures related to the purchase and use of one item. This means that we divided the total GHG emissions and LU of the default and of each circular behaviour alternative by the average lifetime. The lifetime of the default pullover, shirt and trousers and the different environmentally-friendly alternatives were based on data from the Nielsen Company (2012, as presented in Laitala et al., 2018), as this data provided enough granularity for our calculations, allowing for differentiation between different garment types and material composition. For second-hand, repair, and more durable quality, we could not find any data on lifetime prolongation. We assumed a prolongation of +50 % for all three behaviours. The same goes for lifetime prolongation through washing less and washing gently: it has been argued that these behaviours have a positive effect on garments' lifetimes (Laitala and Klepp, 2020), but no data could be found. Here, we assumed a prolongation of +10 %.

3.2.3.2. Material composition. For the default, we selected commonly used material compositions per garment type based on the most recently acquired garment among Dutch consumers (2021, survey documented in Koch et al., 2024): cotton-polyester mix for a pullover, full cotton for a shirt, and jeans (cotton-elastane mix) for trousers (see SI 4). For recycled and more environmentally-friendly alternatives, we altered the material composition of a default pullover, shirt, and pair of trousers, considering material-specific changes in weight, garment lifetime, washing frequency, washing temperature and drying activities (see SI 5). For recycled materials, the default material composition (e.g., conventional cotton) was replaced by the recycled alternative (recycled cotton). As the recycled content in garments on the market varies strongly (between 5 and 50 %, Kort et al., 2023), we incorporated this element as a range in our calculations. Regarding environmentally-friendly garments, we also incorporated a range, covering different types of environmentally-friendly material alternatives (hemp, jute, kenaf, linen, and lyocell). We selected them as environmentally-friendly as they result in a reduction in GHG emissions or LU compared to the default material composition. We also included organic cotton as an environmentally-friendly material – even though it requires more land than conventional cotton farming – because of biodiversity benefits of organic farming practices (Rahmann, 2011). We excluded polyester and wool from the environmentally-friendly material selection. Wool was excluded because woollen garments are associated with more GHG emissions and LU compared to the default, even when considering a longer garment lifetime, lower weight, washing frequency and temperature, and a higher amount of hand-washing and air-drying (see SI 6). Polyester garments have lower GHG emissions and LU compared to the default (due to lower weight and longer lifetime, see SI 6). However, because polyester fabrics contribute to environmental pollution through the release of microplastics (Šaravanja et al., 2022; Dalla Fontana et al., 2020; Hernandez et al., 2017), we decided not to select polyester as an environmentally-friendly material. Furthermore, we did not consider the different materials' recyclability after use. Mechanical shredding of textile waste results in short, low quality fibres, often leading to

downcycling and limited further recyclability (Arafat and Uddin, 2022; Celep et al., 2022; Bryce, 2021).

3.2.3.3. Product price. The prices of the default garments were determined based on typical prices of a big, widely used clothing retailer: €50 for a pullover, €25 for a shirt, and €60 for a pair of trousers. More durable garments and garments made of environmentally-friendly materials, such as bast fibres, lyocell or organic fibres, are generally sold at a higher price compared to the default. With the hybrid method used in our study, a higher product price results in higher environmental pressures for the garment production and wholesale/retail. This assumption seems reasonable for durable garments as they are generally sold in different stores in a higher price segment compared to default garments. The higher environmental pressures for production and wholesale/retail thus seem justified by a more resource-intensive design, manufacturing and sale. Environmentally-friendly garments, however, are likely to be manufactured in the same countries and sold in the same stores as default clothes. We therefore assumed that the environmental pressures stemming from production and wholesale/retail would not differ between default garments and environmentally-friendly alternatives. Differences in fibre production and transport were still considered (see SI 6, Table S6.4 for more information).

3.2.3.4. Allocation among different users. Circular behaviour related to rethink, reuse and recycling involves more than one user. We distributed the environmental pressures among the different users based on the economic value the garment has at the stage of transfer. For second-hand, we assume a price of 20 % in comparison to the new price, which means that the first user of the garment gets allocated 80 % of the environmental pressure and the second user 20 %. We assume that garments do not have any value left at the point they are disposed of. As a consequence, the environmental pressures of the waste collection get fully allocated to the first user. The environmental benefit from heat recovery and recycling of disposed garments is fully allocated to the second user. This means that the energy generated through incineration is allocated to the energy user, and the environmental benefit from recycling is allocated to the buyers of garments made of recycled materials. Recycled fibres therefore only bear the environmental pressure of the recycling process (system model cut-off by classification, Ecoinvent, 2023).

3.2.3.5. Substitution rate. For second-hand purchasing, the environmental effects highly depend on the extent to which a second-hand garment prevents a consumer from buying a new piece of clothing. This substitution rate varies strongly between studies among European consumers (Patwary, 2020), between 28.5 % (i.e., each second-hand garment replaces 28.5 % of a purchase of a newly produced garment, Stevenson and Gmitrowicz, 2012) and 60 % (Farrant et al., 2010). We therefore used both the minimum and maximum substitution rate as a range in our calculations.

3.2.3.6. Rental. For clothes rental, we calculated the annual GHG emissions and LU related to replacing the annual use of one clothing item by a rental service. A specific pullover, for example, is worn about 3.5 times a year on average for 7 consecutive days. We therefore assumed that a person would need 3.5 rental pullovers within one year to replace the item. Whether clothes rental leads to a positive or negative TRP, and to what extent, highly depends on what the business model looks like and how it is used by consumers. Following Piontek et al. (2020), we base our calculations on a business model that provides each customer with a curated box containing three pieces of clothing, which are used for a fixed period of time before the box is exchanged for a new one. Apart from the number of users over the lifetime of the rental garment and the degree to which rental replaces new purchases (substitution rate), the choice of transport has a strong effect on the environmental impact of clothes rental (Johnson and Plepys, 2021; Piontek et al., 2020; Zamani et al., 2017). While we did not include transport in the default option of a garment purchase, we decided to take it into account in the rental option to show potential rebound effects that can arise from transport. We varied the following four variables:

- Transport mode: car, public transport, bike, delivery (including 20 g LDPE packaging)
- Transport distance (consumer to rental shop) for car and public transport options: 5 km, 3 km, 1 km
- Number of users over garment lifetime: 5, 10, 15
- Substitution rate: 33 %, 50 %, 100 %

The combination of these variables results in 72 scenarios, which we compared to the annual environmental pressure of a default item. We used these 72 scenarios to define the range for the TRP for rental clothes (for more information, see SI 7).

3.3. Reasonably achievable reduction potential (RARP) per behaviour (step 3)

The RARP of the adoption of each circular behaviour is calculated by multiplying the TRP with the number of people that would be willing to engage in the circular behaviour but do not do so yet (behavioural plasticity, BP). Specifically, we used Eq. (7):

$$RARP = TRP^{*}BP^{*}AH^{*}HN \quad (7)$$

AH is the average number of adults per household and
HN is the number of households in the Netherlands.

The number of households was retrieved from CBS (2024b, 2024c) for the year 2017 to match the year of the household expenditure data (Section 3.1.1). We derived the data on behavioural plasticity from a survey among a representative sample of the Dutch adult population ($n = 2542$) that was held in 2021 and has been described in an earlier publication (Koch et al., 2024). The survey measured respondents' self-reported current uptake of circular behaviour (regarding clothes and other goods and services) and willingness to engage in circular behaviour if two major obstacles (price and inconvenience) would be removed. We define behavioural plasticity of a given circular behaviour as the share of consumers who do not currently engage in the behaviour but would be willing to do so under the condition that the behaviour was as easily accessible and not more expensive than the current standard. Behavioural plasticity is thus calculated as the difference between its current uptake rate *c* (i.e., the share of consumers that report to engage in the behaviour) and the willingness rate *w* (i.e., the share of consumers that would be willing to adopt the behaviour) (see Koch et al., 2024). Table 3 provides an overview of the behavioural plasticity, current uptake rate and willingness rate for each assessed circular clothing behaviour.

3.3.1. Corrections of behavioural plasticity

The self-reported data on behaviour and willingness of consumers to donate and sell garments for reuse from Koch et al. (2024) (37 % and 82 %, respectively) do not correspond with the current behaviour and willingness to purchase second-hand garments (3 % and 26 %, respectively). The gap can partly be explained by the fact that donated clothes often do not end up being reused: more than 60 % of textiles that are brought to second-hand stores in the Netherlands are not sold for reuse but are instead recycled or incinerated (BKN, 2020). To match the potential increase in supply and demand in our calculation, we replaced the behavioural plasticity of donating and selling garments for reuse (45 %) by 12 %, which is the plasticity of purchasing second-hand garments (23 %) multiplied by 50 % behaviour intensity of purchasing second-hand (see introduction of Section 3.2, factor *i*).

Table 3
Current uptake rate, willingness to engage in each behaviour (2021, based on Koch et al., 2024), resulting behavioural plasticity, and maximum behavioural plasticity as a percentage of all adult Dutch consumers.

Circular clothing behaviour	Current uptake (c)	Willingness (w)	Behavioural plasticity (w-c)	Maximum behavioural plasticity (100 %-c)
Rent clothes	1 %	4 %	3 %	99 %
Buy fewer new clothes	25 %	66 %	41 %	75 %
Buy second-hand clothes	3 %	26 %	23 %	64 %[1]
Buy durable clothes	30 %	100 %	70 %	70 %
Buy clothes made of recycled materials	6 %	67 %	61 %	94 %
Buy clothes made of environmentally-friendly materials	14 %	57 %	43 %	86 %
Wash clothes less often	23 %[2]	23 %[3]	0 %	67 %
Wash clothes with energy-efficient washing machine	75 %	97 %	22 %	25 %
Wash clothes at lower temperature	46 %	79 %	33 %	54 %
Wash clothes in eco-mode	33 %	73 %	40 %	67 %
Wash & dry sensitive clothes gently	52 %	81 %	29 %	48 %
Get damaged clothes repaired	25 %[4]	48 %	23 %	75 %
Sell or donate clothes for reuse	37 %	82 %	12 %[5]	63 %
Hand in clothes for recycling	71 %	89 %	18 %	29 %

[1] Technical limitation is 67 % instead of 100 % (see Section 3.3.2).
[2] Data based on Brusdal (2003) and Laitala et al. (2018): Average share of Dutch consumers who wear T-shirts and jeans longer than average before washing.
[3] The main motivation for Dutch consumers to decide when to wash their clothes is that they find that the clothes do not smell and/or look fresh (D&B, 2020). Washing them less often is already the more convenient and less expensive behaviour. Therefore, we assume that the willingness to wear clothes longer before washing them would – under the condition that it was more convenient and less expensive – stay equal to the current behaviour.
[4] Data based on Milieu Centraal (2023): share of Dutch consumers who often or always repair clothes or get them repaired so they can be used longer.
[5] Correction to match supply and demand of second-hand clothes.

3.3.2. Maximum achievable reduction potential

To provide insight into the additional reduction potential that could be achieved if consumers' willingness increased in the future, we compared the RARP with the maximum achievable reduction potential that could be attained if not only the willing consumers adopted a given circular behaviour but also the ones who are currently not willing to do so. To assess the maximum achievable reduction potential, we calculated the maximum plasticity (Table 3). For most behaviours, 100 % adoption would principally be possible. For example, everyone could get their damaged clothes repaired or wash with an energy-efficient washing machine. For second-hand clothing, however, 100 % adoption is technically not possible as new purchases will always be necessary to replace clothes that are damaged or obsolete and can no longer be repaired. As we assumed a lifetime prolongation of 50 % for second-hand clothes compared to the default (see Section 3.2.3), this means that for every second-hand garment, two new garments are needed. The maximum uptake of second-hand clothes is thus 33 %. Given our assumption that the behaviour intensity for purchasing second-hand is 50 % (introduction to Section 3.2), the maximum uptake for this behaviour is 67 % (33 % * 2).

3.4. Total reasonably achievable reduction potential (total RARP) (step 4)

In the previous three steps (Sections 3.1–3.3), we described how we calculated the RARP for each individual behaviour change. In addition, we aim to provide an estimate of the total RARP that could be achieved if consumers adopted all types of circular behaviour they are willing to engage in. For this, it is necessary to account for the interactions between behaviours. For example, if consumers buy fewer clothes, the mitigation potential from buying clothes made of environmentally-friendly materials is reduced. To account for such interactions, we determined how the circular behaviours are related to each other by means of a tree diagram (see Fig. 3, divided into behaviours related to the acquisition and use of clothes, and behaviours related to the washing of clothes).

We follow the approach by Dietz et al. (2009), according to which behaviours can either interact additively or multiplicatively. We treat the behaviours that are depicted horizontally in Fig. 3 as mutually exclusive. For example, clothes can either be bought, rented, reduced or refused. The environmental reduction of these four behaviours can therefore be added together. Based on the formula for the RARP of each behaviour change (see Section 3.3), we can calculate the reduction potential of behaviours that interact additively as shown in Eq. (8):

$$RARP_{b1+b2} = (TRP_{b1} * BP_{b1} + TRP_{b2} * BP_{b2}) * AN \quad (8)$$

$RARP_{b1+b2}$ is the total reasonably achievable reduction potential of mutually exclusive behaviours b1 and b2,

BP_{b1} is the behavioural plasticity of a circular behaviour b1 (e.g., renting clothes),

TRP_{b1} is the TRP of that same behaviour b1,

BP_{b2} is the behavioural plasticity of another circular behaviour b2 that is mutually exclusive to behaviour b1 (e.g. refusing clothes), and

TRP_{b2} is the TRP of that same behaviour b2, and

AN is the number of adults in the Netherlands.

Vertically in Fig. 3, behaviours branch out into combinations of different behaviours. The environmental reductions of these behaviours combine multiplicatively. This means that the adoption of one behaviour reduces the potential environmental gains that can be achieved through the adoption of the other behaviour, so that the reduction potential from adopting both behaviours is less than the sum of the reduction potential of each behaviour separately. In the case of clothes that are bought, for example, there are different options for the material composition: the purchased clothes can either be made of recycled materials, environmentally-friendly materials or the default material composition. Furthermore, for each of those garment types, consumers can engage in different behaviours that extend garment lifetimes (reuse, repair, buy durable quality garment) or in the default. This leads to behaviour combinations, such as buying a garment made of recycled materials and prolonging its lifetime through repair. For these combined behaviours, we use Eq. (9), in which we multiply the TRP (as a percentage of the average annual environmental pressure per person related to clothing (A)) of both behaviours:

$$RARP_{b1*b3} = (100\% - (100\% - (TRP_{b1}/A)) * (100\% - (TRP_{b3}/A)) * A * BP_{b1*b3}) * AN \quad (9)$$

$RARP_{b1*b2}$ is the total reasonably achievable reduction potential of the combination of behaviours b1 and b3,

TRP_{b1} is the TRP of a circular behaviour b1 (e.g., buying clothes made of recycled materials),

TRP_{b3} is the TRP of another circular behaviour b3 that can be combined with behaviour b1 (e.g., repairing clothes), and

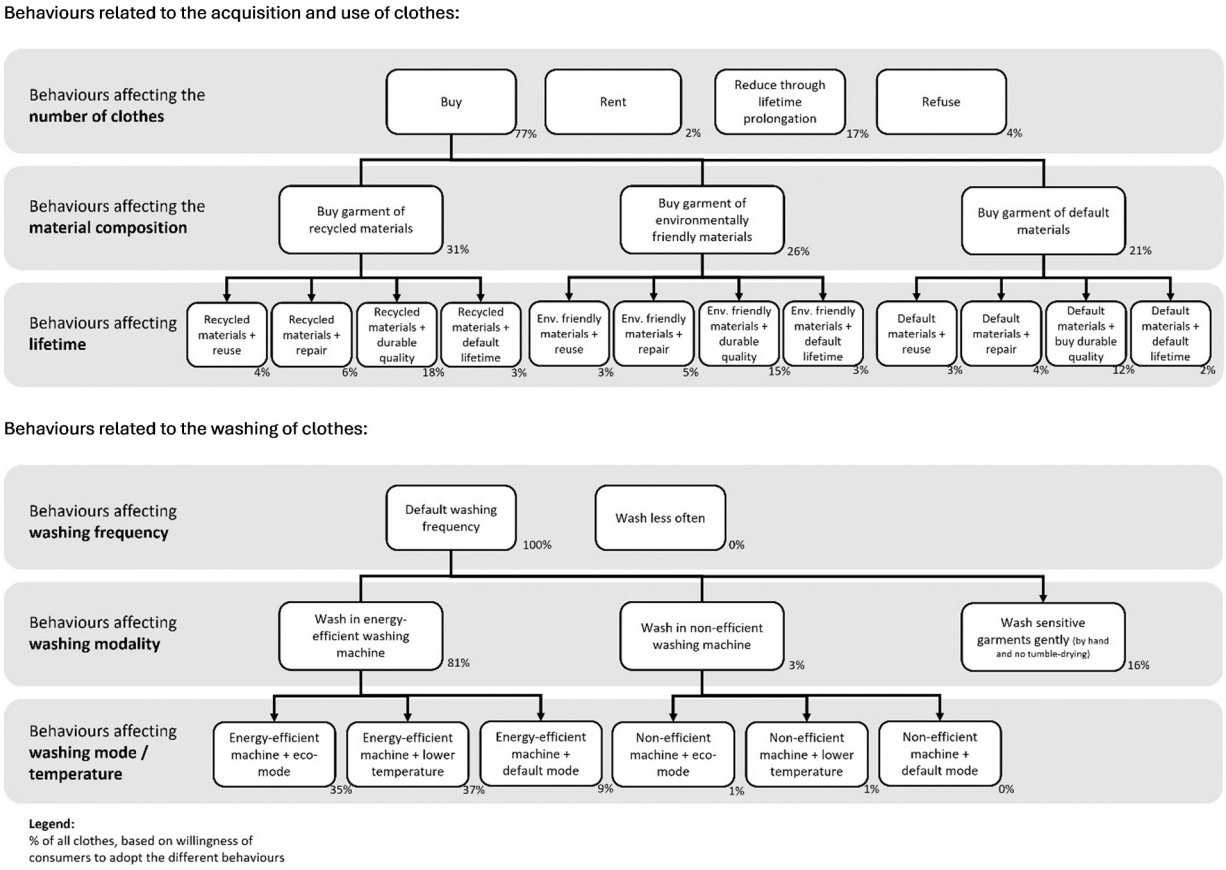

Fig. 3. Schematic overview of the clothing behaviours encompassed in this study, their interactions, and the share of all clothes each behaviour relates to.

BP_{b1*b3} is the behavioural plasticity of the combination of both behaviours b1 and b3 (e.g., the share of people who do not currently buy clothes made of recycled materials and repair clothes but are willing to do so).

For this calculation, we need to know the behavioural plasticity of each behaviour combination. This depends on the share of clothes (s) the combined behaviour applies to. For example, the share of purchased clothes from recycled materials that can be repaired ("recycled materials + repair" in Fig. 3) depends on the share of clothes that would not be rented, reduced or refused and thus be newly purchased, and the share hereof that consumers would purchase from recycled materials. This is the share that can then be repaired. Therefore, the behavioural plasticity of a behaviour combination can be calculated as documented in Eq. (10):

$$BP_{b1*b3} = s_{b1} * BP_{b3} \quad (10)$$

The shares of clothes each behaviour applies to are depicted in Fig. 3. We also corrected for the correlation between the horizontal behaviours by determining the share of consumers that are not doing or willing to adopt either of the circular behaviours (based on survey data collected for the study by Koch et al., 2024). For example, 84 % of consumers reported to have bought garments from neither recycled nor environmentally-friendly materials (and therefore engage in the default behaviour), and 27 % indicated not to be willing to buy clothes from recycled or environmentally-friendly materials. In this case, we distributed the current uptake and willingness rate for two circular behaviours proportionately over the leftover share of 16 % and 73 %, respectively. We applied the same approach to the behaviours related to the washing of clothes. More information on the calculation of each element in Fig. 3 can be found in SI 8.

Following this approach, we obtain a circular scenario in which consumers would perform all circular clothing behaviours they are willing to engage in, and for which the total RARP is calculated. This scenario looks as follows (see Fig. 3): 2 % of garments would be rented instead of purchased, 17 % of current clothes purchases would be reduced as consumers would use their clothes longer (through reuse, repair, buying more durable garments, and washing and drying sensitive garments more gently), and 4 % would be reduced by consumers refraining from new purchases (refuse). The remaining 77 % of clothes would still be bought. These purchased garments would be made from either recycled (31 %), environmentally-friendly (26 %) or conventional materials (default, 21 %). Most garments would be used longer, either through reuse (10 %), repair (15 %) or because they are more durable (45 %). 16 % of clothes made of sensitive materials would be washed and dried more gently (washed by hand more often and air-dried). The rest would be washed in either an energy efficient (81 %) or non-energy efficient (3 %) washing machine, out of which 36 % would be washed in eco-mode and 38 % at a lower temperature.

3.5. Sensitivity analysis

Certain parameters used in our analysis are subject to variability and uncertainties. To investigate to what extent these variabilities might have affected the results of the total RARP, we conducted a sensitivity analysis encompassing seven parameters:

i. Garment price: One main parameter in our analysis is the garment price used for the calculation of the environmental pressures related to a garment's production and wholesale/retail stage (as these elements are calculated based on process analysis, see Section 3.2.1).

Furthermore, large uncertainties and inconsistencies between studies can generally be observed in environmental effects attributed to

washing and drying of clothes (Luo et al., 2023, see Section 2). We therefore included main parameters related to washing and drying in the sensitivity analysis:

ii. washing frequency,
iii. share of laundry that is machine-dried,
iv. energy use for the washing machine and dryer, and
v. environmental intensity of electricity.

Moreover, the average garment lifetimes and the lifetime prolongation are also subject to uncertainties as we could not find recent, reliable and detailed data. Large differences between studies can be observed concerning average garment lifetimes; a literature review by Laitala et al. (2018) shows a range in lifetime of 3.3–6.8 years for T-shirts and 3.7–10.8 for pullovers. For the lifetime prolongation of circular behaviours (reuse, repair, durable garments, washing less often and more gently), we could not find any evidence-based data and had to make use of assumptions (as documented in Section 3.2.3). We therefore included both:

vi. average garment lifetime, and
vii. lifetime prolongation in the sensitivity analysis.

Each of the seven parameters was assessed independently by varying it by ±50 % from the base value used to calculate the total RARP.

4. Results

In this section, we present the results of our analysis. We show the current environmental pressures from adult clothing consumption in the Netherlands (Section 4.1), the extent to which different types of circular behaviour could reduce these environmental pressures (reasonably achievable reduction potential, RARP, Section 4.2), and the total environmental reduction that could be achieved if Dutch consumers adopted all types of circular behaviour they are willing to do (total RARP, Section 4.3). In Section 4.4, we summarize the most relevant findings from the sensitivity analysis.

4.1. The current environmental pressures of Dutch clothing consumption

Table 4 provides an overview of the average annual household expenditure related to the clothing consumption of Dutch adults (for the year 2017), and the resulting annual environmental pressure (see Section 3.1 for the method description and SI 2 for more detailed results). 94 % of the annual expenditure is spent on the purchase of clothes (categories 1 and 2), and the rest is spent on the laundry and drying of clothes (categories 4–6). In total, the purchase and use of clothing by Dutch consumers in 2017 is associated with about 3050 kt of GHG emissions and 650 km^2 of LU. The purchase of clothes causes the highest share of the environmental pressures (71 % in terms of GHG emissions and 90 % in terms of LU). The rest is associated with washing and drying.

Table 4
Annual greenhouse gas emissions and land use related to adult clothing in the Netherlands (2017), based on Benders et al., 2021, CBS, 2017a, and own calculations.

Categories related to clothing purchases and use	Average annual household expenditure	Annual environmental pressure for all Dutch households			
		Greenhouse gas emissions		Land use	
	%	kilotons CO_2 eq.	%	km^2	%
1. Men's clothes purchases	35 %	806.61	26 %	218.77	33 %
2. Women's clothes purchases	59 %	1373.26	45 %	372.45	57 %
3. Clothes repair and rental	0 %	3.16	0 %	0.17	0 %
4. Laundry and dry cleaning services	1 %	6.95	0 %	0.53	0 %
5. Laundry detergent	3 %	382.41	13 %	50.16	8 %
6. Electricity use for washing, drying, and ironing	3 %	482.83	16 %	15.63	2 %
Total of all categories	100 %	3055.22	100 %	657.70	100 %

4.2. Reasonably achievable reduction potential (RARP) per behaviour

To calculate the RARP of the adoption of each circular behaviour, we compared the environmental pressures associated with each circular clothing behaviour with the default. We did this comparison separately for a shirt, a pullover, and a pair of trousers, of which we used the average TRP for the calculation of the RARP. Fig. 4 shows GHG emissions and LU of a default pullover, shirt and trousers over their total lifetime. The production (of fibres and the garment) cause the biggest share in both LU and GHG emissions. Depending on the type of garment, the production of fibres contributes to 86–91 % of total LU and the garment production to 3–4 %. In terms of GHG emissions, the fibre production ranges between 15 and 25 %, and the manufacturing of the garment adds 35–43 %. Wholesale and retail contribute to 26–30 % (e.g., caused by energy use for lighting and heating of stores) and the use phase (washing and drying) to 10–13 %. The environmental pressures related to both transport and waste processing are small (<2 % in terms of GHG emissions and <1 % in terms of LU).

Fig. 5 depicts the RARP of each behaviour change, presented with blue and green dots. It represents the annual reduction of the current environmental pressure of Dutch clothing consumption (as presented in Section 4.1) that could be realised if consumers who are willing to adopt a given circular behaviour would do so (under the condition that the circular behaviour is easy to perform and not more expensive than the current, non-circular default, as described in Section 3.2). Reducing the input of new clothes through buying less, changing the material composition (buying clothes of environmentally-friendly and recycled material), and prolonging garment lifetimes through more durable quality, are the behaviour changes with the highest RARP in terms of both GHG emissions and LU. Clothes rental, second-hand purchasing, repair, and behaviours related to the washing/drying and the disposal of garments have a lower RARP.

For several circular behaviours, Fig. 5 shows a range in the reduction potential (depicted by two dots that are connected with a line). The range is the result of a variation in assumptions used for the calculations of the circular behaviour (see Section 3.2.3). The RARP for buying clothes made of environmentally-friendly garments, for example, varies between different types of materials: while bast fibres (hemp, jute, linen, and kenaf) and lyocell have lower GHG emissions and LU compared to the default (cotton or cotton-blend), replacing conventional by organic cotton leads to an increase in LU (see SI 6 for more details). In the case of recycled materials, the reduction potential highly depends on the recycled content: in the case of a recycled content of 5 %, the RARP is relatively small, while in the case of 50 % recycled content, the RARP is relatively high, especially in terms of LU. For clothing rental, the RARP depends on the transport mode chosen by the consumer to pick up and return rentals, the transport distance, the number of users that rent a rental garment over its lifetime, and the extent to which rental substitutes clothes purchases (substitution rate). These elements were varied in the calculation of the rental option. The reduction potential of rental is highest in the scenario where a rental garment is rented by 15 users, the consumer bikes, and the substitution rate is 100 %. It is lowest in the case of five users, transport by car, and a substitution rate of 33 % (see SI 7 for detailed results). However, as the willingness to rent clothing is generally low, the RARP is low regardless of the variation in

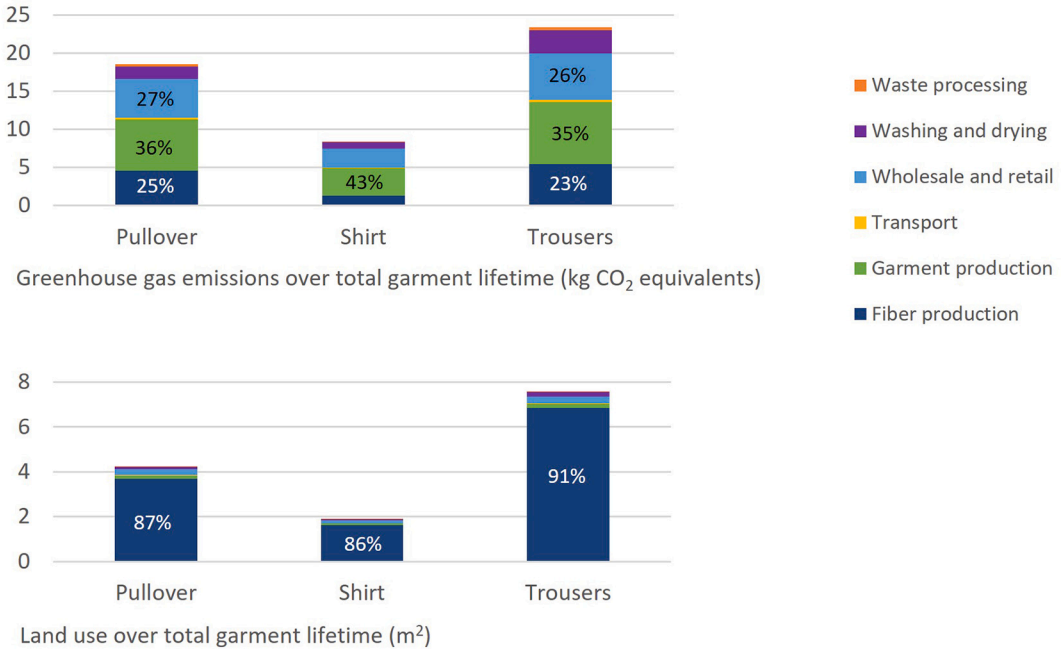

Fig. 4. Greenhouse gas emissions and land use related to a pullover, a shirt, and a pair of trousers over their total lifetime.

transport, number of users, and substitution rate. The substitution rate also influences the reduction potential of second-hand purchasing: while a substitution rate of 60 % (i.e., each second-hand garment replaces 60 % of a purchase of a newly produced garment, Farrant et al., 2010) leads to a reduction in GHG emissions and LU, the reduction is offset in the case of a lower substitution rate of 28.5 % (Stevenson and Gmitrowicz, 2012, see Section 3.2.3), leading to additional GHG emissions and LU.

If consumers' willingness increased and more people adopted the behaviour, the reduction potential would increase. To give additional insights in the additional reduction potential that could be attained if also the consumers who are currently not willing to do so would adopt each behaviour, we can compare the RARP to the *maximum achievable reduction potential* (see Section 3.3.2), represented by the blue and green bars in Fig. 5. Particularly clothes rental, buying fewer clothes, and more environmentally-friendly and recycled materials could lead to a relatively high additional environmental reduction if consumers' willingness to engage in these behaviours was maximised. However, an increasing uptake can also possibly lead to adverse effects (depicted as negative values in Fig. 5) due to variations as explained above. This risk exists for rental, clothes of environmentally-friendly materials, and second-hand purchases.

4.3. Total reasonably achievable reduction potential (total RARP)

The *total RARP* is the total reduction in GHG emissions and LU that could be achieved if consumers would adopt all circular behaviours they are willing to do, thereby accounting for interactions between behaviours (see Section 3.4). Compared to the current situation, 11–19 % of GHG emissions and 3–29 % of LU related to clothing annually could be mitigated in this scenario. This corresponds to an absolute total RARP per year of approximately 345–571 kt of CO_2 equivalents and approximately 22–194 km^2 of land for the Netherlands as a whole or 25–42 kg of CO_2 equivalents and 2–14 m^2 of land per (adult) person. Similar to the findings presented in Section 4.2, the ranges in GHG emissions and LU are the result of the variability of some circular consumer options (environmentally-friendly and recycled materials, rental and second-hand) considered in the calculations. The higher end of the ranges is attained when a higher degree of recycled content in garments is chosen, clothes rental allows for garments to be shared among a high number of users and avoids additional car use, and rental and second-hand garments replace new clothes purchases to a large degree. The choice of environmentally-friendly materials (bast fibres, lyocell, and organic cotton) has little effect on the range in GHG emissions but highly influences the range in LU.

4.4. Sensitivity analysis

To investigate to what extent different main parameters in our calculation may have affected our findings, we conducted a sensitivity analysis. Seven parameters were independently assessed by varying them by ±50 % from their base value used to calculate the total RARP. The detailed results can be found SI 9. We see that variations in lifetime prolongation and in garment price have the biggest effects on the results of the total RARP. The variations show a stronger effect on the total RARP in terms of LU (between −37 % and +65 % for lifetime prolongation and between −91 % and +84 % for garment price) than in terms of GHG emissions (between −2 and +10 % for lifetime prolongation and between −15 % and +10 % for garment price). Changes in average garment lifetime and parameters related to washing and drying have a smaller effect, changing the total RARP with maximum −6 % and +6 %.

5. Discussion

We find that the purchase and use of clothing by Dutch consumers in 2017 is associated with about 3050 kt of GHG emissions and 650 km^2 of LU. Most GHG emissions and LU are related to the material production and manufacturing stage of garments (approximately 60 % of GHG emissions and approximately 90 % of LU). Wholesale and retail and the use phase (washing and drying) contribute to a lesser extent to GHG emissions and LU, while transport and waste processing have the smallest share. These findings are in line with the existing literature (see Section 2).

We aim to provide a realistic estimate of the environmental reduction potential a more circular clothing consumption could bring about by considering behavioural plasticity (i.e., the share of the population that does currently not engage in a circular behaviour but would be willing to do so if the behaviour was easily accessible and not more expensive than the current standard). This results in what we call the

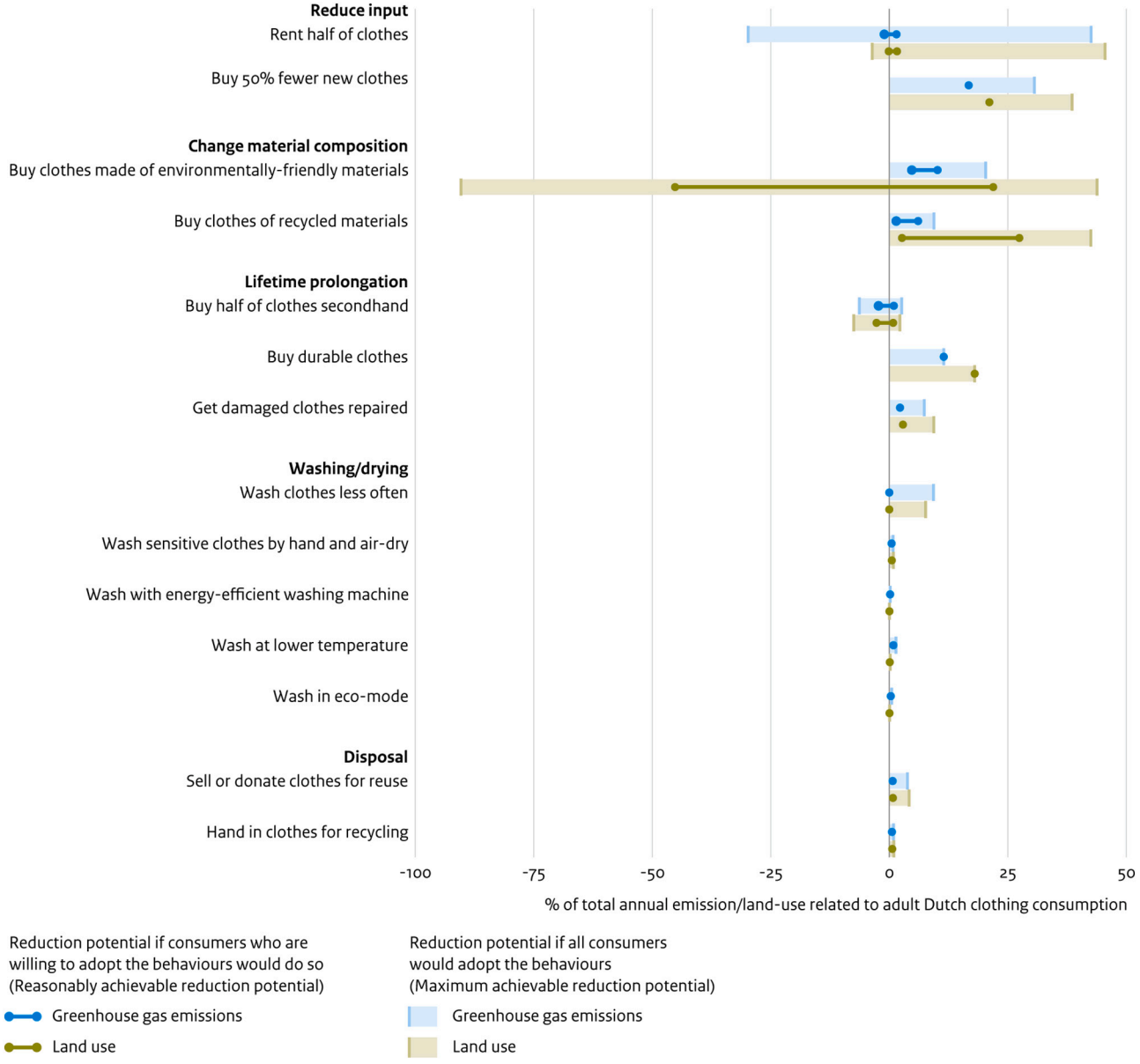

Fig. 5. Reasonably and maximum achievable reduction potential of each circular behaviour in terms of greenhouse gas emissions and land use.

'*reasonably achievable reduction potential*' (RARP). We find the highest RARP (in terms of both GHG emissions and LU) in buying fewer clothes, buying clothes of environmentally-friendly and recycled material, and prolonging garment lifetimes through more durable quality. Clothes rental, buying second-hand and repair have a lower RARP because of a relatively low behavioural plasticity. This means that only a fraction of the population can be expected to adopt these types of behaviour if made more easily accessible and affordable. If behavioural plasticity was not considered, the environmental benefits of the mentioned behaviours would be overestimated by a large degree (e.g., 96 % for clothes rental or 77 % for reuse as their behavioural plasticity is only 4 % and 23 %, respectively).

Furthermore, our results show that behaviour changes related to washing and drying and to the disposal of clothes have a relatively low RARP. However, this does not mean that more sustainable washing and drying behaviours are irrelevant. If, in the future, garment lifetimes are prolonged more through circular measures (such as durable quality, reuse, and repair), the use phase becomes relatively more important and a higher relative reduction of the environmental pressures related to clothes can be expected from changes in washing and drying.

We enriched the analysis on the RARP of the different types of circular consumer behaviour by considering a range in how they could be implemented, based on relevant aspects mentioned in other studies (see Section 3.2.3). For example, the RARP of buying clothes made of recycled materials highly depends on the share of recycled content that is applied in a garment. Considering such variability leads to ranges of the RARP and provides insights into possible adverse effects and trade-offs. The results show that in the case of clothes rental, second-hand purchases, and buying clothes of environmentally-friendly materials, adverse effects can arise. For rental, this is the case when a garment is rented out to a low number of users over its lifetime, when rental garments do not fully replace new clothing purchases, or consumers use their car for pick-ups and returns of rental garments. Willingness to rent clothing is generally low, which means that these adverse effects in particular require more attention if willingness and uptake increases further. In the case of second-hand purchasing, adverse effects may occur when the substitution rate of second-hand garments is low (i.e., consumers buy second-hand garments in addition to new ones instead of

replacing new purchases). In the case of buying clothes made of environmentally-friendly materials, a trade-off between GHG emissions and LU can be observed when it comes to the use of organic cotton, meaning that an increased uptake of organic cotton is expected to lead to higher LU. However, organic farming practices have other environmental benefits, such as soil quality and biodiversity improvements, that are not considered in this study (Rahmann, 2011).

To answer our research question, simply taking the sum of the RARP of all individual behaviours would lead to an overestimation of the environmental mitigation potential of circular clothing behaviour, due to interactions between certain behaviours. For example, if consumers buy fewer clothes, the mitigation potential from buying clothes made of environmentally-friendly materials is reduced. Moreover, certain consumers are willing to do several behaviours that are mutually exclusive, such as buying a garment made of environmentally-friendly or recycled materials. After accounting for such interactions and overlaps, we find that more circular consumer behaviour in the Netherlands (based on what consumers would be willing to do if made more easily accessible and less expensive) could mitigate between 11 and 19 % of GHG emissions and 3–29 % of LU related to clothing annually. The range is the result of the variability in some circular behaviours (e.g., recycled content in garments made of recycled materials, as described in the previous paragraph). The reduction corresponds to about 345–571 kt of CO_2 equivalents and about 22–194 km^2 of land per year for the Netherlands overall or 25–42 kg of CO_2 equivalents and 2–14 m^2 of land per (adult) person. This total RARP, which accounts for interactions between behaviours, is up to 69 % lower (in terms of both GHG emissions and LU) than the simple sum of the RARP of all individual circular behaviours. This shows how important it is to account for interactions to avoid overestimation of the environmental effects – an aspect previous studies on circular clothing consumption have not looked at.

5.1. Theoretical and practical implications

Our findings indicate two ways in which policy measures could contribute to an increased circular consumption of clothing in the Netherlands. One way is to target the 'willing' consumers, by stimulating consumers that are willing to adopt circular behaviour to actually do so. Buying fewer clothes, more durable clothes and clothes made of environmentally-friendly materials and of recycled materials (if the recycled content is high) have the highest RARP. Therefore, in order to mitigate as much of the environmental pressures as possible, policies should target those behaviours first. The behavioural plasticity measure, which we used to calculate the RARP, reflects consumers' willingness to adopt a circular behaviour when doing so would be as easy and not more expensive than existing alternatives. This implies that ensuring easy accessibility and more attractive prices of circular clothing options is a crucial first step to help consumers turn their willingness into actual behaviour. In addition, future research could investigate what other factors – apart from accessibility and price – might hinder consumers to turn their willingness into actual behaviour, and what interventions could help to close this gap. Especially in the case of buying fewer clothes, which is already cheaper and relatively easy to perform, other influencing factors are likely to play a role, such as personal and social norms, materialistic values, status, contextual factors (e.g., discounts), and impulsive purchase behaviour (e.g., Joanes et al., 2020; Flynn et al., 2016).

In addition, policies could be implemented to target the 'unwilling' consumers, by trying to increase their willingness to adopt circular clothing behaviours. Particularly clothes rental, buying fewer clothes, and buying clothes of more environmentally-friendly and recycled materials could lead to a relatively high *additional* environmental reduction if not only the willing but also the currently unwilling consumers would engage in these behaviours (*maximum achievable reduction potential*, see Fig. 5). Possible reasons for the limited willingness in the case of clothes rental, for example, are people's concerns about quality and hygiene and their fear to damage rental items (Lang, 2018). In the case of second-hand purchasing, willingness may be limited due to people's embarrassment to buy and wear used clothes and hygiene concerns (Laitala and Klepp, 2018). Future research could support the transition towards more circular clothing consumption by examining such reasons for low willingness for circular behaviours, conditions under which consumers are likely to transform their willingness into actual behaviour, and effective policy measures to stimulate willingness and facilitate behaviour change.

Apart from policy measures targeting the 'willing' and 'unwilling' consumers directly, the uptake of circular clothing behaviours could be further stimulated by measures that target clothing producers and retailers, for example by setting design requirements for clothes that are being sold in the country (e.g., minimum recycled content or quality criteria to improve durability). Potential adverse effects of circular behaviour should be considered when stimulating a more circular clothing consumption to avoid rebound effects. For clothes rental, adverse effects can, for example, happen when rental leads to additional car use for pick-ups and returns at the rental store. Locating rental stores in central places could be a way to avoid such rebound effects. Moreover, the substitution rate of both rental and reused clothing could be improved by making it easier to find second-hand garments in specific size, colour and quality, so that they fully satisfy consumers' needs and wishes.

Future research could help to address the limitations of our study (see Section 5.2) by collecting reliable and detailed data on garment lifetimes and lifetime prolongation, by contributing to a better understanding of the environmental impact related to wholesale and retail of clothes in different price segments, and by improving our behavioural plasticity estimates with more objective data from observations or experiments.

5.2. Limitations

We aimed to give a realistic estimation of the environmental reduction potential of circular clothing consumption by considering evidence-based data on behavioural plasticity. Our study has three main limitations that we would like to address.

First, the hybrid approach, which we applied to calculate the GHG emissions and LU of a default garment and the various circular alternatives to determine the TRP and eventually the RARP (Section 3.2), has the advantage of being less labour intensive than process analysis while still providing more detailed and accurate results than input-output analysis (Van Engelenburg et al., 1994; Bullard et al., 1978). However, it comes with a few limitations. One such limitation is that the pressures related to certain stages of the garment life cycle, namely the manufacturing of garments and the distribution to the consumer via wholesale and retail, are based on a financial breakdown of the price of the garment (Van Engelenburg et al., 1994). In order to allocate the environmental impacts of the production and distribution to one garment, we used the consumer price of an average garment; the resulting environmental effects for a piece of clothing are therefore dependent on the price used in the analysis. A garment sold for 100 Euros, for example, is assigned ten times the environmental pressures from manufacturing, wholesale and retail compared to a garment sold for ten Euros, even though the actual environmental pressures are likely similar (Steinberger et al., 2009). In the case of wholesale and retail, the discrepancy can only partially be substantiated by a larger shop area and related lighting and heating, or more advertisement related to more expensive garments (Vringer and Blok, 1996). This price-based allocation therefore leads to an underestimation of the environmental effects of manufacturing, wholesale and retail if the selected garment price in the analysis is too low, and to an overestimation if the selected price is too high. As our sensitivity analysis shows (Section 4.4), these uncertainties may have affected our results. When comparing our results on the environmental effects of garment defaults to previous studies, we

see that the environmental effects for the manufacturing stage are in a similar order of magnitude, while our results on GHG emissions of wholesale and retail seem relatively high (see SI 1.a). The fact that our results for wholesale and retail are higher than in other studies, might have to do with an additional limitation in our approach. The data included in the 'Environmental Analysis Program' (EAP), which we used to perform the analysis, does not distinguish between different wholesale and retail subsectors, due to a lack of data. This may lead to an overestimation of the environmental effects of clothing wholesale and retail, as emissions per Euro from other subsectors are likely higher than from clothing wholesale and retail (for example for supermarkets, due to more transportation and use of refrigerators).

Second, we had to make use of assumptions for certain elements in our calculations. Whenever possible, we used empirical data from earlier studies for our analysis (such as garment weights, fibre origins or washing temperatures of default garments). For some parameters however, such as average garment prices, lifetimes, and lifetime prolongation resulting from circular behaviour, data availability is limited (see Sections 3.2.3.1 and 3.5). The results of the sensitivity analysis show that variations in lifetime prolongation and in garment price are particularly important variables in our analysis. We discussed the limitations regarding the price in the previous paragraph. While uncertainties regarding lifetime prolongation may have affected the reduction potential of certain types of circular behaviour (reuse, repair, durable garments, washing less often and more gently), uncertainties regarding garment lifetimes may have impacted the results in two ways: On the one hand, they affect the absolute annual environmental effects of a garment (the longer the assumed lifetime, the lower the yearly environmental effects). On the other hand, they affect the relative environmental effects of the use phase in relation to the production and disposal of the garment (the longer the assumed garment lifetime, the higher the share of the use phase of the total environmental effects because the garment is washed and dried more often over the course of its life). This has implications for the reduction potential of circular behaviours related to washing and drying. Future research to generate up-to-date, empirical data on garment lifetimes and lifetime prolongation is needed to improve our analysis.

Third, to determine the behavioural plasticity of each circular behaviour in our analysis, we used self-reported survey data on consumers' current behaviour and willingness to engage in a circular behaviour if it was easily accessible and not more expensive than the current alternative (Koch et al., 2024). Apart from possible response biases related to self-reported behaviour measures (Gatersleben et al., 2002; Huffman et al., 2014; Kormos and Gifford, 2014), this comes with the limitation that we cannot be sure that if price and accessibility were improved, consumers would actually adopt the behaviours as indicated. There might be other barriers, such as the lack of skills or knowledge in consumers or difficulties in changing their habits (e.g., Carrington et al., 2010; ElHaffar et al., 2020; Joshi and Rahman, 2015) that might prevent them from doing so. Authors of other studies (e.g., WRI, 2025; Dietz et al., 2009) assessed behavioural plasticity based on data on actual behavioural change following behavioural interventions that has been documented in previous literature. However, this data is only available for certain types of behaviour (WRI, 2025), and it is challenging to generalize the findings to the general population due to different samples, years and geographic scopes. The way we measured behavioural plasticity based on willingness has the advantage of having been measured for a representative sample of Dutch consumers in a comparable way for all behaviours.

6. Conclusions

With this study, focused on the case study of the Netherlands, we aimed to improve previous estimations of the environmental reduction potential related to consumers' adoption of circular behaviour with regards to clothing. We did so by also considering behavioural plasticity and interactions between different behaviours. Our results show that these two aspects are important to consider when calculating the environmental mitigation potential of a more circular clothing consumption in order to avoid overestimation and provide a realistic estimate.

We found that a more circular clothing consumption in the Netherlands – taking into account the willingness of consumers if circular options were made more easily accessible and less expensive – could, in total, mitigate between 11 and 19 % of GHG emissions and between 3 and 29 % of LU related to clothing annually. This corresponds to an annual reduction of approximately 345–571 kt of CO_2 equivalents and approximately 22–194 km^2 of land. When considering behavioural plasticity, buying fewer new clothes and choosing garments of more durable quality and more environmentally-friendly and recycled materials have the highest reduction potential in terms of both GHG emissions and LU. Clothes rental, second-hand purchasing, repair, and changes related to the washing/drying and the disposal of garments have a lower reduction potential.

Achieving this estimated environmental reduction requires policy measures to help consumers turn their willingness into action, for example by making sure circular options are financially attractive and easily accessible to consumers. The reduction potential could be further increased by stimulating consumers' willingness regarding consumer behaviour, particularly in terms of clothes rental, reduction of new clothes purchases, repair, and garments of environmentally-friendly and recycled materials. Potential adverse effects of these behaviours (e.g., low substitution rates and additional transport) should be considered when stimulating a more circular clothing consumption to avoid rebound effects. Future research could further develop our work by improving data quality, especially on garment lifetimes and lifetime prolongation related to circular behaviour as well as on environmental pressures related to wholesale and retail.

CRediT authorship contribution statement

Julia Koch: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Harry Wilting:** Writing – review & editing, Supervision, Conceptualization. **Kees Vringer:** Writing – review & editing, Conceptualization. **Linda Steg:** Writing – review & editing, Supervision. **Ellen van der Werff:** Writing – review & editing, Supervision.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2025.07.007.

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