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Environmental impacts of healthcare and pharmaceutical products: Influence of product design and consumer behaviour

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A B S T R A C T

Healthcare and pharmaceutical products are used widely but their environmental impacts are still largely unknown. This paper provides an insight into the influence of product design and consumer behaviour on the environmental impacts of the use and end-of-life of some healthcare and pharmaceutical products, with the aim of identifying improvement opportunities. The influence of product design is assessed through two types of asthma inhaler: hydrofluoroalkane (HFA) and dry-powder devices. Consumer behaviour is examined by considering the use of toothpaste and consumption of nutritional drinks. The results indicate that the use and end-of-life stages contribute significantly (~90%) to the carbon footprint of HFA inhalers, estimated at 26.9 kg CO_2/100 doses. The carbon footprint of dry-powder inhalers is 10 times smaller (2.7 kg CO_2/100 doses). Product design innovations to eliminate HFA propellants could save over 13 Mt CO_2 eq./y globally. The use stage is also the main hotspot for most other environmental impacts across the products considered in the study. The contribution of end-of-life stage is significant for eutrophication and some toxicity-related impacts for inhalers and toothpaste. The impacts of toothpaste and nutritional drinks are highly influenced by consumer behaviour during the use stage. For example, using cold instead of warm water for teeth brushing and a tumbler instead of leaving the tap running would reduce the carbon footprint from the use of toothpaste by 57 times and water consumption by 20 times. These findings highlight that both design innovations and changes in consumer behaviour play a significant role in addressing global environmental challenges. Therefore, in addition to environmental improvements through product development and supply change management, healthcare companies should also focus on providing consumer guidance to help lower the environmental impacts of their products.

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1. Introduction

Healthcare and pharmaceutical products are ubiquitous and yet their environmental impacts are scarcely known, with only a limited number of life cycle assessment (LCA) studies available in the literature. While the use of LCA in the pharmaceutical industry is increasing, most studies compare different chemical routes or processes (De Soete et al., 2017; Jiménez-González and Overcash, 2014), with very few considering consumer products. Furthermore, most studies have considered only cradle-to-gate impacts, omitting the use and end-of-life of pharmaceutical products. For example, Jiménez-Gonzalez et al. (2004) assessed the cradle-to-gate environmental impacts related to the synthesis of a typical active pharmaceutical ingredient (API), showing that most impacts are due to the solvent usage. Wernet et al. (2010) also estimated the cradle-to-gate impacts of producing an API but found that energy consumption in the production process was the main contributor to the impacts. Ponder and Overcash (2010) also reported that most of the environmental burdens in the production of vancomycin hydrochloride (an antibiotic drug) were associated with the energy consumption. Considering cradle-to-gate carbon footprint of 20 anaesthetic drugs, Parvatker et al. (2019) found that GHG emissions of drugs varied enormously, from 11 kg to 3000 kg CO_2 eq. per kg API, depending on the number of synthesis steps in the manufacturing process. A carbon footprint study of intravenous morphine reported that drug sterilisation and packaging caused 90% of the cradle-to-gate impact (McAlister et al., 2016).

A further study, comparing cradle-to-gate impacts of production

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routes of a pharmaceutical intermediate compound (Henderson et al., 2008), reported that the biocatalytic route had lower environmental impacts than the chemical pathway. Similarly, Lee et al. (2016) compared the environmental performance of batch and continuous processes for the synthesis of 4-d-erythronolactone and reported that the continuous process had on average 23% lower environmental impacts in comparison to the batch process. In addition, some studies (Ott et al., 2014, 2016; Brunet et al., 2014) assessed process optimisation opportunities in the production of API using LCA. Other authors (Amado Alviz and Alvarez, 2017) examined options for reducing the impacts from the use of solvents in the synthesis of APIs.

Some studies compared the impacts of different APIs or packaging. For instance, De Jonge (2003) showed how different type and content of API affect the life cycle impacts of different medicines. Focusing on packaging and comparing two primary packaging alternatives used for injectable drugs, Belboom et al. (2011) found that polymer vials had lower environmental impacts than the glass option. Raju et al. (2016) compared cradle-to-gate impacts of polyvinyl chloride (PVC) and aluminium blister packaging of tablets and indicated that the PVC alternative performed better than the aluminium in nine out of 11 impact categories considered.

A few studies also included the impacts of use and/or disposal of pharmaceutical products. For instance, Goulet et al. (2017) assessed the cradle-to-use carbon footprint of a HFC-134a inhaler and a nebuliser, reporting that the use stage caused the majority of the impact of the inhaler (98%) and nebuliser (60% for hand washed and 40% for using a dishwasher). Furthermore, Jeswani and Azapagic (2019) investigated various options to reduce the life cycle environmental impacts of inhalers, showing that using HFC-152a instead of HFC-134a would reduce the global warming and ozone depletion potentials of inhalers used in the UK by 90–92%. Wilkinson et al. (2019) also recommended switching to lower-carbon footprint inhalers to reduce their impact in England. Focusing on the use of disposable and single-use materials in healthcare delivery, Campion et al. (2015) suggested that the environmental burdens of such disposable products can be reduced by considering dematerialisation and end-of-life strategies at the design stage.

Only a handful of LCA studies considered environmental impacts of consumer healthcare and personal-hygiene products. One of these (Koehler and Wildbolz, 2009) considered cradle-to-grave impacts of liquid and bar soaps for hand-washing, concluding that the environmental performance of soaps depends on consumer behaviour as most of the impacts occur in the use and end-of-life stages. The remaining three studies also focused on personal-hygiene and toiletry products, such as shampoo, shaving cream, hand wash and soap (van Lieshout et al., 2015; Golsteijn et al., 2018; de Camargo et al., 2019) also confirmed these findings. Therefore, a closer look at the use and end-of-life stages is warranted.

Product use is often influenced by its design and consumer behaviour. Cradle-to-grave LCA studies of consumer products, in general, often include the use stage. However, aspects related to product design have not been analysed previously, especially for healthcare and pharmaceutical products. For many products, consumer behaviour during their use could also have a significant influence on the environmental performance of the products. Therefore, this paper focuses on the use and end-of-life of healthcare and pharmaceutical products to examine the influence on their environmental performance of two key parameters: product design and consumer behaviour. Several representative products have been selected for these purposes, as detailed in the next section. The results of the study are relevant for both producers and consumers as they provide an insight into the influence of product design and consumer behaviour on the environmental impacts of common healthcare and pharmaceutical products.

2. Methodology

The study follows the ISO 14040/44 guidelines for LCA (ISO, 2006a; 2006b), with the goal and scope of the study discussed in the next section, followed by the inventory data and the impact assessment method used to estimate the impacts.

2.1. Study goal and scope

The main goal of this study is to examine the influence of product design and consumer behaviour on the environmental impacts of the use and end-of-life of some healthcare and pharmaceutical products, with the aim of identifying improvement opportunities. Three types of product are considered for these purposes: (i) asthma inhalers; (ii) toothpaste; and a (iii) nutritional drink. They have been chosen for the analysis as they are widely used around the world so that potential reductions in their respective impacts could have a significant effect. For example, 630 million asthma hydrofluoroalkane (HFA) inhalers and 300 million dry powder inhalers (DPI) are used annually worldwide (UNEP, 2014). The annual consumption of toothpaste and nutritional drinks is even larger, as most people consume them worldwide. Furthermore, it was important to choose sufficiently different products to allow consideration of the influence of the two key parameters for this study: product design and consumer behaviour. The former is examined using inhalers as an example and the latter via toothpaste and a nutritional drink.

Given the focus of the study on the use and end-of-life stages, the system boundary comprises the following activities (Fig. 1):

- transport of the product from a warehouse or manufacturing site to a pharmacy or retailer;
- secondary packaging at pharmacy/retailer;
- activities in the use stage (as listed in Table 1 and detailed for each product in the sections below);
- transport of post-consumer waste to waste management facilities; and
- disposal of post-consumer waste (recycling, landfilling and incineration where applicable; see Table 2 for details).

The manufacturing of the products and their primary packaging are excluded from the system boundary. However, the disposal of primary packaging is considered as part of the end-of-life waste management.

2.2. Inventory data and assumptions

The primary data for the products considered here have been obtained from GlaxoSmithKline (GSK), a major global healthcare and pharmaceutical company. The data are based on UK conditions. The data for the use stage, such as dosage rates, application procedures and storage requirements, have been obtained from the product information sheets or manufacturer's instructions. Water and energy required during the use and end-of-life stages are estimated using product information sheets and data from the literature (South Staffs Water, 2010; Fawcett et al., 2005; Market Transformation Programme, 2008). The use of natural gas boilers is assumed for heating the water, where applicable.

The data on the primary packaging, such as packaging materials and their weights, have been supplied by GSK. The data for paper bags and labels for the secondary packaging have been estimated based on the weight of the pharmacy bags and labels used for the

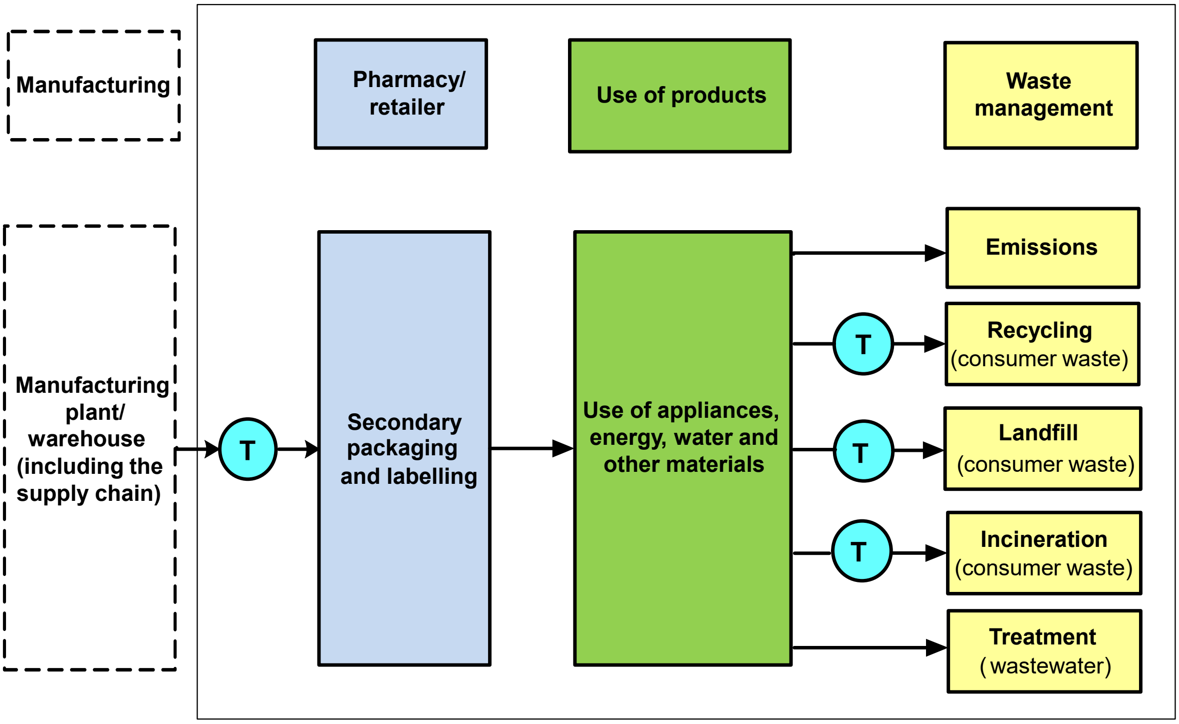

Fig. 1. System boundary for the use and end-of-life stages of healthcare and pharmaceutical products. [Dashed lines denote the life cycle stages excluded from the system boundary. T - transport.]

Table 1
Data and assumptions for the use stage.[a]

Product	Alternative	Functional unit (FU)	Secondary packaging at pharmacy/retailer	Activity in the use stage	Water (L/FU)	Heat (MJ/FU)	Electricity (MJ/FU)	Other materials/ emissions
Inhalers	HFA-134a inhaler	100 doses (18 g canister)	8.5 g (paper bag and labels)	Washing of actuator	4	0.4	–	HFA-134aemissions: 14.4 g[c]
	Dry powder inhaler	100 doses (1.67 packs)	14.5 g (paper bag and labels)	Mouth rinsing	10	–	–	–
Toothpaste	Tap running	100 ml pack	0.5 g (HDPE bag)	Brushing teeth	462	40.6[b]	–	Toothbrush
	Tap turned off				77	6.8[b]		
	Tumbler				23	2.0[b]		
Nutritional hot malted drink	Hob (electric)	32 servings (800 g plastic jar)	1.4 g (HDPE bag)	Preparation of drink and washing up	43[d]	5.6	9.6	Milk: 6.4 L; Washing up liquid: 18 g
	Hob (gas)				43[d]	19.1	–	
	Microwave				29[d]	3.7	4.8	Milk: 6.4 L; Washing up liquid: 12 g

[a] All the products are manufactured by GlaxoSmithKline (GSK).
[b] For warm water option only. Water is assumed to be heated to 30-35 °C.
[c] It is assumed that 80% of HFA is released during the use stage and 20% during the end-of-life disposal.
[d] Water used for washing up of utensils (for the hob option: mug, spoon and milk pan and for the microwave option: mug and spoon).

relevant products, while the data for plastic carrier bags used by the consumer have been obtained from a study by the Environment Agency (2011). The current waste management practices in the UK have been considered for the disposal of packaging materials and the treatment of wastewater generated during the use and end-of-life stages (see Table 2). The relevant products systems have been credited for energy recovery from incineration of waste.

A transport distance of 200 km has been assumed for the transport of the products from a factory or warehouse to a pharmacy or retailer. Following the PAS 2050 methodology (BSI, 2011), consumer transport from the pharmacy or retailer is not considered. The background life cycle inventory (LCI) data have been sourced from the CCaLC (2013) and Ecoinvent (2010) databases. The following sections detail the data and assumptions for each product category considered in this study.

2.2.1. *Inhalers*

Inhalers are used for the delivery of medication to patients suffering from asthma and chronic obstructive pulmonary disease (COPD). There are three main types of inhalers on the market: pressurised metered-dose inhalers (MDI), dry powered inhalers (DPI) and nebulisers. Previously, chlorofluorocarbons (CFCs) were used as propellants in MDI. They have been replaced in many countries with HFA because of the concerns about CFCs' damaging effect on the ozone layer (UNEP, 2014). DPIs are devices that deliver powdered medication without the need for a propellant. Nebulisers convert the liquid drug into inhalable droplets or mist.

In this study, two types of inhaler devices are considered: an

Table 2
Data and assumptions for the end-of-life stage.

Product	Alternative	Paper and cardboard[a] (g/FU[b])	Plastic waste (HDPE and PP)[c] (g/FU)	Mixed waste[d] (g/FU)	Wastewater[e] (L/FU)	Other direct emissions (g/FU)
Inhalers	HFA-134a inhaler	20	–	24	4	HFA-134a: 3.6 g[f]
	Dry powder inhaler	33	–	92	10	–
Toothpaste	Tap running	13	–	37	462	–
	Tap turned off				77	
	Tumbler				23	
Nutritional hot malted drink	Hob (electric & gas)	–	95	10	43[g]	–
	Microwave				29[g]	

[a] Current UK practice for waste paper and cardboard is assumed: 86% recycled, 9% landfilled and 5% incinerated with energy recovery (EC, 2015).
[b] FU: functional unit.
[c] Jar used for the nutritional powder, consisting of a polypropylene (PP) body and a high density polyethylene (HDPE) top. Current UK practice for plastic waste is assumed: 25% recycled, 65% landfilled and 10% incinerated (EC, 2015).
[d] Assumed to be disposed of as municipal solid waste (MSW). In the UK, 62% of non-recycled MSW is landfilled and 38% is incinerated with energy recovery (EC, 2015).
[e] Treated at a municipal wastewater treatment plant.
[f] It is assumed that 80% of HFA is released during the use stage and 20% during the end-of-life disposal.
[g] Wastewater from washing up of utensils (for the hob option: mug, spoon and milk pan and for the microwave option: mug and spoon).

MDI and a DPI. The former is the HFA inhaler *Ventolin® Evohaler®* (salbutamol sulphate) and the latter is the Diskus inhaler *Seretide® Accuhaler®* (fluticasone propionate and salmeterol xinafoate), both produced by GSK. HFA inhalers, which contain HFA-134a (1,1,1,2-tetrafluoroethane) as the propellant, are available in different sizes. In this study, the 18 g canister containing 200 actuations (100 doses) is considered. The dry powder inhaler is available as a disposable device containing, in a blister arrangement, 60 individual doses of an oral inhalation powder.

The aim of this part of the study is to compare the environmental impacts of the use and end-of-life stages of these two types of inhaler device. The functional unit is defined as the 'use of 100 doses'. This corresponds to one 18 g pack of the HFA (*Ventolin®*) inhaler and 1.67 packs of DPI.

The inventory data for the use and end-of-life stages are listed in Tables 1 and 2, respectively. The data for the use stage, such as washing of inhalers, have been obtained from product information sheets. For HFA inhalers, it is recommended to wash the actuator with warm water at least once a week to ensure proper dosing and to prevent blockage of the actuator's orifice. For DPI, it is recommended to rinse the mouth with water and spit the water out after each dose.

With reference to product design, in addition to replacing HFA inhalers with DPIs, the study explores two other options for possible modification of HFA inhalers: (i) the use of a different propellant with a lower global warming potential (GWP); and (ii) reducing the propellant usage per dose in MDIs. Regarding the use of different propellants, HFA-152a (1,1-difluoroethane) has been proposed as a potential replacement for HFA-134a and is currently being investigated by the manufacturer for its safety and formulation behaviour (Noakes and Corr, 2016). The propellant usage per dose in MDIs can be reduced by reducing the size of metering valves and/or use of co-solvents and surfactants. Ethanol as a co-solvent and oleic acid and polyethylene glycol as surfactants are currently being used in some formulations to increase drug or excipient solubility or to enhance valve function (Myrdal et al., 2014). Addition of these excipients can enhance the atomisation of the formulation and hence reduce the amount of propellant needed. For example, Airomir® inhaler, which contains ethanol and oleic acid as excipients, contains 67% less propellant. Data on emissions of propellants for these options are provided in Table 3.

2.2.2. Toothpaste

The aim of this part of the study is to assess the environmental impacts of the use of toothpaste and of its end-of-life waste management. To take into account different consumer behaviour, three options are considered: (i) tap kept running while brushing the teeth; (ii) tap turned off during the brushing; and (iii) using a tumbler for mouth rinsing instead of a tap. Toothpaste is available in various sizes but for the purposes of this study the functional unit is defined as the 'use of 100 ml of toothpaste'.

It is assumed that 1.25 ml of toothpaste is used for each brushing with a manual toothbrush. Six litres of water are considered to be used per brushing for the 'tap running' option, 1 L for the 'tap turned off', and 0.3 L when the tumbler is used (South Staffs Water, 2010). For all three options, the use of both cold and warm water is considered. The inventory data are detailed in Tables 1 and 2.

2.2.3. Nutritional malted drink

Malted drinks, which are marketed as nutritional drinks, are made from wheat, milk and malted barley and are sold in a powdered form. The drink is prepared by mixing 3–4 spoons (25 g) of powder to a smooth paste with a small amount of water and then adding 200 ml of hot milk.

The goal of this part of the study is to estimate the environmental impacts of consuming nutritional drinks and the associated end-of-life waste management. The functional unit is the 'use of an 800 g of nutritional powder', equivalent to 32 servings. This serving size corresponds to a typical pack size available on the market. To take into account different consumer behaviour, three options are considered for preparing the drink: (i) use of an electric hob; (ii) use of a gas hob; and (iii) use of a microwave (see Table 1). The electricity consumption for the hob and microwave is estimated to be 0.3 MJ and 0.15 MJ per serving, respectively (Market Transformation Programme, 2009). The energy used for a gas hob amounts to 0.46 MJ per serving using the efficiency data from Fawcett et al. (2005). For the washing up of utensils (mug, spoon and milk pan), hand washing is assumed. It is estimated that 0.45 L of warm water and 0.2 g of liquid soap are required for the washing per utensil (Market Transformation Programme, 2008). For the inventory data, see Tables 1 and 2.

2.3. Impact assessment

The CML 2001 impact assessment method (Guinée et al., 2001), updated in 2013, has been followed for the estimation of the following impacts: global warming potential (GWP, also known as carbon footprint), abiotic depletion potential (ADP elements and

Table 3
Emissions from modified HFA inhalers in the use and end-of-life stages.[a]

Product	Propellant quantity (g/100 doses)	Use stage emissions (g/100 doses)[d]	End-of-life emissions (g/100 doses)[d]
HFA-152a inhaler	11.7 [b]	9.4	2.3
HFA-134a inhaler with co-solvents and surfactants	6 [c]	4.8	1.2

[a] Data from Jeswani and Azapagic (2019).
[b] The equivalent amount of HFA-152a required in an inhaler would be 34% lower than that of HFA-134a because of the lower molecular weight of HFA-152a.
[c] Data for Airomir®.
[d] It is assumed that 80% of HFA is released during the use stage and 20% during the end-of-life disposal.

fossil), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), ozone layer depletion potential (ODP), photochemical oxidants creation potential (POCP) and terrestrial ecotoxicity potential (TETP). The carbon footprint has been estimated using the IPCC AR5 global warming factors (Myhre et al., 2013).

3. Results and discussion

The environmental impacts have been estimated using CCaLC V3.0 (CCaLC, 2013) and Gabi 6.4 (Thinkstep, 2018). The results are presented first for the inhalers, followed by the toothpaste and finally for the hot malted drinks.

3.1. Inhalers

Fig. 2 compares the environmental impacts of the use and end-of-life stages of the HFA and dry powder inhalers. As can be seen, the DPI has seven impacts lower than the HFA inhaler, some of which by a significant margin. This includes ADP (fossil), AP, MAETP, ODP and POCP, which are net-negative because of the systems credits for energy recovery from waste. The GWP is also much lower for the DPI: estimated at 0.06 kg CO_2 eq. per 100 doses, it is 380 times lower than the GWP of the HFA inhaler (23.4 kg CO_2 eq.). The main reason for this difference is HFA-134a emitted during the use and end-of-life of the HFA inhaler (Tables 1 and 2), which contributes 99.7% to the GWP of these two stages. This in turn is due to the high GWP of HFA-134a which is 1300 times higher than that of CO_2 (Myhre et al., 2013). On the other hand, the HFA inhalers

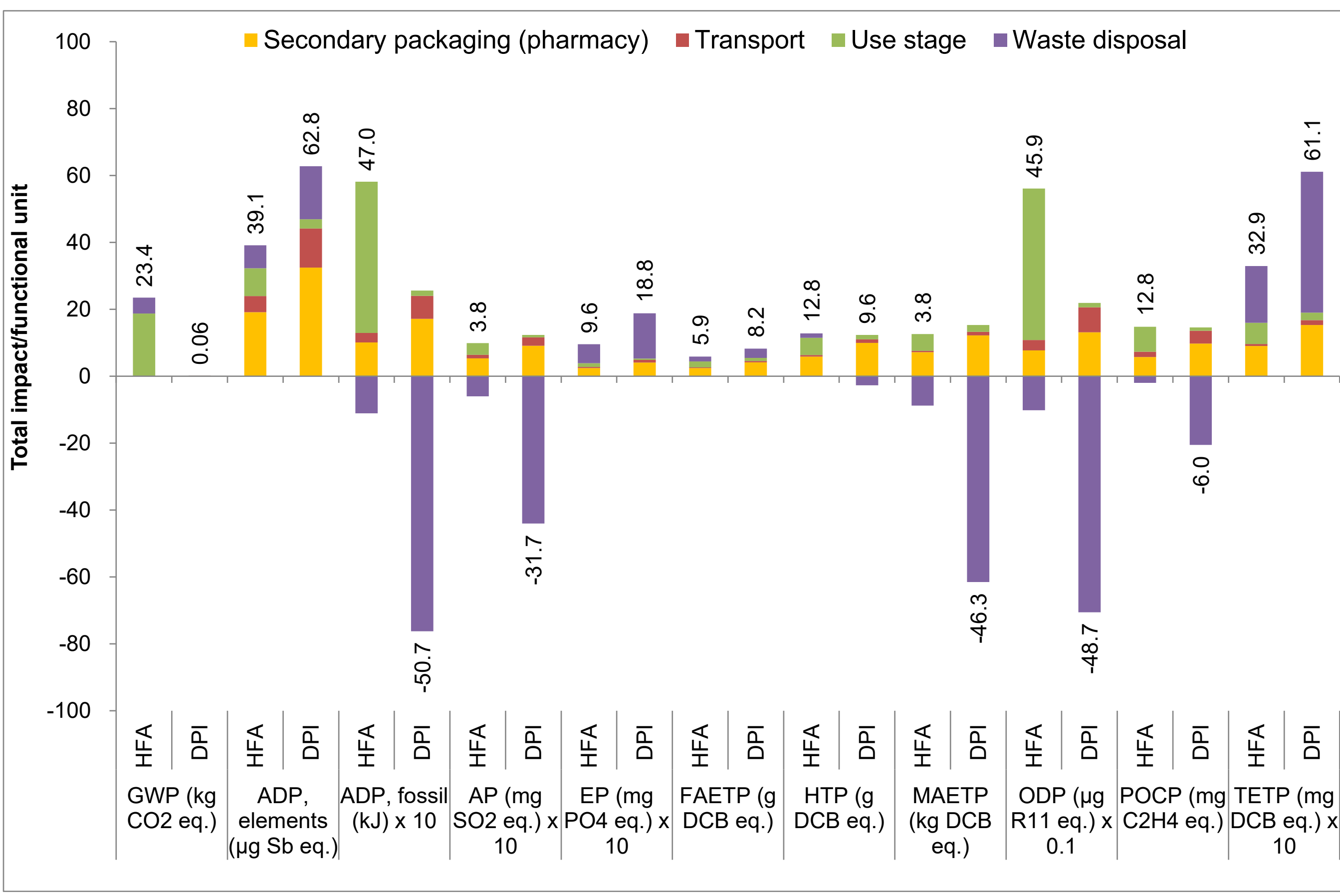

Fig. 2. Environmental impacts of the use and end-of-life management of hydrofluoroalkane (HFA) and dry powder inhalers (DPI).
[Functional unit: Use of 100 doses. Some impacts have been scaled to fit. To obtain the original values, multiply with the factor shown on the x-axis where relevant. GWP: global warming potential, ADP elements: abiotic depletion of elements, ADP fossil: abiotic depletion of fossil resources, AP: acidification potential, EP: eutrophication potential, FAETP: freshwater aquatic ecotoxicity potential, HTP: human toxicity potential, MAETP: marine aquatic ecotoxicity potential, ODP: ozone layer depletion potential, POCP: photochemical oxidants creation potential, TETP terrestrial ecotoxicity potential.]

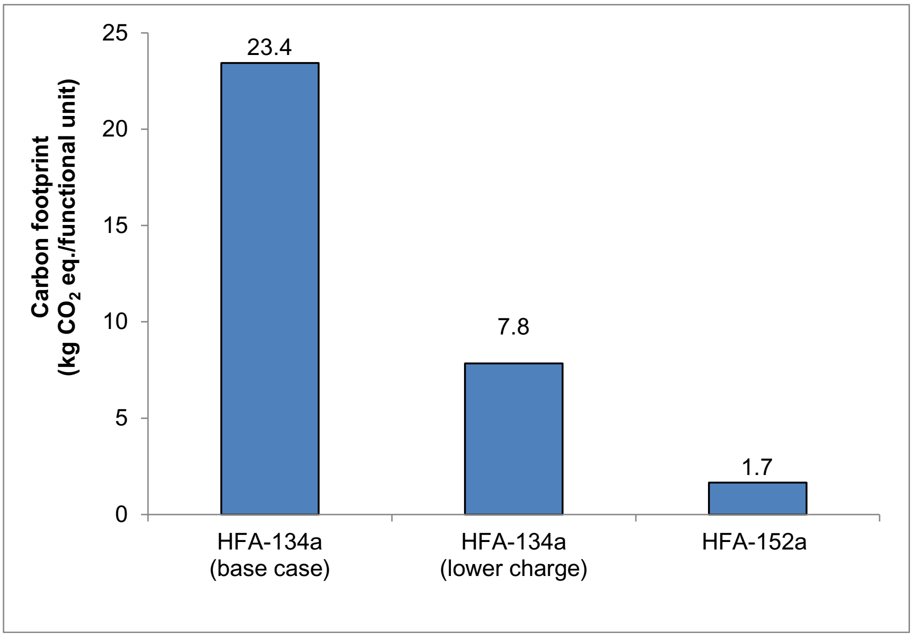

Fig. 3. The carbon footprint of the use and end-of-life management of HFA inhalers in the based case compared with a lower propellant charge and an alternative propellant. [Functional unit: Use of 100 doses.]

are a better option than the DPI for ADP (elements), EP, FAETP and TETP.

As indicated in Fig. 2 for HFA inhalers, in addition to the GWP, the use stage is also the main hotspot for ADP (fossil), HTP, ODP and POCP. This is due to the use of energy to heat up the water used for washing of the inhaler. For both inhalers, waste disposal increases the EP and TETP, while the secondary packaging is the major contributor to ADP (elements), FAETP and HTP.

The effect of product-design related parameters on the carbon footprint of the use and end-of-life management of HFA inhalers can be seen in Fig. 3. The results show that both product-design modifications can substantially reduce the carbon footprint of MDI inhalers. By reducing the amount of propellant in MDIs by 67% ('low-charge pMDI' as in Airomir®), the carbon footprint of the use and end-of-life management would also decrease by 67%. On the other hand, by replacing HFA-134a propellant with HFA-152a, the carbon footprint of MDIs would be reduced by 93%. Since emissions of HFA-134a and HFA-152a do not cause any other environmental impact, the other environmental impacts of the use and end-of-life management of MDIs would remain unchanged.

The above analysis assumes that all HFA contained in the inhalers is emitted into the atmosphere either during the use or in the disposal stage. However, GSK has launched an initiative to collect partially used inhalers to recover the remaining HFA (GlaxoSmithKline, 2013) which can either be incinerated or reused. It is estimated that, on average, the partially used inhaler may still contain 20% of the HFA which can be recovered (GlaxoSmithKline, 2015). The GWP associated with the use and disposal of HFA inhalers would also decrease in proportion to the amount of HFA recovered (i.e. by 20% if all inhalers are recycled).

As mentioned earlier, approximately 630 million HFA inhalers are manufactured annually worldwide, using approximately 9400 t of HFA (UNEP, 2014). Therefore, the GWP of HFA inhalers from the use and end-of-life stages is equivalent to around 12.2 Mt of CO_2 eq. annually. This is equivalent to the annual GHG emissions from 5.5 million diesel cars.[1] This figure is set to increase as the use of HFA in inhalers is projected to grow to 11,500 t by 2025 owing to the replacement of CFCs in some countries where they are still being used in inhalers (UNEP, 2014). Although the replacement of CFCs with HFA inhalers has been beneficial, both in terms of ozone layer and climate change impacts, as this analysis shows, the GWP of inhalers containing HFA is still much higher than that of dry powder devices. However, the latter are not universally suitable for all patients or delivery of all types of respiratory drugs (Covar and Gelfand, 2008) so that HFA inhalers are expected to continue to dominate the market in the foreseeable future (Okamura et al., 2010).

3.2. *Toothpaste*

As indicated in Fig. 4, consumer behaviour with respect to the amount of water used during teeth brushing has a significant effect on the impacts. For example, using warm water and keeping the tap running leads to the GWP of 3.65 kg CO_2 eq. per functional unit, while the use of cold water in a tumbler reduces the impact by 57 times, to 0.06 kg CO_2 eq. All other impacts are reduced by more than 17 times with the use of cold water in a tumbler instead of using warm water and leaving the tap running during the brushing. There are two reasons for this difference: the amount of water used and the energy required to heat the water, with the impact of the latter being more significant. For example, heating the water contributes 90% to the GWP when the tap is left running and 72% for the warm-water tumbler option. Similar trends are observed for ADP (fossil), AP, ODP and POCP, where the use of energy for heating the water is the major contributor.

Waste disposal is the major contributor to EP and the toxicity-related impacts (Fig. 4). The impacts from waste disposal are predominately associated with the treatment of wastewater and hence related to the amount of water used in different options. As a consequence, they are higher for the 'tap running' option than the 'tap turned off' and 'tumbler' scenarios. Regarding the water usage, the 'tap running' option consumes 20 times more than the

[1] GHG emissions from an average diesel car: 177.5 g CO_2 eq./km (DEFRA, 2018); annual mileage per car: 12,400 km (Department for Transport, 2018).

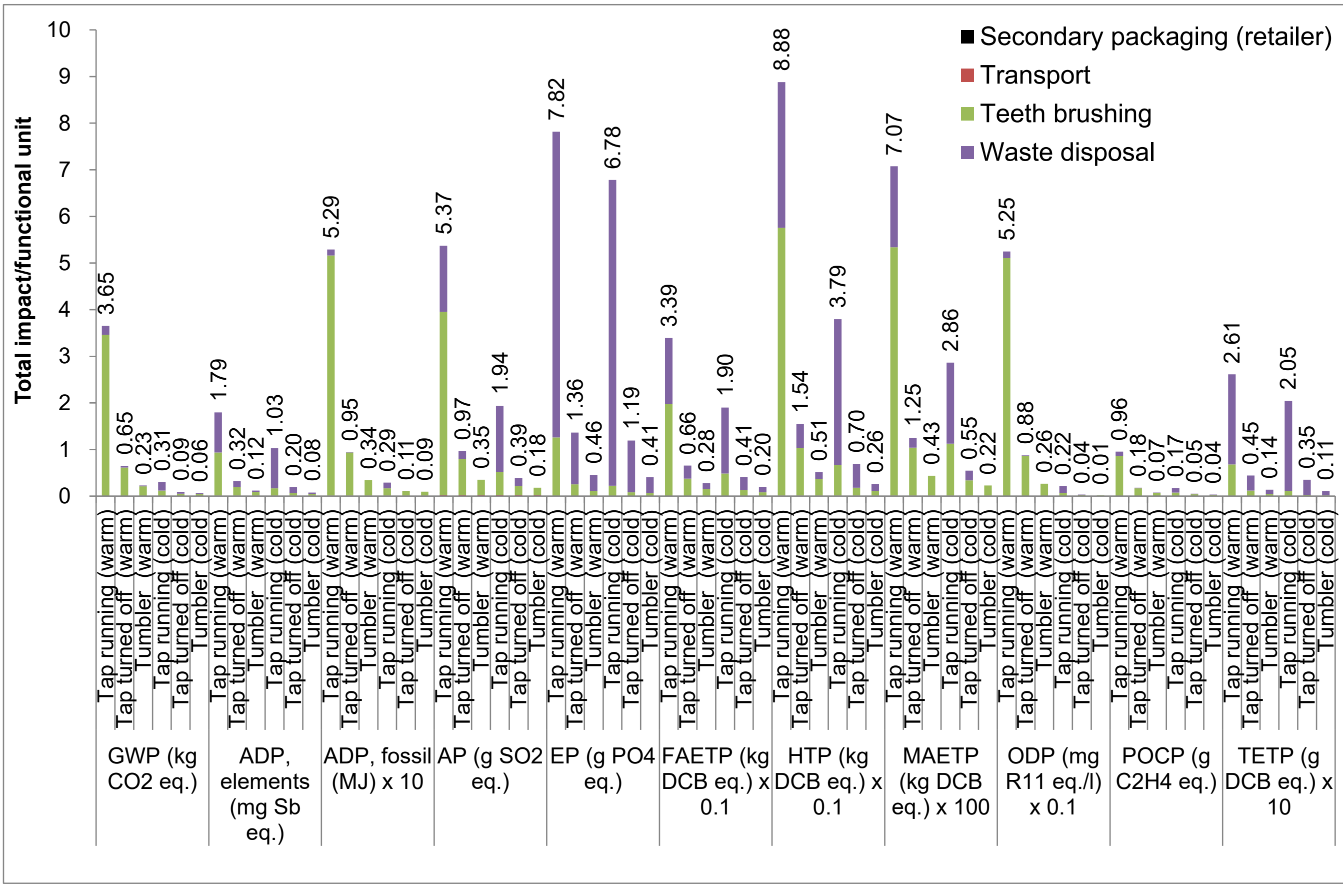

Fig. 4. Environmental impacts of the use and end-of-life management of toothpaste for different consumer behaviour related to water use.
[Functional unit: Use of 100 ml of toothpaste. Some impacts have been scaled to fit. To obtain the original values, multiply with the factor shown on the x-axis where relevant. For the impacts nomenclature, see Fig. 2.]

'tumbler' and six times more than the 'tap turned off' option.

If the tap is left running, by adjusting the flow rate, the consumer can vary the amount of water used between 4 L and 12 L per brushing (South Staffs Water, 2010). The effect of this is shown in Fig. 5, indicating that doubling the amount of water used doubles the GWP for both the cold and warm water options.

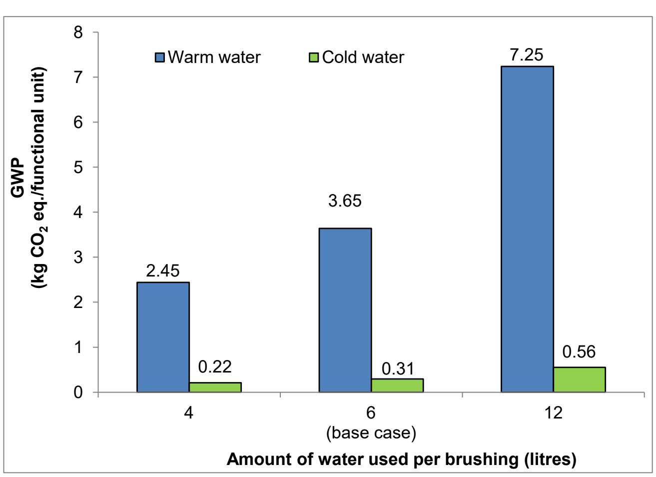

Fig. 5. The effect on the global warming potential (GWP) of the amount of water used during teeth brushing ('tap running' option).
[Functional unit: Use of 100 ml of toothpaste.]

Therefore, this analysis demonstrates that consumer behaviour can affect significantly the environmental performance of consumer products. In the case of toothpaste, by simply turning the water tap off, the GHG emissions, water usage and other environmental impacts can be reduced by six times. Arguably, this is a simple measure that does not require consumers to change their lifestyle and it also saves them money. For consumers that are prepared to change their habits further and switch from using warm to cold water, using a tumbler instead of leaving the water running, the environmental (and financial) benefits would be even greater, reducing the GWP by 57 times and water consumption by 20 times. Furthermore, research shows that warm water does not clean teeth better than cold water and that using too much water to rinse our mouth after the brushing can be counterproductive as it dilutes the effect of fluoride, the main active component in toothpaste (Kristiansen, 2014). Therefore, using a small amount of cold water for teeth brushing is not only beneficial for the environment and consumer costs, but also for the teeth.

3.3. Nutritional malted drink

Preparing one nutritional hot drink with 200 ml of milk heated on an electric hob results in a GWP of 0.35 kg CO_2 eq., or 10.9 kg CO_2 eq. for an 800 g jar containing 32 servings (Fig. 6). Heating the milk on a gas hob or in a microwave reduces the impact to 10.4 and 10.1 kg CO_2 eq. per jar, respectively. For all three options, most of

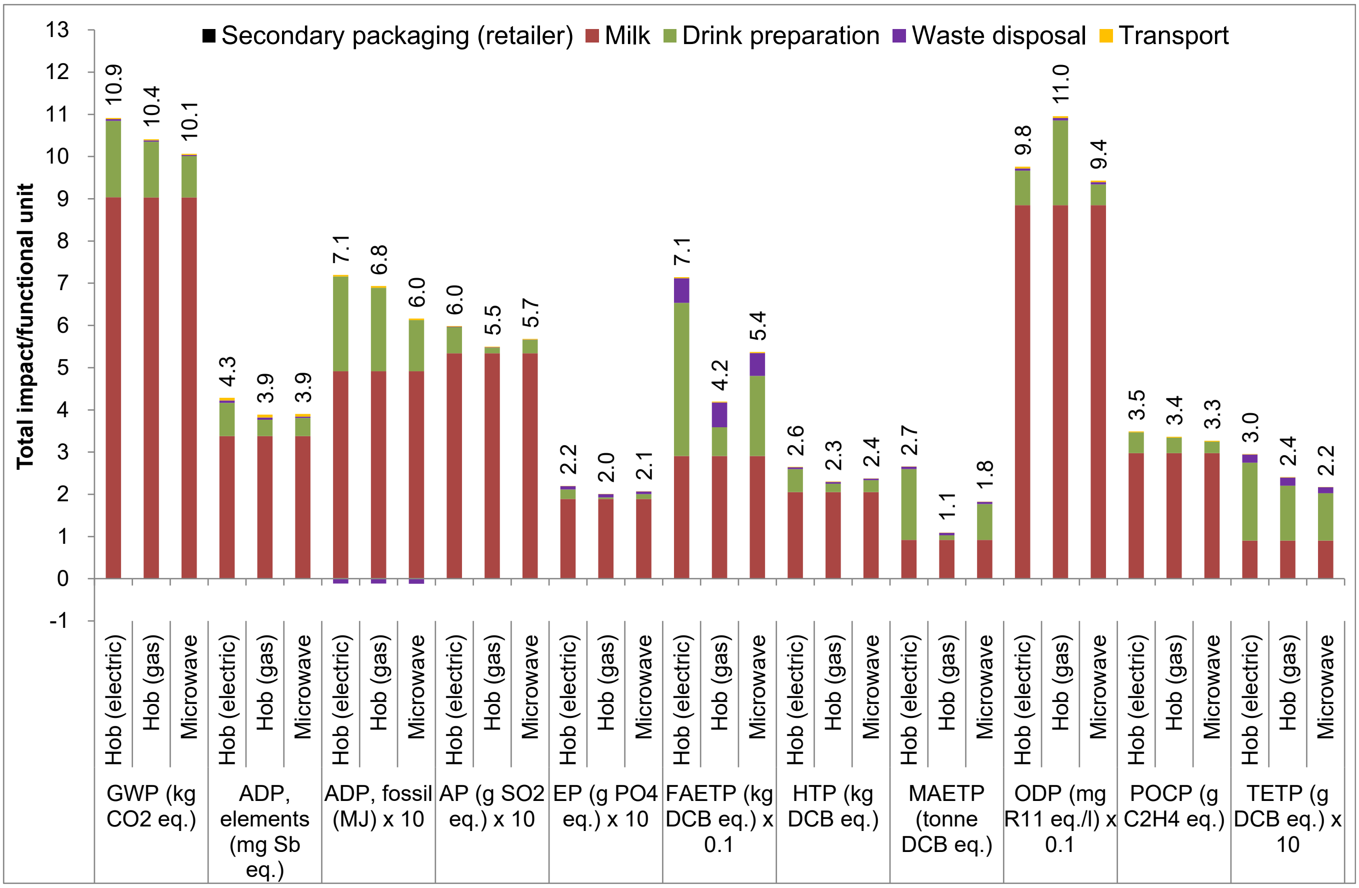

Fig. 6. Environmental impacts of the use and end-of-life management of nutritional malted drinks.
[Functional unit: Use of an 800 g jar (32 servings). Some impacts have been scaled to fit. To obtain the original values, multiply with the factor shown on the x-axis where relevant. For the impacts nomenclature, see Fig. 2.]

the GHG emissions are associated with the milk: 83% when the electric hob is used, 87% for the gas hob and 90% for the microwave. The energy used to heat the milk is the next largest contributor to the GWP, with 14% for the electric hob, 9% for the gas hob and 7% for the microwave. The contribution of end-of-life management is negligible (Fig. 6).

The results in Fig. 6 also suggest that preparing a hot drink on an electric hob has higher impacts for most categories, except for ODP, for which the use of gas hob has the highest impact due to the fire suppressants used in the distribution of gas. However, preparing a hot drink on a gas hob has the lowest AP, EP, FAETP, HTP and MAETP. For the remaining impacts, the use of a microwave is a better option. Similar to the GWP, more than 70% of the impacts for all categories, except FAETP, MAETP and TETP, are associated with the milk. For these three, the drink preparation stage is the major contributor due to the energy consumption.

The above results refer to the case when only one drink is prepared at a time. However, if more than one drink serving is made at the same time, the energy required per serving would be lower for the hob options, while for the microwave option the energy required per serving would remain the same (Market Transformation Programme, 2009). To explore the effect of this on the GWP, the preparation of two and four servings made at a time is considered in Fig. 7.

The results suggest that the use of a microwave for a simultaneous preparation of two servings still has a lower GWP than for the hob options, as was the case for preparing one drink at a time. However, if four servings are prepared together, then using a gas hob is more efficient than the microwave, leading to a slightly lower impact (10 vs 10.1 kg CO_2 eq. per functional unit). Preparing four drinks instead of one using the electric hob reduces the GWP by 6%; the equivalent reduction for the gas hob is around 4%.

A further factor that can influence the impacts of drink preparation is whether the milk is heated in a pan with or without a lid. The above results refer to the latter option. If a lid is used, the energy consumption reduces by 20% (Sonesson et al., 2003). Considering the effect on the GWP as an example, the impact per one drink prepared at a time would be 2–3% lower than when the milk is heated without the lid. Therefore, in the best case – preparing four drinks at a time on a gas hob in a pan with the lid – the GWP would be 10% lower than in the worst case (one drink at a time, electric hob, pan without the lid), equivalent to 9.9 kg CO_2 eq. per functional unit. While these reductions help, the effect on the GWP (and other impacts) of consumer behaviour related to the consumption of nutritional drinks is not as significant as that from the use of toothpaste.

3.4. Cradle-to-grave impact

To put the above results in context and find out how significant the impact from the use and end-of-life stages may be compared to the rest of the life cycle, this section considers the total GWP of the inhalers, toothpaste and nutritional hot drink from cradle-to-grave. These have been estimated by summing up the GWP estimated in this study with the cradle-to-gate data provided by GSK for inhalers, toothpaste and nutritional malted drink (Horlicks®). A

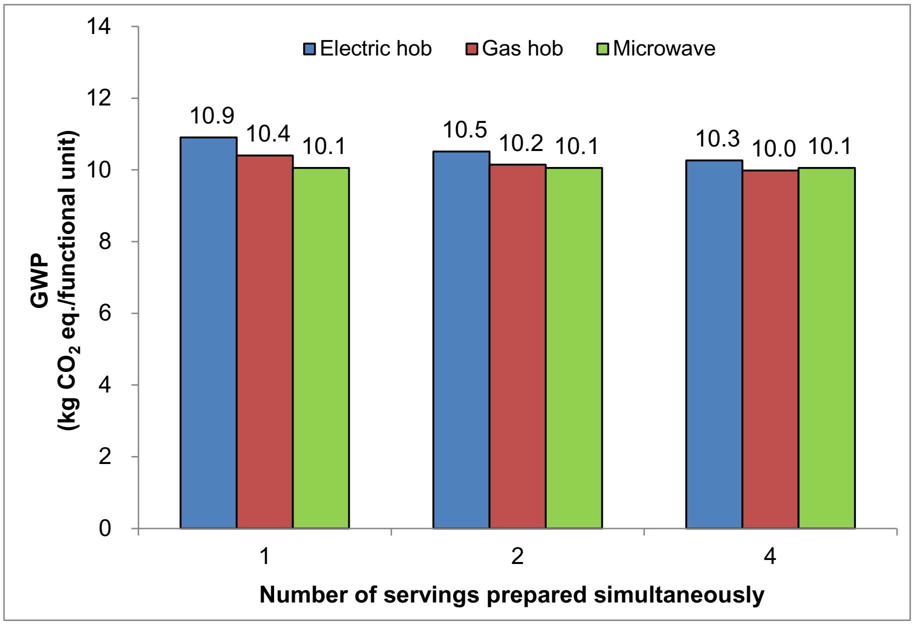

Fig. 7. The effect on the global warming potential (GWP) of the number of drinks prepared simultaneously.
[Functional unit: Use of an 800 g jar (32 servings).]

similar analysis is not possible for the other impacts due to a lack of data for the upstream life cycle stages.

As can be seen in Table 4, the difference in the cradle-to-gate GWP of the two types of inhaler is relatively small: 3.42 vs 2.6 kg CO_2 eq. However, their cradle-to-grave impact is rather different, with the HFA inhalers having 10 times higher GWP than the dry powder inhalers. As discussed in Section 3.1, this is due to the emissions of HFA during the use and end-of-life management of HFA inhalers.

For the toothpaste, the total cradle-to-grave GWP depends on consumer behaviour related to water use. If warm water is used to brush the teeth and the tap is left running, the production of toothpaste contributes only 10% to the total impact (Table 4). If the tap is turned off, the contribution of the toothpaste goes up to 36% and, if a tumbler is used instead, the GWP of toothpaste production is 1.5 times higher than from its use (0.36 vs 0.23 kg CO_2 eq.). The contribution of the production is higher if cold water is used, being responsible for 54% of the impact for the 'tap running' option; for the 'tap off' and the 'tumbler' scenarios, its impact is 3.9 and 5.7 times that of the use stage.

In the case of the nutritional hot malted drink, its consumption and end-of-life are the main contributors (~80%) to the cradle-to-grave GWP. However, unlike the toothpaste, consumer behaviour related to the choice of hob or microwave has a small effect on the total impact, which in turn is largely due to the milk.

3.5. Comparison of results with literature

This section compares the GWP of inhalers estimated in the current work with other studies; comparison of other impacts is not possible as all other studies considered only GWP. Comparison of the results for the toothpaste and nutrition drink is not possible either as this is the first time an LCA study has been carried out for these products.

For pMDI, the results are compared with the studies assessing a similar type of inhaler (i.e. Ventolin). As can be seen in Table 5, the GWP of inhalers estimated in this study falls within the ranges reported in the literature. It can also be observed that there is a large variation in the GWP of DPI in the literature, as the impact depends on the type and size of DPI. Similarly, the environmental impacts of pMDI inhalers also depend on the type and quantity of propellant used in inhalers which vary with size, drug formulations

Table 4
Cradle-to-grave global warming potential of inhalers, toothpaste and nutritional hot malted drink.

Product		Cradle-to-gate (kg CO_2 eq./FU[a])	Use and end-of-life (kg CO_2 eq./FU[a])	Cradle-to-grave (kg CO_2 eq./FU[a])
Inhalers	HFA inhaler	3.42	23.45	26.87
	Dry powder inhaler	2.60	0.06	2.66
Toothpaste	Tap running (warm water)	0.36[b]	3.65	4.01
	Tap turned off (warm water)		0.65	1.01
	Tumbler (warm water)		0.23	0.59
	Tap running (cold water)		0.31	0.67
	Tap turned off (cold water)		0.09	0.46
	Tumbler (cold water)		0.06	0.43
Nutritional hot malted drink	Hob (electric)	2.98	10.92	13.90
	Hob (gas)		10.41	13.39
	Microwave		10.06	13.04

[a] Functional unit (FU): 100 doses for inhalers, 100 ml pack for toothpaste and 32 servings of nutritional hot drinks (800 g jar). Data for the cradle-to-gate impact from GSK and all others estimated in this study.
[b] Average across the toothpaste range.

Table 5
Comparison of cradle-to-grave GWP of inhalers with literature.

Study	HFC-134a pMDI (kg CO_2 eq./100 dose)	DPI (kg CO_2 eq./100 dose)
This study	26.9[a]	2.7
UNEP (2014)	20–30[b]	0.8–6
GlaxoSmithKline (2014)	28[a]	2–2.6
Wilkinson et al. (2019)	22.5–28[a]	–

[a] Data for 18 g Ventolin inhaler.
[b] Data for unspecified pMDI inhaler.

and the use of co-solvents and inhalers (Jeswani and Azapagic, 2019; Wilkinson et al., 2019). Also as mentioned earlier, low-charge pMDI inhalers have 60% lower environmental impacts than those considered in this study (Goulet et al., 2017; Wilkinson et al., 2019).

3.6. Annual cradle-to-grave impact and improvement opportunities

Following on from the analysis in Section 3.4, here we consider the annual cradle-to-grave GWP of the three products to find out how much of the GHG emissions could be saved overall through changes in the product design and consumer behaviour. As an illustration, the analysis is based on the annual sales of these products in the UK (Table 6).

The results in Table 7 reveal that the annual GHG emissions from HFA inhalers are around 30 times higher than from the nutritional hot malted drinks: 1321 vs 44.4 kt CO_2 eq./y. The annual GWP of toothpaste used in the UK is about half of the inhalers and about 12 times higher than that of the nutritional hot drinks. Therefore, this analysis shows that the greatest opportunity for reducing GHG emissions (~1.2 Mt CO_2 eq./y) lies in the possibility of replacing HFA with dry powder inhalers or using different propellants. Globally, this would save 13 Mt CO_2 eq./y, equivalent to annual GHG emissions from 5.9 million diesel cars. However, this would depend on various factors, including the suitability of DPI for different types of drugs, patient health and safety as well as the cost. As mentioned earlier, HFA inhalers are expected to remain a dominant form of treatment for asthma and COPD well into the future (Okamura et al., 2010) so that recycling of partially used HFA inhalers to recover and reuse HFA should be implemented more widely.

Further GHG emission reductions could be achieved by influencing and changing consumer behaviour. Using cold water from a tumbler to brush the teeth could save around 1.5 Mt CO_2 eq. in the UK alone, compared to using warm water and leaving the tap running during the brushing. This corresponds to the annual GHG emissions from 681,000 diesel cars. Another 3150 t CO_2 eq. could also be saved at the UK level if nutritional drinks were prepared using either a microwave or a gas hob and preparing several drinks at a time. However, to influence the behaviour, it is important that consumers are made aware of the environmental implications of their behaviour. Companies can do this through public awareness campaigns (in collaboration with government and consumer organisations) and by providing such information on the packaging.

4. Conclusions

This study has assessed the environmental impacts of three types of widely-used healthcare and pharmaceutical products: asthma inhalers, toothpaste and nutritional drinks. The focus has been on the use and end-of-life stages to examine the influence of product design and consumer behaviour and identify improvement opportunities. The global warming potential from these stages has also been compared to the impact from the rest of the supply chain. These results have been used to evaluate the overall scope for the improvements based on the annual consumption of the products in the UK.

The results suggest that the carbon footprint of the use of hydrofluoroalkane (HFA) inhalers, toothpaste and nutritional hot drinks is significantly higher than from the rest of the life cycle, including their production. For HFA inhalers, most of the impact is due to the release of HFA during their use. The use of warm water for teeth brushing is the major contributor to the carbon footprint of toothpaste while for the nutritional hot drink, it is the consumption of milk and energy to prepare the drink. The other activities, such as transport and packaging, have a relatively low contribution to the carbon footprint. A similar trend is noticed for most other LCA impacts; however, for some categories, other life cycle stages are also relevant. For both inhalers, eutrophication and terrestrial ecotoxicity are largely caused by waste disposal, while the secondary packaging is the major contributor to depletion of elements, freshwater ecotoxicity and human toxicity. Waste disposal is the major contributor to eutrophication and toxicity-related impacts for toothpaste as well, which are associated with the wastewater treatment.

The case of inhalers highlights that for some healthcare and pharmaceutical products the impacts during the use and end-of-life stages are more influenced by product design than by consumer behaviour. It goes without saying that pharmaceutical companies have to be more concerned about safe and effective delivery of drugs while designing and developing healthcare products and devices. However, if that can be achieved in a more environmentally sustainable way, then it is a win-win situation. In the case of inhalers, the replacement of CFC with HFA has been beneficial, both in terms of ozone depletion and climate change impacts. However, the carbon footprint of HFA inhalers is still very high. Therefore, further product design innovations are required for delivery of all types of respiratory drugs without the use of HFA propellants in a cost-effective way. However, any such designs should be evaluated on environmental performance before being implemented; it is suggested that this work be carried out as part of future research.

As shown in this study, the impacts from the use of some other products, such as toothpaste and nutritional drinks, can be

Table 6
Annual sales of inhalers, toothpaste and nutritional hot drinks in the UK.

	Quantity	Unit	Comments/Reference
HFA inhalers	49.2 M	18 g (100 dose) packs eq.	In 2016, 53.1 million HFC-134a MDI inhalers were used in the UK with an average size of 16.7 g (Jeswani and Azapagic, 2019), which is equivalent to 49.2 million MDI inhalers of 18 g considered in the study.
Dry powder inhalers	15.5 M	60 dose packs eq.	Data from Jeswani and Azapagic (2019)
Toothpaste	434 M	100 ml packs eq.	Estimated using data on tooth cleaning frequency for the UK population from The Health and Social Care Information Centre (2011).
Nutritional hot malted drinks	2650	t	Data for hot malted drinks requiring milk, estimated using annual retail sales data from Key Note (2013).

Table 7
Annual global warming potential of inhalers, toothpaste and nutritional hot malted drinks sold in the UK.[a]

Annual carbon footprint (t CO_2 eq./y)	HFA inhalers	Dry powder inhalers	Toothpaste [b]	Nutritional hot drinks [b]
Cradle-to-gate	168,100	14,540	157,542	9871
Use and end-of-life	1,153,200	710	361,522 (28,210–1,584,100)	34,479 (33,056–36,208)
Cradle-to-grave	1,321,300	15,250	519,064 (185,752–1,741,642)	44,350 (42,927–46,079)

[a] Sales data for 2012 as in Table 6.
[b] Average values for different consumer behaviour, with the range of values shown in brackets.

influenced significantly by consumer behaviour. This suggests that, in addition to making environmental improvements through product development and supply change management, companies, government bodies and consumer organisations should also focus on providing consumer guidance to help lower the environmental impacts of personal care and pharmaceutical products. Future research should aim to identify the most effective ways of providing such guidance and engaging consumers in changing behaviour.

Author contribution statement

Harish Jeswani: Methodology; Modelling; Formal analysis; Writing - original draft. **Adisa Azapagic**: Conceptualisation; Funding acquisition; Investigation; Methodology; Project administration; Supervision; Writing - review and editing.

Declaration of competing interest

The authors declare no conflict of interest.

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