Beyond recycling: an LCA-based decision-support tool to accelerate Scotland's transition to a circular economy

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Highlights

- The circular economy requires a shift from weight-based targets to impact-driven targets.
- A new environmental LCA tool is introduced to aid comprehensive policy development.
- Whole life cycle thinking is applied to account for the environmental impacts of waste.
- A holistic view of the environmental cost of waste is presented which promotes prevention and the circular economy ethos.

Beyond recycling: an LCA-based decision-support tool to accelerate Scotland's transition to a circular economy

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Abstract

Resources and waste strategies have recently seen a shift in focus from weight-based recycling targets to impact-driven policies. To support this transition, numerous decision-support tools were developed to help identify waste streams with the highest impacts. However, the majority of these tools focus solely on greenhouse gas emissions and show a narrow picture of the overall environmental impacts. Furthermore, they cover burdens associated with direct waste management activities and hence fall short when it comes to highlighting the substantial benefits that can be achieved by preventing waste in the first place.

This paper quantitatively demonstrates the necessity to adopt impact-based targets that go beyond estimating the greenhouse gas emissions of waste and highlights the substantial benefits of waste reduction and prevention. Using a state-of-the-art waste environmental footprint tool, the paper quantifies the overall environmental impacts of Scotland's household waste and shows how targeting 'heavy' materials does not necessarily have the highest overall environmental benefit.

Results show that embodied environmental impacts of household waste dominate the total environmental burdens, contributing more than 90% to the whole life cycle impacts, and hence policymakers should prioritise interventions that aim at waste reduction and prevention. Moreover, our analysis shows that food and textile wastes are high-priority materials in Scotland, with the largest contribution to overall environmental burdens; up to 42% and 30%, respectively. Considering the overall environmental impacts of specific waste materials will enable policymakers to develop more granular and targeted interventions to accelerate our transition to a sustainable circular economy.

Keywords

Life cycle assessment; Policy development; Resource and waste management; Circular economy; Zero waste

Abbreviations

APC – Air Pollution Control

DQS – Data Quality Score

EoL – End of Life

GHG – Greenhouse Gases

ILCD – International Reference Life Cycle Data

IPCC – Intergovernmental Panel on Climate Change

LA – Local Authority

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

MRF – Material Recovery Facility

PRN – Packaging Waste Recovery Note

RWM – Resource and Waste Management

SWEFT – Scottish Waste Environmental Footprint Tool

UN SDGs – United Nations Sustainable Development Goals

WARM – WAste Reduction Model

WCA – Waste Composition Analysis

WEEE – Waste Electrical and Electronic Equipment

1 Introduction

The world produces over 2 billion tonnes of municipal solid waste every year, which is expected to rise to 3.4 billion tonnes by 2050 (Kaza et al., 2018). Globally, only 19% is recycled or composted, with the rest incinerated or sent to controlled landfill sites (19%) or, worse still, disposed of in uncontrolled landfills or open dumps (62%), thus waste is a global pandemic (Kaza et al., 2018; Campitelli and Schebek, 2020; Iqbal et al., 2020). Existing policies are attempting to reduce this burden with a heavy focus on diverting waste from landfills and increasing recycling rates, emphasising activities higher up the waste hierarchy. A recent example is Europe’s new circular economy action plan that includes a recycling target of 65% for municipal waste (European Commission, 2020; European Parliament, 2018). This is a weight-based target that prioritises the diversion of heavy waste materials from landfills and subsequently maximises recycling rates rather than focusing on interventions that have the greatest environmental benefits. Other weight-driven strategies include the UK Government’s Packaging Waste Recovery Note (PRN) (UK Government, 2007) and England’s Recycling Credits Scheme (DEFRA, 2005), which look at incentives based on weight. By collecting heavy and easy-to-manage materials (e.g., glass and garden waste), councils and local authorities can claim greater recycling rates, thus supporting weight-based national targets. This focus results in recycling efforts which are not well designed to maximise environmental benefit as they do not account for environmental impacts. Following an impact-based approach such as greenhouse gases (GHG) emissions (hereafter referred to as carbon impacts) for resource and waste management (RWM) in general, and recycling in particular, will shift this focus to maximise environmental sustainability (Acosta et al., 2020; DEFRA, 2018; Maes et al., 2020). Also, to support the shift toward a more circular economy, the focus should be on monitoring resources as opposed to waste (DEFRA, 2018; Van Ewijk and Stegemann, 2016), i.e. target the consumption of resources and optimise their reuse higher up the waste hierarchy. This implies considering the impacts of materials that become waste from a life cycle perspective, i.e. including the embodied impacts in the production, manufacture, and transport of waste. By highlighting these embodied impacts, intuitively the aim should be to target their reduction, i.e. through reduced consumption and waste prevention. Given that the perspective is from the RWM sector, policymakers have the power to influence change in this area only, thus approaches are waste-centred as opposed to consumption-based (Reike et al., 2018; van Ewijk and Stegemann, 2020; Wiprächtiger et al., 2021).

Numerous countries have realised that it is time to move beyond weight-based targets. For example, in England, the Department for Environment, Food and Rural Affairs (DEFRA) published their waste strategy outlining the necessity to move away from weight-based targets and reporting towards impact-based targets, focusing initially on carbon impacts (DEFRA, 2018). The strategy has been followed by a detailed plan proposing new indicators (e.g., domestic greenhouse gas emissions from waste management, and carbon footprint of a basket of consumer goods) to assess progress toward the government’s objectives linked to resource use, waste production, and waste management (DEFRA, 2020). Also, the Welsh Government has recently launched its Beyond Recycling strategy to accelerate their transition to a circular, low carbon economy, adopting a number of indicators such as carbon savings per capita from recycling and the Welsh Carbon Metric (Welsh Goverment, 2021a, 2021b). Regionally, the Association of Cities and Regions for Sustainable Resource Management (ACR+) launched their ‘More Circularity, Less Carbon’ campaign urging members to cut carbon impacts linked with local resource management by 25% by 2025 (ACR+, 2019). Other projects in this domain include: the International Solid Waste Association’s Circular and Low-carbon Cities project (International Solid Waste Association, 2020), the Waste

Reduction Model (WARM), a waste-specific carbon footprint tool developed by the US Environmental Protection Agency (EPA and ICF, 2019a), and the Scottish Carbon Metric (SCM), a carbon footprint tool developed by Zero Waste Scotland (Salemdeeb and Lenaghan, 2020). This governmental shift is supported by academia on an international scale with various studies assessing impact-based initiatives and environmental footprinting of waste management systems (Haupt et al., 2018; Khandelwal et al., 2019; Roberts et al., 2018; Wang et al., 2021; Zhang et al., 2021).

In Scotland, there is a target to recycle 70% of waste from all sources by 2025 (McIver, 2012). A review of official waste statistics, published by the Scottish Environment Protection Agency (SEPA) reveals that Scotland’s recycling rates have seen an improvement of approximately 9% , from 52% in 2014 to 60.7% in 2018 (Scottish Environment Protection Agency, 2020). However, the carbon impact of different waste materials on climate change is disproportionate to the amount of waste generated under each category. For example, by weight 23% of waste from all sources in Scotland originated from households whereas households accounted for 55% of the carbon impacts of all Scotland’s waste (Kowalski and Lenaghan, 2018). Many of the high tonnage waste materials which dominate the national waste stream have relatively low carbon impacts, when considering their life cycle, such as wood and glass wastes. However, food waste, for example, is a carbon intensive waste material which only contributes 5% of Scotland’s total waste by weight, but 22% of all waste carbon impacts (Kowalski and Lenaghan, 2018). Therefore, weight-based targets are not enough, we must transition to impact-based accounting and targets if we are to combat environmental challenges. Additionally, carbon impacts are often the focus of any existing impact-based targets, but this is not the sole proxy for environmental sustainability. There are numerous environmental indicators that should also be assessed and considered when developing environmental sustainability policies and targets in the RWM sector (and indeed all sectors).

The aim of this paper is to highlight the importance of impact-based targets and the need for impact accounting tools to look beyond carbon and incorporate additional important environmental indicators, enabling comprehensive policy development in Scotland. There is a need for a new tool that marries life cycle thinking and holistic environmental sustainability, accounting for the whole life cycle impacts of waste as well as impact indicators that are poorly represented by a carbon proxy, i.e. using life cycle assessment (LCA) to a fuller extent. Thus, this work introduces the Scottish Waste Environmental Footprint Tool (SWEFT), an LCA-based decision support tool that aims to quantitatively demonstrate the importance of impact-based accounting through evaluating the environmental impact of Scotland's waste, not just carbon impacts. This tool is Scotland-specific to help policymakers in Scotland holistically assess the impact of our waste.

To illustrate the value of this work, Section 2 reviews existing methods used globally to support policymakers in moving away from weight-based targets, outlining their approach and boundaries, and identifying their limitations as decision making tools, regarding the development of holistic policies. The shortcomings of using carbon as the sole proxy for environmental sustainability are discussed in Section 3, outlining the necessity to go beyond carbon to estimate the overall environmental impacts of waste and materials and contribute to the development of comprehensive environmental policies. Section 4 introduces SWEFT, a tool developed by the authors to achieve the objectives of the study. A case study of 2018 Scotland's national household waste data is then presented in Section 5. Finally, Section 6 discusses the results of the case study, a comparison against existing tools, and the limitations of SWEFT and future recommendations.

2 Carbon accounting tools: status quo

Numerous dedicated and powerful waste LCA tools, models and software have been developed over the years that offer practitioners a way to consider the overall environmental impacts of the waste sector (Clavreul et al., 2014; Iqbal et al., 2020; Levis et al., 2013; Wang et al., 2021). Extensive review studies have been carried out comparing differences in these tools in terms of methodological choices, system boundaries, and granularity (Baltar de Souza Leão et al., 2020; Friedrich and Trois, 2013; Laurent et al., 2014b; Maalouf and El-Fadel, 2019, 2018; Martire et al., 2018; Vea et al., 2018). In this section, we compare a selected number of LCA-based decision-support tools (**Table 1**) that target specific regions. These tools have been developed by governments or international organisations to estimate the environmental impacts of waste and are used by policymakers. Although these tools are developed to address the same issue, their methodologies vary widely. The Intergovernmental Panel on Climate Change (IPCC) method covers direct impacts associated with activities taking place within the waste sector such as emissions due to biological waste degradation and waste combustion (IPCC, 2006). The Entreprises pour l'Environnement (EpE) Protocol (EpE, 2013) and IWM (EPIC and CSR, 2004) methods provide further insights by expanding the scope of the analysis to incorporate activities and direct and indirect emissions linked to the disposal and treatment of waste. The Institute for Global Environmental Strategies (IGES) GHG calculator (Menikpura and Sang-Arun, 2013) and WRATE (Golder Associates, 2014) go a step further to include benefits associated with waste management activities such as energy recovery and material substitution. The US EPA's WARM (EPA and ICF, 2019a) and the SCM (Salemdeeb and Lenaghan, 2020) expand the scope the furthest to include upstream embodied impacts, associated with the initial production of material, before being discarded.

Table 1. Existing emissions accounting tools for waste management systems considered in this study.

Authority/Institution	Accounting tool	Geographic region	Assessment type
Entreprises pour l'Environnement (EpE)	**EpE Protocol**	EU	Direct & indirect emissions
Intergovernmental Panel on Climate Change (IPCC)	**IPCC, 2006**	Worldwide	Direct emissions
Institute for Global Environmental Strategies (IGES)	**IGES GHG calculator**	Asia	Direct & indirect emissions
Environment Canada; CSR & EPIC	**IWM**	Canada	Direct & indirect emissions
Zero Waste Scotland	**SCM**	Scotland, UK	Direct, indirect & embodied emissions
US Environmental Protection Agency	**WARM**	US	Direct, indirect & embodied emissions
Environment Agency	**WRATE**	UK	Direct & indirect emissions

Notes:

CSR - Corporations Supporting Recycling; EPIC - Environment and Plastics Industry Council; IWM - Integrated Waste Management Model for Municipalities; SCM – Scottish Carbon Metric; WARM - Waste Reduction Model; WRATE - Waste and

Resources Assessment Tool for the Environment.

Under “Assessment type”, direct emissions refer to purely the management of waste (i.e., Scope 1 emissions); indirect emissions account for benefits from energy recovery and/or material displacement (Scope 2 and 3 emissions), and embodied emissions also consider upstream impacts from material production.

While tools such as EpE, IGES, IWM, and WRATE apply life cycle thinking, the boundaries are limited in that waste is not seen as the end-of-life stage of a product, but rather a product of its own whose life cycle only starts when the useful life ends, and materials enter the waste stream. On the other hand, WARM and the SCM report the whole life cycle impacts of waste to highlight the benefits of waste reduction in the first place, i.e. through reduced consumption, the corresponding production impacts are avoided. Additionally, they highlight the importance of developing policies that help the RWM sector to emphasise activities higher up the waste hierarchy and promote circular economy. Considering waste carbon footprint only from the point of origin of the waste, e.g. a car taken to the scrap metal dealer, hinders this development of more comprehensive and meaningful policies. The consumption of resources in the production of materials/products should be targeted, highlighting the impact of waste at the start of the supply chain, as this is key for policy development (Christensen et al., 2020). This is an approach well developed in other contexts, e.g. buildings, where a life cycle assessment of a built asset covers from material extraction (cradle) to disposal of demolition waste (grave) (British Standards Institution, 2011; Pomponi et al., 2020).

Additionally, most of the tools in **Table 1** do not consider other environmental impact categories, such as water footprint, land use and material use. By focusing solely on the carbon impacts, there is a risk of problem-shifting where concerted effort to reduce the impacts in one area results in a greater impact in another (Van den Bergh et al., 2015). The

SCM, IGES, WARM and IPCC tools only assess carbon footprint while IWM and WRATE widen the scope to include several non-carbon environmental impact categories, including acidification, aquatic ecotoxicity, human toxicity, resource depletion and eutrophication. Nevertheless, these tools do not take into consideration the whole life cycle perspective; a barrier that impedes the development of holistic waste policies, as discussed above, and hinders the move toward a circular economy. This is the gap that this paper addresses, i.e. combining multiple environmental impact categories with a whole life cycle underpinning for waste assessment through the development of a novel tool, SWEFT.

A key aim of SWEFT is to give policymakers and relevant stakeholders in the RWM sector in Scotland a more comprehensive understanding of the environmental impacts of waste and promote the circular economy ethos by demonstrating the value of reducing waste compared to merely managing it. Generally, waste reduction can be achieved by taking upstream actions (e.g., following eco-design principles, adopting new business models, and using waste as a resource) or downstream measures (e.g., prolonging the lifetime of a product, design for repair, and reuse) to accelerate the transition to a circular economy. As the perspective here is from those working in, and developing policies for, the RWM sector, this work takes a waste-centred approach as opposed to consumption-based. While nationwide strategies should focus on consumption-based approaches, policymakers in the RWM sector can only develop downstream policies from the perspective of waste. It is important to tackle environmental challenges from as many angles as possible and SWEFT aims to an important weapon in our arsenal. The following section reviews and details the new environmental impact categories added to the tool.

3 Environmental impact categories

To achieve the key aim of SWEFT, it is important to first know what other environmental indicators are available, and second, which offer the most diverse and pertinent information to enable policymakers to design policies aligned with sustainable development principles, e.g. the United Nations Sustainable Development Goals (UN SDGs). This section provides an overview of indicators that can be used to determine the holistic environmental impact of waste. **Table 2** presents the environmental indicators included in SWEFT. These indicators are recommended in the International Reference Life Cycle Data System (ILCD) Handbook (Wolf et al., 2012); a series of detailed technical documents to help LCA practitioners in business and government maintain consistent and high-quality results.

Saint (2020) conducted a thorough review on these impact categories, which are collated and quantified by the ILCD 2011 Midpoint+ life cycle impact assessment (LCIA) method used in SWEFT, and their relation to the UN SDGs. Climate change is the most common metric to evaluate environmental sustainability due to the quantity and quality of evidence available for GHGs compared to other environmental measures, as well as the urgent nature of the issue (IPCC, 2019, 2014a). However, if other impacts are not assessed, measured, and reported, their relative importance could be overlooked. Therefore, the relationship between climate change and each of the other midpoint impact categories is discussed below, contesting the suitability of the climate change indicator as the sole proxy of environmental sustainability.

Table 3 illustrates the relationship between the UN SDGs and the midpoint impacts categories presented in **Table 2**. It shows how holistic policies that consider overall environmental impacts – not only carbon burden – could help achieve a number of UN SDGs. These findings align well with similar studies including the European Commission’s Joint Research Centre (Sala et al., 2019) and Wang et al. (2021), who evaluated streamlining LCAs by identifying the most critical environmental indicators in terms of total environmental impacts. For waste, more than most environmental issues, the environmental indicator considered is vital to the policy questions being asked (DEFRA, 2018); to understand waste and materials, using multiple indicators is particularly important because of their broad potential impacts. For example, in a bid to reduce plastic pollution, bio-based plastics are becoming increasingly popular and their associated carbon impacts are lower than those of fossil-based plastics by 90%. Nevertheless, when other impact categories such as land and water use are considered, bio-based plastics demonstrate significantly higher impacts. Compared to polyethylene terephthalate (PET), bio-based plastics are 1,300% and 890% more damaging in terms of land and water use, respectively (Salemdeeb and Saint, 2020). These estimates align with the findings of a study that confirmed bio-based plastics are equally, or more harmful than fossil-based plastics for most of the environmental indicators (Walker and Rothman, 2020). Therefore, by focusing on the carbon impacts of these waste streams, other impacts are overlooked and thus less likely to be addressed through research and technological developments. The following section details the method behind the development of SWEFT and its components.

Table 2. Environmental impact categories and the recommended LCIA method and indicator (ILCD, 2011).

Impact category	**LCIA method**	**Indicator**	**Unit**
Climate change (carbon footprint)	Baseline model of 100 years (IPCC, 2014b)	Radiative forcing as Global Warming Potential (GWP100)	kgCO_2-eq
Water use	AWARE (Boulay et	Available WAter REmaining	m^3

	al., 2018)	per area in a watershed	
Material use (abiotic resource depletion)	CML 2002 (Guinée et al., 2002)	Scarcity	kg antimony [Sb] -eq
Land use	Model based on Soil Organic Matter (Mila i Canals et al., 2007)	Soil Organic Matter (SOM)	kg, deficit
Particulate matter (PM)/ respiratory inorganics (air quality)	RiskPoll model (Rabl and Sparado, 2004)	Intake fraction for fine particles	kg $PM_{2.5}$-eq
Ozone depletion	Steady-state ODPs 1999 (WMO, 1999)	Ozone Depletion Potential (ODP)	kgCFC-11-eq
Human toxicity (cancer effects)	USEtox model (Rosenbaum et al., 2008)	Comparative Toxic Unit for humans	CTU_h
Human toxicity (non-cancer effects)	USEtox model (Rosenbaum et al., 2008)	Comparative Toxic Unit for humans	CTU_h
Ecotoxicity (freshwater)	USEtox model (Rosenbaum et al., 2008)	Comparative Toxic Unit for ecosystems	CTU_e

Ecotoxicity (terrestrial and marine)	No methods recommended		
Ionising radiation (human health)	Human health effect model (Frischknecht et al., 2000)	Human exposure efficiency relative to U^{235}	kgU^{235}-eq
Ionising radiation (ecosystems)	No methods recommended		
Photochemical ozone formation	LOTOS-EUROS (van Zelm et al., 2008)	Tropospheric ozone concentration increase	kgC_2H_4-eq
Acidification	Accumulated Exceedance (Posch et al., 2008; Seppälä et al., 2006)	Accumulated Exceedance (AE)	mole H^+-eq
Eutrophication (terrestrial)	Accumulated Exceedance (Posch et al., 2008; Seppälä et al., 2006)	Accumulated Exceedance (AE)	mole N^+-eq
Eutrophication (aquatic)	EUTREND model (Struijs et al., 2013)	Fraction of nutrients reaching freshwater or marine end compartment	kgP-eq or kgN-eq

Table 3. Relevant Sustainable Development Goals (summarised from those presented above) and the impact categories that correlate with each (taken from Wulf et al., 2018).

Sustainable Development Goal (SDG)	**SDG number**	**Directly correlated impact categories**
Good health and well-being	3	Ozone depletion Human toxicity (cancer and non-cancer) Particulate matter/respiratory inorganics (air quality) Ionising radiation Photochemical ozone formation
Clean water and sanitation	6	Water use
Responsible consumption and production	12	Material use (abiotic resource depletion) Land use
Climate action	13	Climate change (carbon footprint)
Life below water	14	Eutrophication (freshwater and marine) Ecotoxicity (freshwater and marine)
Life on land	15	Acidification Eutrophication (terrestrial) Ecotoxicity (terrestrial)

4 Methods

4.1 SWEFT development

Life cycle assessment and life cycle thinking are rapidly growing paradigms in the context of sustainable production and consumption and waste management (Campitelli and Schebek, 2020; Christensen et al., 2020). Within an LCA, the emissions and resources associated with a specific product are documented in a life cycle inventory (LCI) (British Standards Institution, 2006a; Guinée et al., 2011, 2002). Built in accordance with the ILCD Handbook (Wolf et al., 2012) and adhering to the ISO 14040 and 14044 standards (British Standards Institution, 2006b, 2006a), SWEFT and its underlying components cover 33 waste categories, as defined in the EUROSTAT Guidance on EWC-Stat Waste Categories (Eurostat, 2010). SWEFT is an Excel-based tool and the model formulation is based on a widely-used computational structure using matrix algebra (Heijungs and Suh, 2002).

The data collection method follows a stepwise process, as shown by the flowchart in **Figure 1** (see Supplementary Information (SI) 1, for a more detailed description). Following a waste composition analysis (WCA) of the generated waste, each of the waste categories are further disaggregated into specific materials, to provide a percentage split of material types that create a comprehensive LCI. For example, the plastic waste category is broken down into polymer type (HDPE, PET, PVC, etc.) and the food waste category comprises different food groups (carbohydrates, dairy, etc.). This detailed percentage split allows the production impacts, i.e. material extraction, manufacturing, and transport, to be more accurately quantified. The waste management technologies currently covered are broadly termed 'recycling', 'incineration', and 'landfilling'. Note that, depending on the waste category, a number of waste treatment technologies might be included under each broad category. For example, the recycling process of food waste in SWEFT is modelled based on a Scottish-specific split between anaerobic digestion and composting. A full breakdown of the LCI and waste management technologies covered is provided in SI 2. This LCI is then used to conduct the LCIA, applying the ILCD 2011 Midpoint+ method presented above (Section 3).

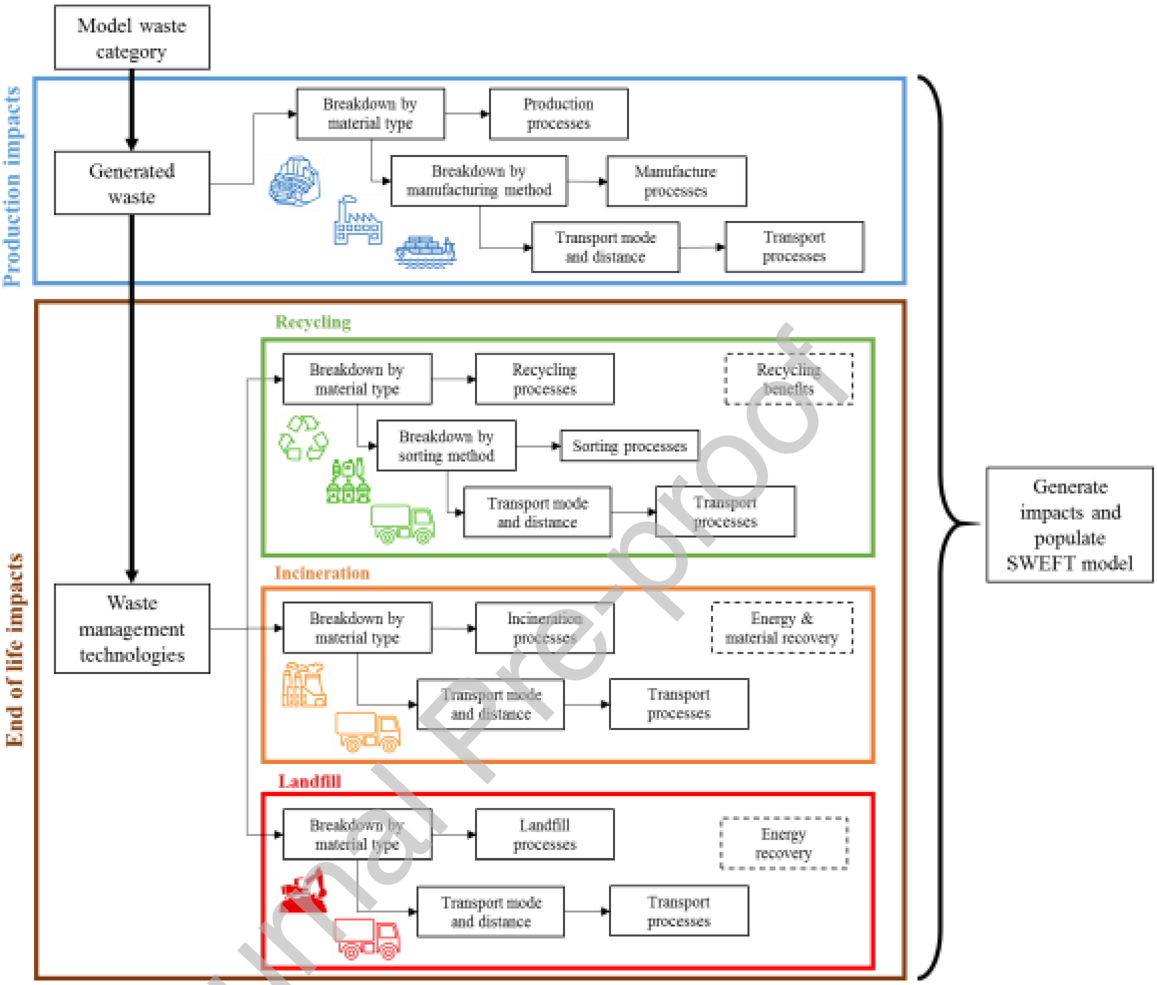


Figure 1. Flowchart illustrating the system boundaries and research method which follows a stepwise, iterative process. Sorting processes include pre-treatment, sorting at material recovery facilities (MRFs), etc.; incineration processes include recycling bottom ash and air pollution control (APC) measures to filter flue gas; landfill processes include leachate treatment and biogas capture; the dotted boundaries represent benefits.

In terms of the LCI, it is important to know the composition of waste streams to determine the environmental impacts of both the production and the end-of-life (EoL) treatment activities. The percentage contribution of each component within a waste category will differ from the percentage contribution which is recycled or incinerated, as shown in **Figure 2** for the example of plastic wastes. To create the LCI, the SWEFT model is populated with 492 life cycle processes extracted from robust and internationally used databases, primarily from the ecoinvent (v3.5) database (Moreno Ruiz et al., 2018) but also from the Waste Electrical and Electronic Equipment (WEEE) LCI (Ecosystem, 2018) and agri-footprint (Agri-footprint, 2020) databases. SWEFT uses a data collection hierarchy, where Scottish specific data is preferentially used, followed by UK-specific, European then global data (see SI 1). Where appropriate processes were not available from these databases, data were derived from grey literature, such as governmental and organisational reports, and peer-reviewed academic sources. These processes are assigned to each material type/component within each waste category (i.e., the split), and for each life cycle stage (**Figure 1**). Moreover, and within each life cycle stage, SWEFT takes into account all end-of-life routes of a specific material across all waste streams. For example, our analysis is based on 80% of household glass waste being collected kerbside with other recyclables and hence sent to a MRF for sorting first while the remaining 20% of glass is separately collected via ‘Bring Banks’ and ‘Household Waste Recycling Centers’ across Scotland. The full LCI and supporting sources for all waste categories, and their composition, are provided in the Supplementary Information (See SI 2).

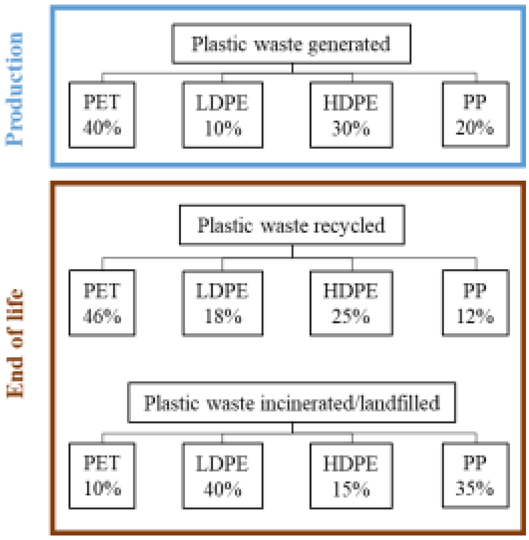


Figure 2. Breakdown of plastic waste by sub-category for production and end of life stages, based on the composition of plastic waste in Scottish municipal waste in 2018. Note that plastics landfilled and incinerated have the same composition split.

4.2 Data quality assessment method

The robustness of underlying data used in the development of SWEFT was assessed using a hybrid data quality assessment method which is based on the widely-used pedigree matrix (Weidema et al., 2013). The assessment method, discussed in detail by Salemdeeb et al. (2021) and provided in SI 4 as a template, scores data through two stages: (i) data robustness and evidence, and (ii) the level of confidence and consistency with existing literature. Stage (i) is a semi-quantitative assessment of the quality criteria of datasets based on five independent characteristics; technological representativeness, geographical representativeness, time-related representativeness, reliability, and completeness (Weidema et al., 2013). Stage (ii) aims to check the consistency of the model factors with existing literature and whether the new factors align with current understanding to evaluate the 'level of confidence' in modelling different waste categories. Results from both assessment stages are then used to estimate an overall data quality score (DQS) based on the following scoring scale: Excellent = DQS ≤ 2; Good = 2 < DQS ≤ 4; and Poor = 4 < DQS ≤ 5.

The aim of this data quality approach is to give non-technical experts a useful overview of the quality of the tool's results. It balances the detail required to assess each data point for multiple types of robustness with an indication of the overall quality of the results for decision making purposes. Policymakers can then use these DQSs alongside SWEFT results to make more informed decisions. Furthermore, the results of the assessment will enable SWEFT developers to design a model-upgrade strategy that targets priority areas, while considering available resources and time constraints.

5 Case study results

This section presents an evaluation of SWEFT through a case study of Scotland's 2018 national household waste data. The functional unit of this assessment is the total household waste tonnages generated in Scotland in 2018, i.e. over 1 year. The system boundaries of this case study follow those presented in **Figure 1** and the goal is to show how SWEFT can quantitatively demonstrate the embodied environmental impact of Scotland's waste. The WCA and data collection behind this case study have been presented above and can be found in the Supplementary Information (SI 2). In 2018, Scotland generated nearly 2.4 million tonnes of waste, of which 44.6% was recycled, 42.9% landfilled and 12.4% incinerated (SEPA, 2018). To illustrate impacts for carbon and beyond, five key indicators (i.e., carbon footprint, water use, land use, material use, and air quality) are discussed in this paper for the robustness of their impact assessment method and relative ease of understanding by stakeholders, policymakers, and non-technical audiences. These indicators align with recommendations in other work assessing key environmental impact indicators (Kaiser et al., 2021; Life Cycle Initiative, 2017; Steinmann et al., 2016).

5.1 Environmental impacts of Scotland's household waste

Table 4 lists the total environmental impacts of Scotland's household waste in 2018, in absolute values, across the five selected indicators as well as the amount of waste generated. The whole life cycle environmental impacts of Scotland's household waste, across all 16 indicators listed in **Table 2**, are presented in the Supplementary Information (SI 3); SI 3 also lists the factors (i.e., environmental intensities per tonne of waste) that are used in this analysis.

Table 4. Overall environmental impacts of all Scottish household waste in 2018. SI prefixes and units: M = a million units, k = a thousand units, and t = metric tonne.

Environmental indicator	**Unit**	**Total impacts**
Waste generated	Mt	2.4
Carbon footprint	$MtCO_2eq$	5.4
Water use	Mm^3	2,428
Land use	Mt, deficit	14.9
Material use	kt antimony [Sb] eq	0.4
Air quality	Mt $PM_{2.5}eq$	5.7

The following sections present these environmental impacts in terms of the major waste categories. Firstly, the whole life cycle carbon impacts of Scotland's waste are explored through the different life cycle stages, to highlight the importance of considering the embodied impacts of producing the materials that become waste. Secondly, impacts over the five key environmental indicators are analysed, highlighting the significant waste categories from a whole life perspective. The quality of the data underpinning this analysis is assessed in Section 5.4. Section 6 then provides a discussion of these environmental impacts and a comparison with other carbon accounting tools.

5.2 Whole life cycle carbon impacts

To illustrate the importance of including upstream embodied impacts when assessing waste, the climate change impact category (i.e., carbon footprint here) is used due to its widespread use and relative ease of understanding. **Figure 3** presents the most impactful waste categories, in terms of whole life cycle carbon impacts, for total tonnes of waste generated and managed. Each waste category is broken down into the production impacts associated with material extraction, manufacturing and transporting the materials that become waste and end of life impacts linked to waste management activities (i.e.,, 'Recycled', 'Incinerated', and 'Landfilled'). The net, overall carbon impacts are also presented for each waste category. Our analysis shows that the production burden dominates the whole life cycle burdens, as illustrated in **Figure 3**. In terms of carbon impacts, the production carbon impacts of all household waste contributes to 90.4% of the whole life cycle carbon burdens. When considering other key environmental indicators, discussed in this paper (see Section 5.3), production environmental impacts reach as much as 99.9% of the whole life burden for material use.

Figure 3 shows some waste categories, such as textile, food, and plastic wastes, have much higher production impacts than others, in particular glass and wood wastes. In terms of target materials, priority should be given to waste categories with the highest embodied impacts (i.e.,, textile, food, and plastic wastes) to maximise carbon savings. **Figure 3** also suggests that reducing waste, in particular carbon-intensive materials, is an effective policy measure to substantially reduce whole life cycle impacts and ultimately contribute to our fight against climate change. For example, Scotland adopted two nationwide waste reduction targets of 15% and 33% for total waste arising and food waste, respectively (Scottish Government and Natural Scotland, 2016; Scottish Government and Zero Waste Scotland, 2019). However, as advocated above, carbon impacts are not the sole proxy of environmental sustainability, it is important to review environmental impacts holistically and consider other key indicators.

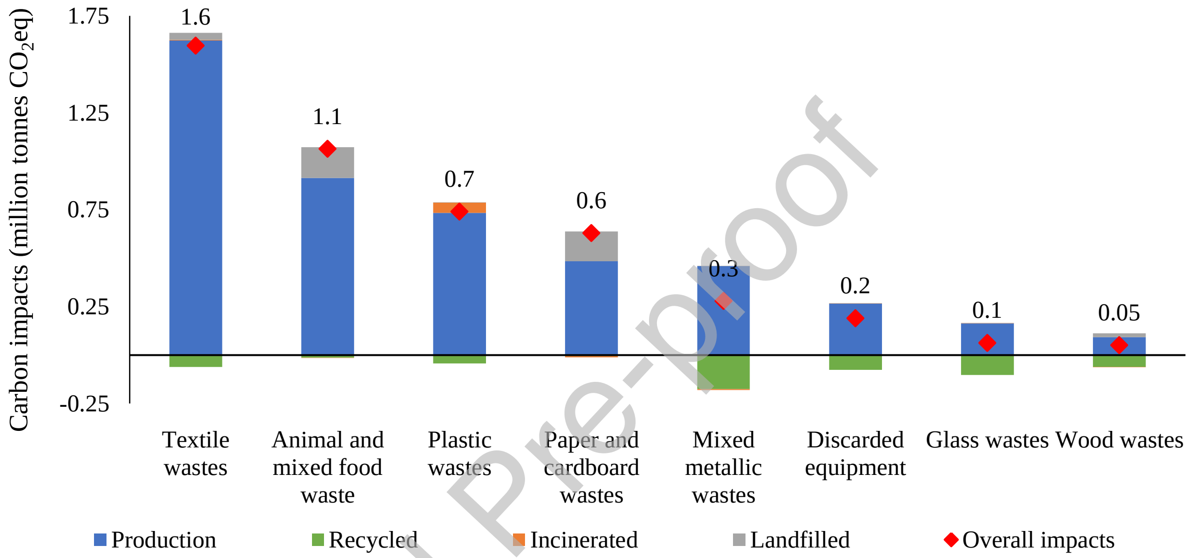


Figure 3. Total carbon impacts of Scotland’s 2018 household waste for key material categories, broken down by production and end of life (‘Recycled’, ‘Incinerated’, ‘Landfilled’) impacts. See SI 3 for raw data.

5.3 Environmental impacts

Figure 4 presents the results of a hotspot analysis carried out to understand the overall environmental impacts of Scotland’s 2018 household waste across the five key indicators (i.e.,, carbon footprint, water use, land use, material use, and air quality). The contribution of the eight major waste categories, in terms of tonnes generated and whole life cycle impacts, is presented while the other relevant waste categories are grouped to keep the percentage impacts in perspective of the total household waste generated. Focusing on tonnes of waste generated, textile wastes constitute only 3% which is unlikely to contribute significantly to weight-based recycling targets but, when considering whole lifecycle environmental impacts, textiles are among the most impactful categories, especially in terms of the carbon footprint (30%), air quality (29%) and water use (23%). In SWEFT, textiles have a detailed composition of knit cotton (13%), woven cotton (13%), viscose fibre (11%), and polyester (63%) (Ellen MacArthur Foundation, 2017) (see SI 2) and require energy and material (water) intensive production and manufacturing processes.

Also, the discarded equipment waste category (i.e., WEEE) takes up a small percentage of waste by weight (2%) and its carbon footprint is one of the lowest of the eight categories reviewed at 4%. However, it has one of the highest impacts in terms of material use at 11%. SWEFT models the composition of WEEE as large (34%) and small (28%) domestic appliances, fridge/freezers (27%), TV/display equipment (9%), and lighting (1%) with a large metal content (84%, including steel, aluminium, and copper). This large consumption of metallic raw materials contributes significantly to the material use impacts; indeed, they are similar to material use impacts of mixed metallic wastes (17%).

Animal and mixed food waste contributes 16% by weight but has high impacts across most indicators; 42% contribution to land use, 36% material use, 32% water use, 20% carbon impacts and 9% air quality impacts. It is well known that food production is a resource intensive process, and this is strongly supported by these results. Across all the environmental indicators except for carbon, the production impacts completely overshadow EoL impacts. Landfilling significantly contributes to the net carbon impact due to the release of methane from anaerobic decomposition in landfills. There is also a small carbon benefit from the incineration of food waste due to its caloric value and the grid energy that is offset. Here, the recycling of food waste is taken as anaerobic digestion and composting. As it cannot be recycled into a similar product or reused, the production impacts cannot be displaced thus there is little benefit for this waste management activity across the environmental indicators. Thus, the only effective solution to reducing the impacts of food waste is reduced consumption.

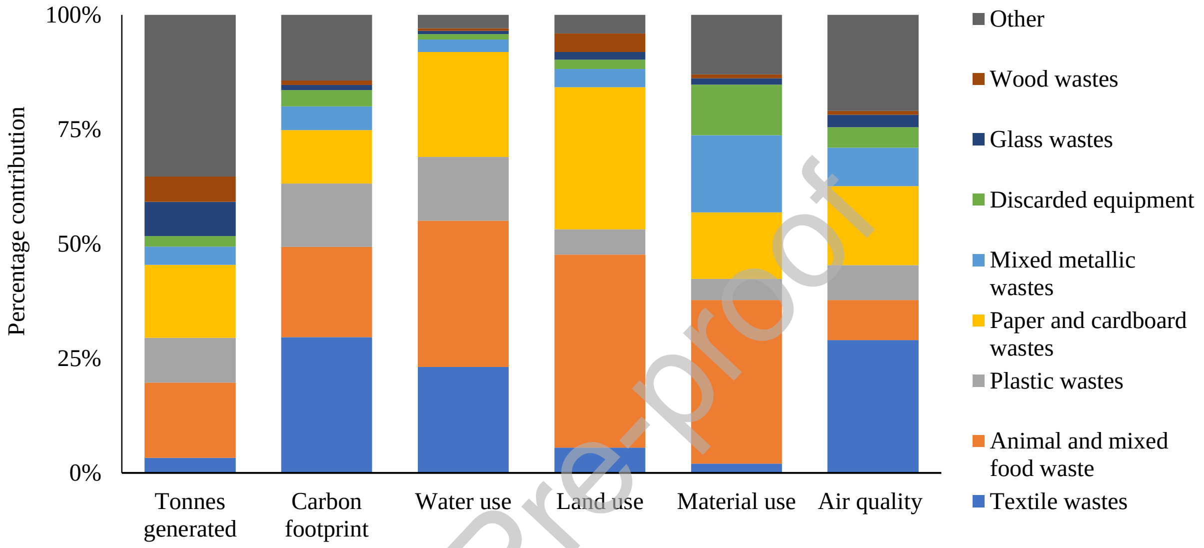


Figure 4. Percentage contribution of top waste categories in terms of life cycle impacts and tonnes of waste generated in each category, for Scotland's 2018 household waste data. See SI 3 for raw data.

The hotspot analysis presented in **Table 5** also shows that targeting a specific waste material to increase recycling rates might not necessarily contribute in the same level to impact-based environmental targets. For example, glass waste, a widely recycled material with well-established recycling technologies and high recycling rate, constitutes 8% by weight but only 1% to 3% of environmental impacts, with the biggest impact being on air quality. This observation does not suggest that efforts in the management of glass wastes should be stopped, but it highlights where the opportunities for improvement lie by embedding more comprehensive assessments into current waste policies and why efforts should focus on additional waste categories when considering a spectrum of environmental indicators. Weight-based targets would overlook these impacts as weight is a poor proxy for environmental impacts, shown by the lack of similarity across the profiles in **Figure 4**. An environmental impact-driven approach would show key categories such as textiles and food waste. **Figure 4** and **Table 5** show that no one environmental impact indicator is similar; different materials are significant for each impact type. The key message here for policymakers is that over-exploiting natural resources is harmful, hence waste prevention and reduction are powerful tools in limiting the environmental impacts from materials.

Table 5. Heatmap of life cycle environmental impacts; the absolute data are provided in the Supplementary Information (SI 3).

Household waste category*	Waste generated	Carbon footprint	Water use	Land use	Material use	Air quality
‘Others’	1.0E+00	4.8E-01	9.2E-02	9.6E-02	3.6E-01	7.2E-01
Animal & mixed food waste	4.7E-01	6.6E-01	1.0E+00	1.0E+00	1.0E+00	3.0E-01
Paper & cardboard wastes	4.5E-01	3.9E-01	7.2E-01	7.4E-01	4.1E-01	6.0E-01
Plastic wastes	2.8E-01	4.7E-01	4.3E-01	1.3E-01	1.3E-01	2.6E-01
Glass wastes	2.1E-01	3.9E-02	2.0E-02	4.0E-02	3.8E-02	9.2E-02
Wood wastes	1.6E-01	3.1E-02	1.9E-02	9.6E-02	2.4E-02	3.0E-02

Mixed metallic wastes	1.1E-01	1.8E-01	8.7E-02	9.4E-02	4.7E-01	2.9E-01
Textile wastes	9.3E-02	1.0E+00	7.2E-01	1.3E-01	5.8E-02	1.0E+00
Discarded equipment	6.6E-02	1.2E-01	3.7E-02	4.9E-02	3.1E-01	1.6E-01

[*] For each indicator, the maximum value is set to 1 and the results of the other waste categories within that indicator are calculated relative to this result. The heatmap highlights hotspots, i.e. the waste categories with the highest impacts per indicator. Waste categories are sorted in descending order by waste tonnages generated.

5.4 Data quality assessment

Table 6 presents the data quality scores for key waste categories; results of the data quality assessment for all household waste categories analysed are provided in the Supplementary Information (SI 4). A red-amber-green colour code is used for easy visual interpretation: Excellent DQS = Green; Good DQS = Amber; and Poor DQS = Red. The data quality assessment shows that all key waste categories achieve a "Good" score for data robustness and evidence, meaning that data is reasonably reliable, complete, and technologically, geographically, and temporally representative. In terms of confidence and consistency with existing literature, half the waste categories achieve an "Excellent" score. These results indicate the underlying data is robust, however, there is still room for improvement.

Table 6. Overall data quality status and scores for the most impactful household waste categories.

Household waste	Stage (i)	Stage (ii)

category	(robustness and evidence)	(confidence and consistency)
Textile wastes	Good (3.0)	Excellent (2.0)
Animal and mixed food waste	Good (3.4)	Good (3.0)
Plastic wastes	Good (2.9)	Excellent (2.0)
Paper and cardboard wastes	Good (2.9)	Excellent (2.0)
Mixed metallic wastes	Good (3.3)	Good (4.0)
Glass wastes	Good (2.6)	Good (3.0)
Discarded equipment	Good (3.4)	Good (4.0)
Wood wastes	Good (2.7)	Excellent (2.0)

6 Discussion

6.1 Beyond carbon impacts

The case study results presented above demonstrate why a whole life cycle environmental impact assessment is necessary to develop comprehensive resources and waste management policies.

In terms of the importance of shifting from weight-based to impact-based targets, the discarded equipment waste category provides a strong example, with a minimal weight contribution but significant impact on material use, as well as an impact on air quality. These findings align well with current literature surrounding the significant impacts of discarded equipment on material use (Bigum et al., 2017; Messmann et al., 2019) and the importance of the waste hierarchy upper levels; prevention, reuse and recycling (Zhang et al., 2017). The material use indicator is becoming increasingly important given the concerns surrounding the depletion of finite resources and exceeding the Earth's carrying capacity. This is emphasised by the Earth Overshoot Day, when humanity exhausts natures budget for the year, which for 2019 occurred on the 29th July and has been steadily advancing over the last four decades, except for 2020 when Earth Overshoot was slowed by the global Covid-19 crisis (Lenzen et al., 2020). By focusing efforts and reduction targets on carbon intensive materials without considering other environmental impacts, policymakers could inadvertently overlook the environmental burden across other areas. There should be a stronger emphasis on these other indicators and the need to address them.

Table 5 showed the life cycle environmental impacts of key household waste categories, in terms of relative impact. The analysis showed that animal and mixed food waste has the highest relative impacts across most of the environmental indicators, as well as the most tonnes generated for a single waste category. Our observation aligns with the Scottish Government's current focus on food waste, where its management and reduction are prioritised with a reduction target of 33% by 2025 and a ban on biodegradable municipal waste going to landfill from 2025 (Scottish Government and Natural Scotland, 2016). As the goal of our work is to quantitatively demonstrate the environmental impacts of waste, policymakers can make more informed decisions based on these varied impacts; they can better balance the impacts of introducing new policies and avoid tackling only one issue which could risk shifting the problem elsewhere, e.g. bio-based plastics.

The results presented in Section 5.3 were derived from the total household waste generated for each waste category, therefore impacts are somewhat defined by the weight of waste. There are certain waste categories that contribute to a very small percentage of generated waste by weight, such as discarded vehicles, batteries, or chemical wastes (approximately 0.08%). If the results are considered per tonne, as in **Figure 5**, the most impactful waste categories become different from those presented in **Figure 4**. Textile waste is still a significant contributor, with the highest impact intensities for three of the five impacts. However, in terms of material use, food waste (11%) is overshadowed by batteries, which dominates that environmental indicator at 34%, discarded equipment (24%), and mixed metals (21%). Indeed, batteries become an important contributor across all the environmental indicators, surpassing the carbon intensity of food waste at 11% (versus 6%) and almost matching its water use intensity at 11%, as well as similar intensities to textiles for land use and air quality at 13% and 32%, respectively.

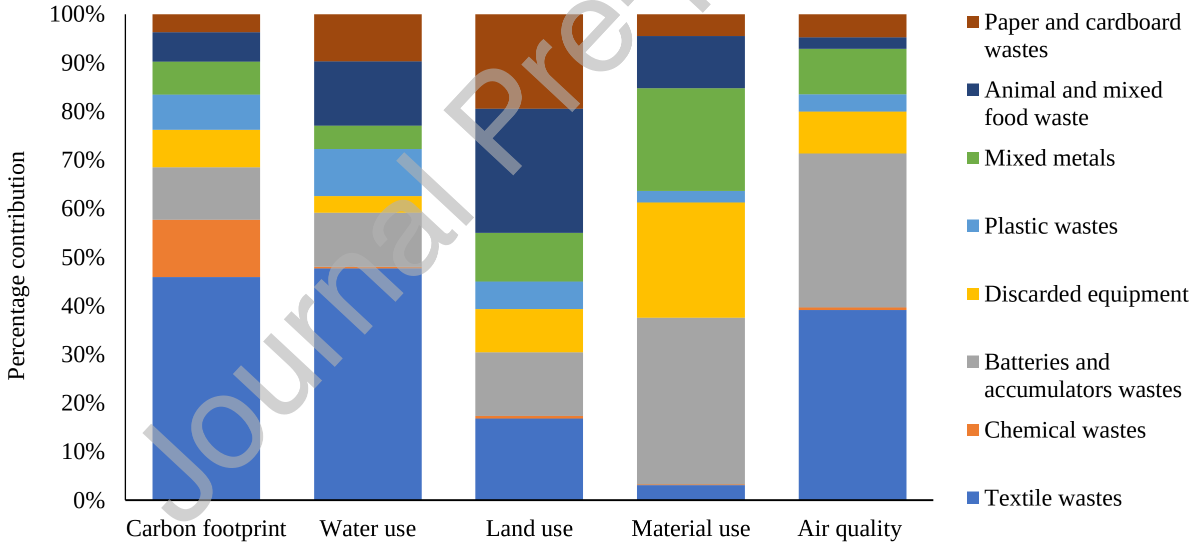


Figure 5. Percentage contribution of most impactful household waste categories in terms of net impact intensity across the five environmental indicators, presented per tonne of waste generated and managed in Scotland in 2018. See SI 3 for raw data.

The intensity indicators shown in **Figure 5** are highlighted to show how the footprint of a single waste category can vary across several environmental indicators. Though some of the waste categories in **Figure 5** make up an insignificant proportion of overall household waste, it should be borne in mind that their potential impacts are significant. For example, with the rise of electric vehicles (EVs), the market for batteries is rapidly increasing and thus their contribution to the waste stream will rise. Secondary batteries, e.g. rechargeable batteries used in EVs, can have a lifespan of 10-15 years so the impacts of this generated waste stream, shown in **Figure 5**, will not be realised for years to come (Aichberger and Jungmeier, 2020; Raugei and Winfield, 2019). The environmental impact of batteries is receiving increased attention and there are attempts to make the producers of EV batteries responsible for their end-of-life collection and management (Beaudet et al., 2020; Propulsion Quebec, 2020; Reuters, 2018). However, it is also important to consider the embodied impacts now so that sustainable practices can be implemented in the production stage, and to design the product for longevity and ease of material capture and reuse. These indicators reveal the arduous task facing policymakers to identify priority target materials in future policies to promote sustainable production and consumption practices.

6.2 Comparison with existing tools

A comparison of SWEFT results against most environmental modelling tools, listed in **Table 1**, is difficult due to differences in methodological approaches, background assumptions, system boundaries, etc. In this section, we compare the carbon factors of SWEFT and the US EPA's WARM (**Figure 6**), due to the similar ethos in taking a circular view of LCA as well as the availability and transparency of their tool and documentation. Both tools consider production impacts, thus incorporating the upstream embodied impacts of the materials that become waste. However, WARM does not differentiate between household and non-household waste, unlike SWEFT. In terms of waste categories, the materials covered in WARM are grouped to align with the categories in SWEFT. For example, SWEFT's ‘discarded equipment’ waste category refers to WEEE and thus correlates with WARM’s ‘electronics’ category. WARM does not have a dedicated textiles waste category but the carpet category is often used as a proxy material for textiles by WARM users. Furthermore, lumber, medium-density fibreboard (MDF) and wood flooring in WARM are grouped and compared against SWEFT’s ‘wood wastes’ category.

In terms of the production impacts, **Figure 6**A shows the variation across the two models. There is limited consistency between the models with only glass, food, and mixed metallic wastes showing relatively similar impacts. The largest discrepancy occurs in the textiles waste category which can be attributed to differences in defining textile wastes in both models; WARM’s ‘carpets’ category, which is used as a proxy for textiles, covers primarily plastic-based products. In SWEFT, textiles have a more detailed composition of knit cotton (13%), woven cotton (13%), viscose fibre (11%), and polyester (63%) (Ellen MacArthur Foundation, 2017). A significant difference is also observed in discarded equipment. Examining the WARM documentation surrounding the electronics category (EPA and ICF, 2019b), products considered include desktop central processing units, flat-panel displays, and hard-copy devices. Whereas the discarded equipment category in SWEFT expands the list of products to include large and small domestic appliances, such as fridges and dishwashers.

When it comes to the end of life, most of the waste categories show similar impacts for waste management via landfilling, as shown in **Figure 6**B. SWEFT and WARM results are comparable in five out of the eight categories covered in this analysis: food waste, discarded equipment, glass waste, mixed metallic waste, and plastic waste. Noticeable differences between SWEFT and WARM are in the textile (2,726%), paper and cardboard (1,192%), and wood (186%) waste categories. Both SWEFT and WARM exclude biogenic carbon from their calculations, i.e. carbon that is naturally absorbed and released, in accordance with IPCC guidance (IPCC, 2006), and both consider methane gas utilisation from controlled landfills. However, WARM includes a factor for 'landfill carbon storage' which accounts for the biogenic organic matter that will not decompose and is permanently stored in the landfill (EPA and ICF, 2019a). This is considered an anthropogenic carbon sink and is counted as a benefit. Additionally, carbon storage potential is accounted for in durable wood products, e.g. lumber and MDF, but not in nondurable products, such as paper, which can help explain the significant net benefits of landfilling wood wastes versus the net emissions from paper and cardboard wastes. There is a large difference between the models for textile wastes as this is assumed to be represented solely by 'carpet' in WARM, i.e. plastic polymers, thus a non-biodegradable material, so there are no associated landfill emissions or storage (EPA and ICF, 2019a). Also, as with all energy displaced by waste management practices, the sources and nature (i.e., marginal or average) of the underlying energy mix being offset will affect the reported impacts from landfill gas utilisation. If the embodied impacts of producing materials were included in WARM, this would highlight the negative impact of landfilling valuable resources.

For recycling, **Figure 6**C shows a consistent lack of agreement between the models. All waste categories show a significant discrepancy, with differences ranging from -214% for glass wastes to 99% for paper and cardboard. These differences may be attributed to the material composition of each waste category as well as the assumptions behind material displacement and losses. For example, SWEFT disaggregates textiles into types, i.e. polyester, viscose fibre, and cotton, giving more representative impacts. In terms of the material displacement and losses for textiles, closed loop recycling is assumed in SWEFT with losses at the sorting facility and reprocessing stages. EPA states that the life cycle energy and material requirements for processing carpet into secondary products are not included in WARM due to paucity of data (EPA and ICF, 2019a). Additionally, material specific recycling processes are modelled in SWEFT which may help to explain the large difference (-125%), beyond the fundamental differences between Scottish and American waste management and the national/regional energy mix and associated factors. The variability observed here is common in LCA waste studies due to differences in local conditions, assumptions, and data (Laurent et al., 2014a, 2014b), where responsibility ultimately lies with the practitioners (Scrucca et al., 2020).

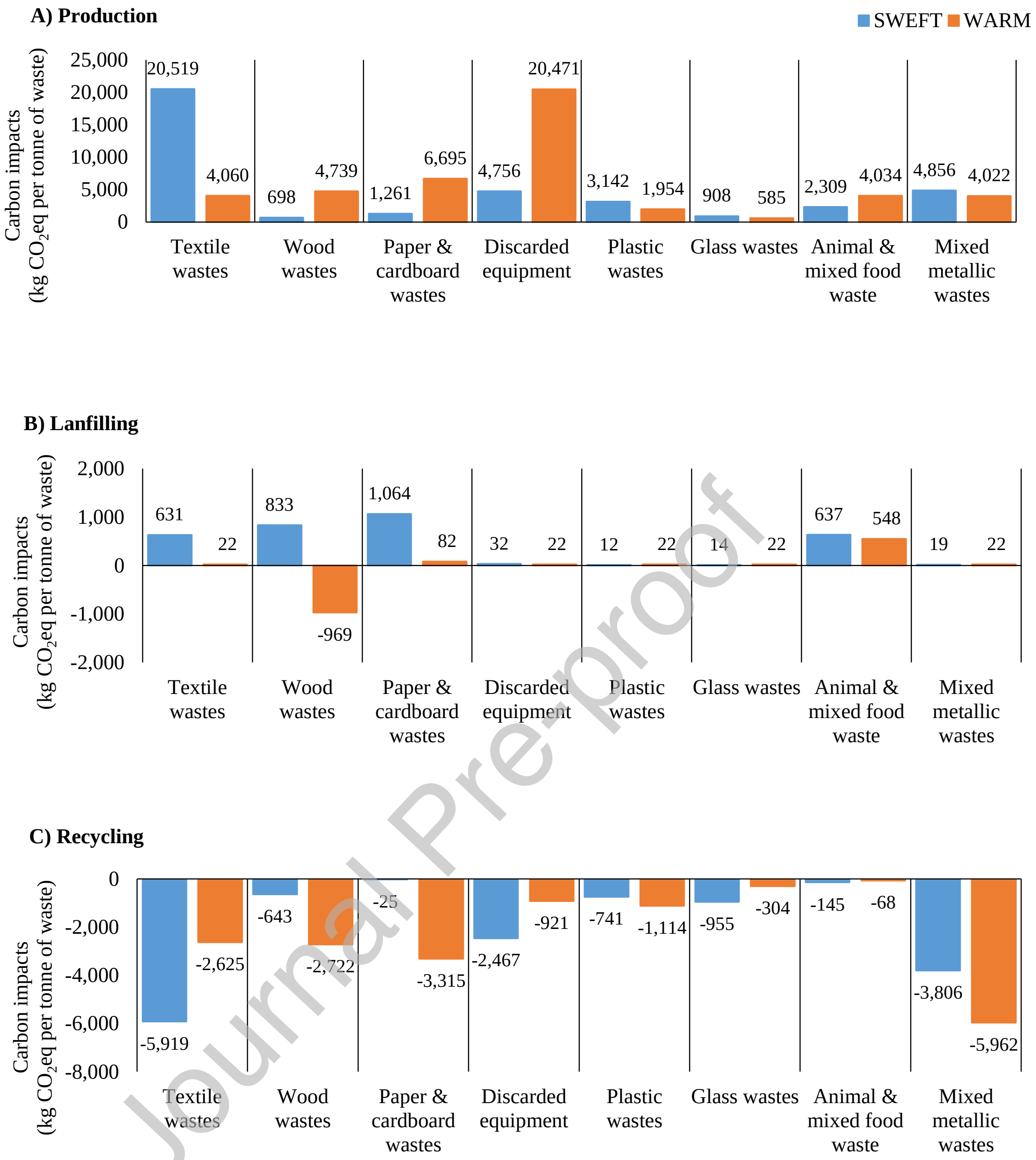
The discarded equipment waste category also shows a significant difference across the tools, -168% for SWEFT versus WARM. Again, this comes down to the assumptions behind the materials in the waste category. Overall, SWEFT applies an approximate composition of 80% metals, 10% glass and 10% other materials, such as plastic or circuit board components (Ardente and Talens Peiró, 2015; Gallego-Schmid et al., 2018). WARM, however, has a much higher percentage of plastic across the types of electronics within their discarded equipment waste category which have a very low recovery rate (EPA and ICF, 2019b). Therefore, given the greater proportion of highly recyclable materials assumed in SWEFT compared to WARM, there is greater offset potential and thus more net benefits reported. Also, for wood-based wastes, including paper and cardboard, ‘forest carbon storage’ (i.e., the carbon sequestered by trees that is left undisturbed when recycling/reusing a wood-based material offsets the use of virgin wood) is considered in WARM which has significant associated benefits (EPA and ICF, 2019a), as shown in **Figure 6**C. The lack of similarity shown for recycling impacts highlights the need for tailored, transparent, and contextualised approaches which SWEFT can provide. Users can input their own WCA or use nationally relevant assumptions.

When it comes to incineration (**Figure 6**D), the differences between SWEFT and WARM are more varied; only glass and mixed metallic wastes show relatively similar results while the remaining six waste categories show noticeable differences. The most significant is the discarded equipment waste category (-97%); SWEFT reports very low impacts which is an artefact of the processes behind the model and the caloric values of the materials within the waste category. As discussed in the comparison for recycling, the proportion of metal and glass is higher in the SWEFT waste category composition; the higher plastic content assumed in WARM results in relatively high net emissions (EPA and ICF, 2019b). Textile wastes also show a significant difference (-63%) with WARM showing substantially higher emissions than SWEFT. As discussed for the landfilling and recycling emissions, ‘carpets’ are taken to represent the textile waste category in WARM which are primarily composed of plastics. Indeed, the plastic and textile waste category incineration emissions in WARM are very similar.

The differences observed between food (75%) and paper/cardboard (57%) wastes are similar to the textile and discarded equipment waste categories, with WARM reporting higher net benefits. Discrepancies could simply be down to differences in the energy mix and marginal energy sources that are being replaced as well as the efficiencies of the combustion processes, with low system efficiencies of waste-to-energy plants in the US (EPA and ICF, 2019c). In WARM, recovered energy is assumed to displace non-baseload power plants, i.e. marginal electricity emissions offset. The actual energy mix varies regionally in the United States and, consequently, WARM applies a different CO_2-intensity depending on where the electricity is offset (EPA and ICF, 2019c). The US national average carbon intensity of marginal electricity reported in the WARM documentation is 0.762 kg CO_2eq per kWh, compared to the UK average of 0.269 kg CO_2eq per kWh used in SWEFT. Therefore, the offset potential of energy from waste in the US, i.e. in WARM, is higher. WARM only considers the emission factors for mass burn facilities but both WARM and SWEFT offsets include avoided metal manufacture due to metal recovery from bottom ash, which contributes to the lower net emissions observed in SWEFT (-97%).

A caveat to the reported benefits here is the importance of assessing these impacts from a whole life cycle perspective. As per the waste hierarchy, energy from waste is not a sustainable choice and when the embodied impacts of producing these materials are accounted for, incineration has little benefit (**Figure 3**). Additionally, this comparison only considers carbon impacts; evaluating the holistic whole life cycle environmental impacts, as in **Figure 4**, illustrates the need for waste reduction and reuse as opposed to burning it.

Both the US EPA's WARM tool and SWEFT broadly match the waste hierarchy when it comes to best waste management practices: they reveal that waste reduction has the highest environmental benefits which is followed by recycling, incineration, and then landfilling. Nevertheless, results from the US EPA's WARM tool and SWEFT are, unsurprisingly, not well aligned, highlighting the need for greater consistency in the way life cycle thinking environmental tools used in policy development are built. The most significant differences come from the inclusion of a 'forest carbon storage' factor in WARM and the material composition for waste categories like textiles and discarded equipment, as well as the fundamental differences between US and UK waste management practices and marginal energy mix. Assessing SWEFT in the context of existing environmental accounting tools enables the validation of the underlying methodology and factors, as discussed in Section 4.2.


A) Production
SWEFT
WARM
Carbon impacts (kg CO2eq per tonne of waste)
25,000
20,000
15,000
10,000
5,000
0
20,519
4,060
698
4,739
1,261
6,695
4,756
20,471
3,142
1,954
908
585
2,309
4,034
4,856
4,022
Textile wastes
Wood wastes
Paper & cardboard wastes
Discarded equipment
Plastic wastes
Glass wastes
Animal & mixed food waste
Mixed metallic wastes
B) Lanfilling
Carbon impacts (kg CO2eq per tonne of waste)
2,000
1,000
0
-1,000
-2,000
631
22
833
-969
1,064
82
32
22
12
22
14
22
637
548
19
22
Textile wastes
Wood wastes
Paper & cardboard wastes
Discarded equipment
Plastic wastes
Glass wastes
Animal & mixed food waste
Mixed metallic wastes
C) Recycling
Carbon impacts (kg CO2eq per tonne of waste)
0
-2,000
-4,000
-6,000
-8,000
-5,919
-2,625
-643
-2,722
-25
-3,315
-2,467
-921
-741
-1,114
-955
-304
-145
-68
-3,806
-5,962
Textile wastes
Wood wastes
Paper & cardboard wastes
Discarded equipment
Plastic wastes
Glass wastes
Animal & mixed food waste
Mixed metallic wastes

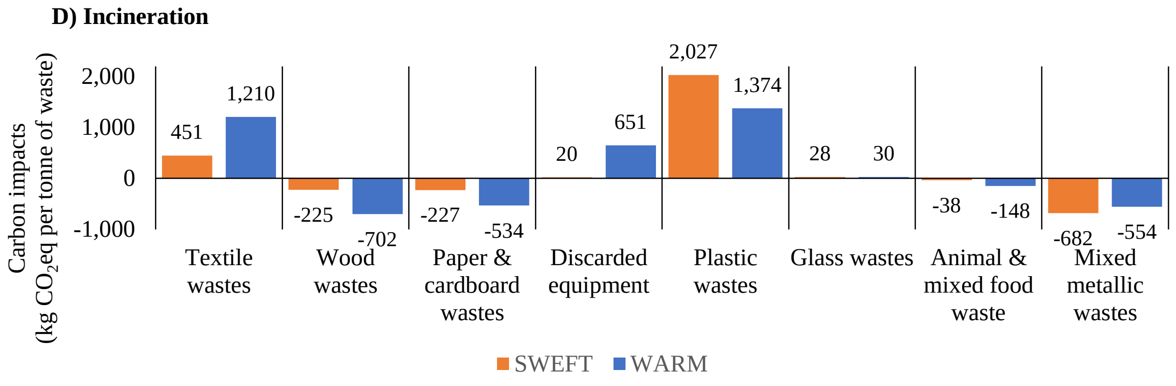


Figure 6. Comparison of carbon impacts per tonne of waste material A) produced, B) landfilled, C) recycled and D) incinerated (termed 'combusted' in WARM) for SWEFT versus WARM..

6.3 Limitations and recommendations

The sensitivity of the results of environmental assessments based on life cycle thinking are inherently high due to a number of factors that are thoroughly discussed and widely covered (Chen et al., 2021; Qin et al., 2020). The tool presented here is our first step toward a robust and comprehensive tool to quantitatively assess the holistic environmental impacts of Scotland's waste from a whole life perspective, accounting for the production impacts of materials that become waste to promote greater consideration of waste reduction and prevention. This contribution aims to align with the Scottish Government commitment to explore options to go beyond recycling and reduce the environmental impacts of waste on the total environment. Although the geographical focus of our analysis is Scotland, our findings could benefit other countries, especially those with similar waste management operation activities, to explore their options in moving beyond weight-based targets.

To effectively communicate the level of uncertainty associated with SWEFT, we adopted a hybrid data quality assessment method, presented in Section 4.2, to enable policymakers to understand the robustness and confidence in the results. In addition, the SWEFT development strategy follows an iterative and adaptive process that aims at continuously reviewing assumptions, updating life cycle inventory datasets and adding new features with an increasing level of ambition. Thus, to keep up to date with evolutions in waste management and life cycle processes, SWEFT will be reviewed and updated periodically.

The second limitation of SWEFT is the sole focus on the environmental impacts of future policies, one of the three pillars of sustainability (i.e., environment, economy, and society). The results of this tool should be considered alongside economic and social implications in order to design policies that not only reduce burdens on the environment but also ensure economic viability and social equity. Moreover, the technical feasibility of any future policies should be considered alongside the three pillars to ensure successful implementation. For example, the processes used in SWEFT do not account for complications in waste processing of certain materials such as bio-based plastics contaminating fossil-based plastic recycling streams. Thus, it is recommended to consider practical implications associated with future policies, and it would be highly beneficial to run techno-economic assessments alongside SWEFT.

The results from SWEFT can be used to contribute to our understanding and measure progress toward sustainable development policies, such as the SDGs. As shown in **Table 3**, the 16 environmental impact indicators covered by SWEFT can be aligned with certain SDGs and the key indicators presented in this paper correlate to goals 3, 6, 12, and 13. Through better management of the most environmentally impactful waste categories, and most importantly promoting their prevention and reduction, the RWM sector can work toward these goals alongside other sectors for a multi-faceted approach. However, comparing the overall environmental impacts across 16 indicators might be a challenging task for policymakers, especially those who might not have the technical expertise on the ILCD 2011 Midpoint+ LCIA method used in SWEFT. This might also lead to a rise in the 'apples-and-oranges' scepticism, so our future development plan for SWEFT would incorporate normalisation and weighting factors to aid interpretation by policymakers. Following this step, we will explore options as to how the results can be linked directly to the SDGs to further accelerate the sustainable movement. These actions to effectively communicate the findings of SWEFT to policymakers will be useful when exploring how the conclusions of this study can support the design of circular economy strategies across all priority waste categories.

6.4 Policy implications

Our analysis has quantitatively demonstrated the significant environmental cost of waste. Additionally, it has highlighted the necessity to ‘move up’ the waste hierarchy and prioritise waste policies that aim at reducing waste arisings. As the scope of this paper covers the perspectives of policymakers in the resource and waste management (RWM) sector (i.e. downstream policy measures such as waste reduction, design for repair, and reuse), this section briefly outlines waste policy areas that can be considered by policymakers to reduce waste arisings. Our recommendations can be categorised into two groups: traditional regulatory instruments and fiscal measures. Under the traditional regulatory instruments, one option to be explored is the introduction of mandatory waste reduction targets. A prominent example of this measure is Scotland’s legally-binding target to reduce food waste by one third by 2025 (Scottish Government and Zero Waste Scotland, 2019; Salemdeeb and Saint, 2021). Another measure to explore is the introduction of market restrictions to ban problematic materials. Numerous countries (including Scotland) have already adopted similar actions targeting single-use plastics but there is an opportunity to consider other problematic single-use non-plastic items (UK Government, 2021; Scottish Government, 2021a). Moreover, our results identified ‘batteries and discarded electronic equipment’ as a waste stream with high environmental burden, which is especially important with the increasing demand for electronics and batteries (McDonald, 2021). Reforms to the current Extended Producer Responsibility (EPR) schemes are urgently required to promote resource efficiency in the electrical and electronic sector and reduce demand on virgin materials. Such reforms need to place the onus on the producer to introduce measures to adopt circular economy practices, prolong the lifetime of products, and ensure they are captured for recycling at the end of their lifetime.

On the other hand, fiscal measures to be considered by policymakers include imposing a levy/charge on single-use items to shift people's obsession with the convenient throw-away lifestyle, and providing financial support and financial subsidies to industries to address the waste crisis. An example of the former 'stick' approach is the latest announcement by the UK Government to give the power, through the amended Environmental Bill, to national authorities to introduce charges on 'all single-use items', not just single-use plastics (Legislation.gov.uk, 2021). The Scottish Government adopted the 'carrot' approach and introduced a £2 million Textile Innovation Fund to support businesses working in this sector to address issues associated with textile waste and throwaway culture (Scottish Government, 2021b).

However, a major consideration of policy instruments that aim at preventing waste is the potential knock on (i.e., rebound) environmental effects. Waste prevention interventions at the household level could lead to increased effective income which subsequently results in expenditure on alternative products and services (Zink and Geyer, 2017). That is to say, when people adopt practices that aim at prolonging the lifetime of a product or reducing demand on new products by embracing repair and reuse activities, they consequently have more money available that may then be spent on other products and services. As this additional expenditure is likely to generate waste and additional environmental burden, the environmental benefits of reducing waste in the first place can be partially or completely offset. For example, Salemdeeb et al. (2017) estimate that the rebound effect might reduce greenhouse gas savings associated with food waste prevention activities at the household level by up to 60%. Therefore, policies prioritising waste prevention must explicitly consider rebound effects to prevent burden shifting (Font Vivanco et al., 2016).

SWEFT, the tool presented in this paper, can be used as a 'thermometer' of the environmental impacts of waste and materials discarded in Scotland and monitor progress made by introducing waste-related policies. To aid the interpretation of SWEFT results by policymakers, future update plans for the tool would incorporate normalisation and weighting factors (Section 6.3).

It is worth reiterating that this study adopts a waste-centred approach as we explore the role policymakers in the RWM sector can play in promoting circular economy practices. To accelerate the transition of Scotland to a circular economy, upstream actions across all disciplines (e.g., eco-design, manufacturing, international trade, domestic logistics, and customer behaviour) will be essential, in particular those targeting activities further up the supply chain as they will achieve the highest impact (Corrado et al., 2020; Sala et al. 2020).

7 Conclusions

Resources and waste management policies have recently shown a clear shift in focus from weight-based targets in favour of impact-driven measures, in particular developing policies that support our fight against climate change. To support the development of such policies, the Scottish Waste Environmental Footprint Tool (SWEFT), presented in this paper, provides policymakers with necessary insights to understand the whole life cycle environmental impacts of waste generated and managed in Scotland.

In this paper, SWEFT was demonstrated through a case study based on Scotland’s 2018 household waste data. The case study results highlighted the importance of including the embodied impacts of waste, which dominate the whole life cycle impacts. For example, our analysis shows that embodied carbon impacts associated with the production of textile and plastic wastes, before being discarded, account for 97.8% and 93.2%, respectively, of their total whole life cycle carbon burden. Hence policymakers should prioritise interventions that aim at waste reduction and prevention.

The second key objective of SWEFT is to quantitatively confirm that focusing solely on the climate change impacts of waste risks neglecting other important sustainability indicators, such as material use, water use, land use and air quality. SWEFT results also showed that food and textile wastes are key target materials to prioritise when addressing the environmental impacts of wasted resources in Scotland; their contribution to the impacts of all household waste range from 9%-42%, and 2%-30%, respectively, across the five indicators covered in this study.

Finally, this paper highlighted the level of discrepancies between life cycle thinking waste management tools used in the policy field due to inconsistencies in the methodological approaches used, system boundaries adopted, data sources considered, and allocation methods applied. These challenges can only be solved by continuous collaboration between policy experts, LCA practitioners, and academics to develop a harmonised framework to take into consideration life cycle thinking in designing environmental policies. This concerted effort will enable the development of holistic, targeted waste management policies, prioritising reduction and prevention over other waste treatment options, and accelerating our transition to a sustainable circular economy.

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Declarations

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Conflicts of interest/Competing interests

The authors declare no financial incentives or competing interests.

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Declaration of interests

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

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