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Environmental impact, economic and carbon footprint assessment of end-of-life PVC flex banners and its potential upcycling opportunities in the fashion industry

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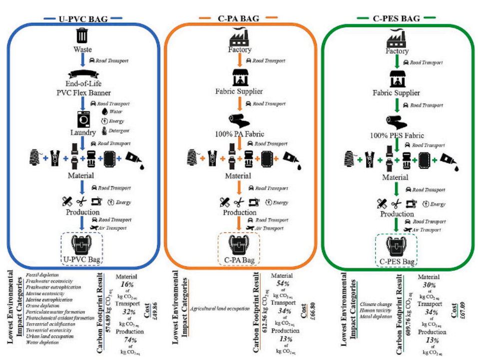
HIGHLIGHTS

- PVC flex banners contribute to environmental pollution when discarded.
- End-of-life PVC flex banners can be upcycled in the fashion industry.
- There is a lack of studies reporting on the upcycling of these banners.
- Upcycled PVC bags are economical, less impactful, and have a low carbon footprint.
- Research provides a methodological framework for both industry and academia.

GRAPHICAL ABSTRACT



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ABSTRACT

This article employs life cycle assessment (LCA) using openLCA software to compare the environmental and economic indicators of upcycled fashion accessories made from end-of-life polyvinyl chloride (PVC) flex banners with those made from conventional materials like nylon and polyester. Six bags were designed, produced from end-of-life PVC flex banners, and compared to nylon and polyester fabric bags. Data related to the manufacturing process of these bags, including material usage, transport, and production, were analysed for comparison. The LCA results revealed that upcycled bags made from end-of-life PVC flex banners are more environmentally friendly than their nylon and polyester counterparts. Out of the 16 environmental impact categories analysed in the study, U-PVC bags were shown to have a lower impact in 12 categories: 1) fossil depletion, 2) freshwater ecotoxicity, 3) freshwater eutrophication, 4) marine ecotoxicity, 5) marine eutrophication, 6) ozone depletion, 7) particulate matter formation, 8) photochemical oxidant formation, 9) terrestrial acidification, 10) terrestrial ecotoxicity, 11) urban land occupation, and 12) water depletion. Moreover, the carbon footprint of U-PVC bags was 574.89 kg $CO_{2\ eq}$, which is lower than the carbon footprints of C-PA bags at 612.56 kg $CO_{2\ eq}$ and C-PES bags at 609.76 kg $CO_{2\ eq}$. Additionally, the average manufacturing cost of U-PVC bags was £49.86, compared to £66.80 for C-PA bags and £67.09 for C-PES bags. This indicates that U-PVC bags are not only more environmentally sustainable but also more economical compared to C-PA and C-PES bags. Our research highlights the

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potential to upcycle end-of-life PVC flex banners into shoulder backpack bags, demonstrating the viability of PVC upcycling to reduce environmental impact.

1. Introduction

PVC flex banners are frequently used indoors or outdoors for advertising and marketing. These are surfaces with a three-layer structure formed by laminating $CaCO_3$ and PVC resins as well as plasticisers and additives on polyester fabrics produced by weaving or knitting technology (Mouna et al., 2022; Novak et al., 2020; Saini et al., 2023; Simonian et al., 2022). Today, these advertising and marketing tools, which are frequently used in many places (especially municipal buildings, shopping centres, museums, universities, etc.), are widely used with digital printing technology (Cuc and Secan, 2024; Jauhari et al., 2018; Rao, 2018; Saini et al., 2023; Sharma and Rong, 2014). Although communication tools such as fabric banners, metal banners and LED screens are occasionally used for advertising and marketing purposes, these cannot overtake PVC flex banners due to their installation and maintenance costs. The fact that PVC flex banners are easily accessible, portable and hangable, as well as the fact that they do not require high costs by their users, makes them attractive and creates a global PVC flex banner market (Ismail et al., 2014; Ragaert et al., 2019; Wongtanasuporn et al., 2019).

In 2022, when the most produced plastic types on a polymer basis are analysed, it is seen that PVC is one of the most widely used plastic types and PVC is the third most produced polymer type in the world with a rate of 12.7 % (Bombelli et al., 2017; Plastics Europe AISBL, 2023; Wang et al., 2022). The global PVC market size was valued at $68.96 billion in 2022 and is expected to grow from $72.08 billion in 2023 to $95.88 billion by 2030, showing a CAGR of 4.2 % during the forecast period. Asia Pacific (especially China, a leading country) dominated the PVC market with a market share of 56.19 % in 2023 (Fortune Business Insights, 2024). The steady growth in the PVC market also affects the production of PVC flex banners. According to Flex Banner Market data published by Transparency Market Research (2023), the global flex banner industry was valued at $2.5 billion in 2022. However, the flex banner industry is believed to grow at a CAGR of 6 % between 2023 and 2031, reaching a value of $4.2 billion by the end of 2031.

PVC production emphasises creating a synthetic film through extrusion or calendaring, which is then coated onto a fabric substrate. This process is relatively straightforward but still requires some finishing steps. In contrast, polyester production includes several stages: polymerisation, spinning, drawing, and weaving or knitting, followed by finishing. This makes polyester fabric production more complex because it involves additional steps, particularly in fibre creation and textile construction (Smelik, 2023). Similarly, nylon fabric production is more intricate and time-consuming, involving detailed processing steps like polymerisation, spinning, and texturing (Yao and Ray, 2004). As mentioned earlier, PVC production focuses only on creating a synthetic layer that bonds to the fabric, making it simpler than other processes. It requires fewer resources and chemical steps and mainly concentrates on plasticising and shaping the material. PVC flex banners, typically used for short-term purposes, present a significant solid waste challenge that must be addressed once they are no longer needed (Ghosh et al., 2018; Rao, 2018). Currently, most end-of-life PVC flex banners, classified as plastic waste, are either piled up in landfills, buried, or burned. This improper waste management strategy poses serious risks to the environment and public health (Amobonye et al., 2021; Babaremu et al., 2022; Evode et al., 2021; Gopinath et al., 2020; Qureshi et al., 2020; Shen et al., 2020; Vollmer et al., 2020).

While recycling, particularly mechanical methods are often seen as a preferred solution for disposing of end-of-life PVC flex banners, but it has been determined that this method alone is insufficient (Cholake et al., 2018; Kamble and Behera, 2021; Lewandowski and Skorczewska, 2022; Uttaravalli et al., 2021; Yadav et al., 2018). Upcycling, which falls under the reuse category, presents a valuable opportunity for these banners, particularly within the fashion industry (Ghosh et al., 2018; Uttaravalli et al., 2021). To stay within the 1.5 °C carbon budget, it is estimated that plastic production needs to be reduced by 50 % by 2050 (Ellen MacArthur Foundation, 2023).

Upcycling allows for the creation of high-value-added products that address both environmental and economic concerns through their innovative designs. This method offers a unique opportunity for repurposing PVC flex banners that have reached the end of their lifecycle, especially in the production of bags. A small yet growing number of upcycling fashion brands have begun producing items such as bags from these end-of-life PVC flex banners (Cuc and Secan, 2024; Ellen MacArthur Foundation, 2021). The materials involved in upcycling do not undergo any physical or chemical treatments; instead, they are creatively transformed into new, value-added fashion products (Caldera et al., 2022; Vats and Rissanen, 2016).

Upcycling can yield sustainable products that are economically and socially viable, utilizing waste materials in the design and manufacturing processes, thus contributing to a circular economy (Han et al., 2017; Enes and Kipoz, 2020; James and Kent, 2019; Wu et al., 2022). The circular economy supports upcycling initiatives, as it is a regenerative system designed to slow down material and energy cycles while minimising resource inputs, waste, emissions, and energy loss (Geissdoerfer et al., 2017; Ly, 2021; van Dam et al., 2020).

The research focuses on the life cycle assessment of upcycled bags produced from end-of-life PVC flex banners and aims to identify the environmental and economic value of these bags, creating a value-added market in the fashion industry and providing a solution to the PVC flex banner-based solid waste problem. Thus, U-PVC (upcycled PVC) bags were compared with C-PA (conventional polyamide/nylon) and C-PES (conventional polyester) bags, which are in line with the LCA method. Recycling (especially mechanical recycling) suggestions for the post-consumer use of end-of-life PVC flex banners have been noted in some academic studies (Bompa et al., 2021; Cholake et al., 2018; Mehta et al., 2023; Mishra and Jain, 2019; Saravanan et al., 2015; Vishnuvardhan et al., 2021). There is currently insufficient research in the fashion industry regarding the post-consumer use of end-of-life PVC flex banners, highlighting a significant gap that needs to be addressed. Therefore, the fashion industry should compare upcycled products with that of conventional materials. Upcycled bags, produced from end-of-life PVC flex banners, can serve as an alternative product for the fashion industry, offering environmental and economic benefits. Reusing waste materials to create new fashion products, combined with innovative technologies, presents a more practical alternative to conventional fast fashion items.

2. Methodology

The LCA process has been developed to assess the environmental impacts of upcycled bags produced from end-of-life PVC flex banners and to compare them with conventional bags produced from PA and PES woven fabrics. The research consists of two stages: manufacturing and analysis-interpretation. The methodological approach (ISO, 2006a; ISO, 2006b) used in the research is based on the content detailed in ISO 14040:2006 (environmental management - LCA - principles and framework) and ISO 14044:2006 (environmental management - LCA - requirements and guidelines) (Klopffer, 2012; Pryshlakivsky and Searcy, 2013; Rana et al., 2015a) and follows four steps:

a. Goal and scope, i.e., defining the purpose of the study, the boundaries of the system and the required data (both environmental and economic).
b. Life cycle inventory (LCI), i.e., designing a life cycle flowchart, specifying inputs and outputs.
c. Life cycle impact assessment (LCIA), i.e., creation of inventories for required environmental impact categories and calculation of impact indicators.
d. Interpretation, i.e., identification of problems deemed important, confirmation of the accuracy and consistency of the data, and recommendations about the results.

LCA was carried out using openLCA 2.2.0 software and the OzLCI2019 database. ReCiPe 2016 Midpoint (H) method in openLCA software was preferred for LCIA (Huijbregts et al., 2017; Huijbregts et al., 2020). Descriptions of the terms used in the study are explained in Table 1. In addition, the impact indicators selected by the researchers to evaluate the environmental impacts of U-PVC, C-PA and C-PES bags for this study are presented in Table 2. The functional units used in the study related to material, transport, and energy consumption were reported in grams for material, kilometres and litres for transport and kilowatt-hours and litres for production, respectively (Tables 3–5). The flow category process allows one to identify the root source or structure of the input and output into the LCA model. This is related to carbon footprint inventory analysis, which quantifies the production, material, energy, and transport inputs and outputs (Demirdelen et al., 2023; Li et al., 2024). The methodology section of the study presents in detail the LCA steps followed in the evaluation of upcycled bags produced from end-of-life PVC flex banners and their comparison with conventional bags produced from PA and PES woven fabrics.

2.1. Research gap and significance of the study

There is a possibility of firms that could report on the upcycling of plastics, which is not well-documented in the academic literature. A systematic review of the literature on PVC (Saatcioglu and Venkatraman, 2024) highlighted a growing market for PVC due to its durability, accessibility, and cost-effective solution for marketing and industrial applications. In the analysed LCA studies, some academic studies addressed the environmental impacts of fashion products. Most of these studies are based on assumption scenarios and focus on fast fashion products or compare a fast fashion product with another fast fashion product within the scope of the research. However, most of the LCA studies evaluating fashion products do not reflect a real manufacturing process, and the data (material, energy, water, etc.) identified are not precise. In the production of a fashion product, each fashion product group contains its unique details. For example, factors such as materials, types of machinery and production facilities used in the production of a fashion product can vary. It is very essential that LCA studies are based on a real scenario. Therefore, the fact that this study focuses on an upcycling fashion product and is based on a real scenario significantly different from other studies. Our research focuses on a detailed evaluation of life cycle assessments based on actual scenarios, setting it apart from other research on fashion and textile products that often rely on hypothetical data. In addition, this study aims to adapt a potential fashion product to the fashion industry by contributing to waste management by emphasising environmental and economic sustainability.

Table 2
Selected impact categories included in the method.

Impact category	Impact acronym	Unit
Agricultural land occupation	ALOP	m^2a
Climate change	GWP	kg CO_2 $_{eq}$
Fossil depletion	ADPF	kg oil $_{eq}$
Freshwater ecotoxicity	ETP	kg 1,4-DB $_{eq}$
Freshwater eutrophication	FEP	kg P $_{eq}$
Human toxicity	HTP	kg 1,4-DB $_{eq}$
Ionising radiation	IRP	kBq U235 $_{eq}$
Marine ecotoxicity	MAEP	kg 1,4-DB $_{eq}$
Marine eutrophication	MEP	kg N $_{eq}$
Metal depletion	MDP	kg Fe $_{eq}$
Natural land transformation	NLT	m^2
Ozone depletion	ODP	kg CFC-11 $_{eq}$
Particulate matter formation	PM	kg PM10 $_{eq}$
Photochemical oxidant formation	PCOP	kg NMVOC
Terrestrial acidification	TAP	kg SO_2 $_{eq}$
Terrestrial ecotoxicity	TETP	kg 1,4-DB $_{eq}$
Urban land occupation	ULOP	m^2a
Water depletion	WDP	m^3

Table 1
Table of the nomenclature.

°C	the degree Celsius	kg SO_2 $_{eq}$	kilograms sulphur dioxide equivalent
AD	activity data	km	kilometre
Al	aluminium	kWh	kilowatt-hour
$CaCO_3$	calcium carbonate	l	litre
CAGR	compound annual growth rate	LCA	life cycle assessment
CF	carbon footprint	LCCA	life cycle cost analysis
CMYK	cyan, magenta, yellow, key	LCI	life cycle inventory
cm	centimetre	LCIA	life cycle impact assessment
C-PA bag	conventional polyamide/nylon bag	LED	light-emitting diode
C-PES bag	conventional polyester bag	m^2	metre square
D	denier	m^2a	square metre of land per year
EF	emission factor	m^3	cubic metre
g	grams	CH_4	methane
g/m^2	grams/metre square	mm	millimetre
GHG	greenhouse gases	N	nitrogen
ISO	International Organization for Standardization	NOx	nitrogen oxide
kBq U235 $_{eq}$	kilobecquerel uranium 235 equivalent	N_2O	nitrous oxide
kg	kilograms	oz	ounce
kg 1,4-DB $_{eq}$	kilograms1,4-dichlorobenzene equivalent	P	phosphorus
kg CFC-11 $_{eq}$	kilograms chlorofluorocarbon-11 equivalent	P1-P6	Products 1, 2, 3, 4, 5, 6
kg CO_2 $_{eq}$	kilograms carbon dioxide equivalent	PA	polyamide/nylon
kg Fe $_{eq}$	kilograms iron equivalent	PE	polyethylene
kg N $_{eq}$	kilograms nitrogen equivalent	PES	polyester
kg NMVOC $_{eq}$	kilograms non-methane volatile organic compound equivalent	pH	potential of hydrogen
kg oil $_{eq}$	kilograms oil equivalent	PVC	polyvinyl chloride
kg P $_{eq}$	kilograms phosphorus equivalent	RQ1-RQ3	research questions 1, 2, 3
kg PM10 $_{eq}$	kilograms particles with a diameter of 10 μm or less	TL	Turkish lira
		U-PVC bag	Upcycled PVC bag

Table 3
Materials used for U-PVC, C-PA and C-PES bags.

Materials (g)		PVC flex banner	PA woven fabric	PES woven fabric	PES yarn	PES zip	AL zip fastener	PES strap	PA clasp	PES label	PE glue
U-PVC bag	P1	228.1	–	–	1.2	16	10	41.5	–	0.1	0.1
	P2	379.9	–	–	1.4	8.5	5	65.3	13.7	0.1	0.1
	P3	220.3	–	–	2.3	20.3	15	83.4	20.5	0.1	0.1
	P4	321.6	–	–	2.4	26.9	15	66.4	20.5	0.1	0.1
	P5	366.7	–	–	2	23.6	20	87	20.5	0.1	0.1
	P6	209.8	–	–	2	–	–	–	–	0.1	0.1
C-PA bag	P1	–	496	–	1.2	16	5	41.5	–	0.1	0.1
	P2	–	496	–	1.4	8.5	5	65.3	13.7	0.1	0.1
	P3	–	620	–	2.3	20.3	10	83.4	20.5	0.1	0.1
	P4	–	930	–	2.4	26.9	10	66.4	20.5	0.1	0.1
	P5	–	930	–	2	23.6	20	87	20.5	0.1	0.1
	P6	–	465	–	2	–	–	–	–	0.1	0.1
C-PES bag	P1	–	–	480	1.2	16	5	41.5	–	0.1	0.1
	P2	–	–	480	1.4	8.5	5	65.3	13.7	0.1	0.1
	P3	–	–	600	2.3	20.3	10	83.4	20.5	0.1	0.1
	P4	–	–	900	2.4	26.9	10	66.4	20.5	0.1	0.1
	P5	–	–	900	2	23.6	20	87	20.5	0.1	0.1
	P6	–	–	450	2	–	–	–	–	0.1	0.1

2.2. Goal and scope definition

The primary aim of the study was to produce upcycled fashion accessories from PVC flex banners. This plastic becomes waste in a very short time and brings these products to the fashion industry. The reuse of PVC flex banners can create a new field for the fashion industry and contribute to the circular economy economically as well as environmentally (Saatcioglu and Venkatraman, 2024). Thus, problems arising from the disposal of end-of-life PVC flex banners in plastic waste management, which is a serious challenge for developed, developing or underdeveloped countries almost everywhere in the world, can be minimised. Therefore, researching U-PVC bags produced from end-of-life flex banners as an alternative product for the fashion industry will provide an advantage for this industry, one of the largest industries in the world.

The design and manufacturing processes of the products in the project were carried out between 15 January, 2024 and 15 October 2024. The study was conducted in Turkey and the UK between the specified dates. The manufacturing, which is the first stage of the project, was carried out in the Fashion Studio of the Textile and Fashion Design Department, Faculty of Fine Arts, Canakkale Onsekiz Mart University in Turkey. The analysis-interpretation, which is the second stage of the project, was carried out in the Textile Laboratory of the Manchester Fashion Institute, Faculty of Arts and Humanities, Manchester Metropolitan University in the UK. The project leverages the strengths of both institutions effectively, and there are no issues associated with utilizing facilities across these two countries.

Within the scope of the project, end-of-life PVC flex banners were collected from recycling centres in Turkey. Afterwards, the collected end-of-life PVC flex banners were washed in a domestic washing machine and ensured they were suitable for making bags (TS 12957) Turkish Standards Institute (TSI). Six U-PVC bags were manufactured (including pattern development, cutting and sewing).

The main material that constitutes the upcycled bags produced is end-of-life PVC flex banners and other textile accessories. These include PES yarn (135 Tex 100 % PES), PES bag strap (width 3.5 cm), PA bag clasp (width 4 cm), thick tooth PES zip (width 3 cm), Al zip fastener (color coated), PES label (height 2 cm and width 5 cm) and PE glue.

It is assumed that the same PVC bags were produced in 100 % PA woven fabric (600 D nylon Cordura ripstop fabric) and 100 % PES woven fabric (20 oz. and 600 D thick waterproof outdoor canvas fabric). In this scenario, nylon and polyester fabrics, which are some of the most widely used fabrics in conventional bag production today, were preferred. In addition, it is assumed that all other textile materials used in U-PVC bags made of end-of-life PVC flex banners were also used in C-PA and C-PES bags. Based on the above analysis, it can be noticed that there is a dearth of literature reporting on the life cycle and economic assessment of upcycled products from used flex banners, hence this study investigates the life cycle impact of used PVC flex banners through the research questions are mentioned below:

- RQ1 – what are the environmental indicators resulting from the life cycle assessment (cradle-to-gate) of U-PVC, C-PA, and C-PES bags?
- RQ2 – what are the carbon footprint indicators of U-PVC, C-PA, and C-PES bags?
- RQ3 – what are the economic indicators resulting from the life cycle assessment of U-PVC, C-PA, and C-PES bags?

The assessment-interpretation process followed the 'cradle-to-gate' approach, which covers the life cycle of a product or process from the acquisition of materials – raw and waste - (cradle) to the stage where it is delivered to the factory (gate). This approach enables the assessment of the product life cycle from resource extraction (cradle) to the factory (gate) (i.e., before transport to the consumer) (Fonseca et al., 2023; Gonzalez et al., 2023). Indicators covering the material, transport, and production headings covering the manufacturing processes of U-PVC, C-PA and C-PES bags produced with this approach were evaluated. In the study, the environmental and economic data of three scenarios (U-PVC, C-PA and C-PES bags) were evaluated and compared. The system boundaries of the LCA reflecting the manufacturing processes of U-PVC, C-PA and C-PES bags are shown in Fig. 1(a) and Fig. 1(b).

Fig. 1(a) illustrates the system boundary of U-PVC bags. The process for scenario one begins with the disposal of end-of-life PVC flex banners, which have turned into waste. (A) refers to PVC production in China and (B) refers to retail sale and user consumption in Turkey. It then continues with the production and transport processes (C) and concludes at the fashion house, the factory gate (D).

Fig. 1(b) outlines the system boundaries for C-PA and C-PES bags. The processes for these two scenarios (scenario two and scenario three) start with the production of PA and PES woven fabrics (A) and conclude at the fashion house, defined as the factory gate (B).

Table 4
Details of distance travelled, and fuel consumed for U-PVC, C-PA and C-PES bags.

Details of travel	Distance travelled (km)	U-PVC bag (litres)						C-PA bag (litres)						C-PES bag (litres)					
		P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
Factory to Supplier	245	–	–	–	–	–	–	16.66	16.66	16.66	16.66	16.66	16.66	16.66	16.66	16.66	16.66	16.66	16.66
Supplier to Depot	15	–	–	–	–	–	–	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Depot to Fashion Studio	4.6	–	–	–	–	–	–	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Waste to Recycling Centre	1	0.07	0.07	0.07	0.07	0.07	0.07	–	–	–	–	–	–	–	–	–	–	–	–
Recycling Centre to Depot	23	1.56	1.56	1.56	1.56	1.56	1.56	–	–	–	–	–	–	–	–	–	–	–	–
Depot to Laundry	1	0.07	0.07	0.07	0.07	0.07	0.07	–	–	–	–	–	–	–	–	–	–	–	–
Laundry to Fashion Studio	4.7	0.32	0.32	0.32	0.32	0.32	0.32	–	–	–	–	–	–	–	–	–	–	–	–
Yarn Supplier to Fashion Studio	15	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Zip Supplier to Fashion Studio	23	1.56	1.56	1.56	1.56	1.56	–	1.56	1.56	1.56	1.56	1.56	–	1.56	1.56	1.56	1.56	1.56	–
Bag Strap Supplier to Fashion Studio	22	1.5	1.5	1.5	1.5	1.5	–	1.5	1.5	1.5	1.5	1.5	–	1.5	1.5	1.5	1.5	1.5	–
Bag Clasp Supplier to Fashion Studio	23	–	1.56	1.56	1.56	1.56	–	–	1.56	1.56	1.56	1.56	–	–	1.56	1.56	1.56	1.56	–
Label Supplier to Fashion Studio	23	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56
Glue Supplier to Fashion Studio	0.5	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Fashion Studio to Cargo Company	2.7	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Cargo Company to Airport	39.7	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65
Airport (Turkey) to Airport (the UK)	2735	32,820	32,820	32,820	32,820	32,820	32,820	32,820	32,820	32,820	32,820	32,820	32,820	32,820	32,820	32,820	32,820	32,820	32,820
Airport to Cargo Company	3.7	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Cargo Company to Fashion House	15	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02

Table 5
Background systems and required data designed OzLCI2019 database.

Resource (inputs and outputs)	U-PVC bag	C-PA bag	C-PES bag	Flow Category
End-of-life polyvinyl chloride flex banner alone (input) - g	287.73	–	–	Flows / Building products / Framed screens for windows & doors / Fiberglass fly screen with DINP plasticised polyvinyl chloride (SPVC) bead
100 % Nylon fabric alone (input) - g	–	656.16	–	Flows / Fabric, fibre, floorcover, foam / Nylon fabric / Import US solution dyed nylon SDN6 yarn & weave textile
100 % Polyester fabric alone (input) - g	–	–	635	Flows / Fabric, fibre, floorcover, foam / Polyester fabric / Dye treat polyester upholstery fabric
Polyester yarn (input) - g	1.8	1.8	1.8	Flows / Fabric, fibre, floorcover, foam / Polyester fabric / Spin white polyester 10 % melt PETG filament
Polyester zip (input) - g	15.8	15.8	15.8	Flows / Fabric, fibre, floorcover, foam / Polyester fabric / Dye treat polyester upholstery fabric
Aluminium zip fastener (input) - g	10.83	10.83	10.83	Flows / Metals / Aluminium color coated / Aluminium color coated / Add AI3004 cold rolled annealed white polyester coat aluminium sheet 33%PCR
Polyester strap (input) - g	57.2	57.2	57.2	Flows / Fabric, fibre, floorcover, foam / Polyester fabric / Dye treat polyester upholstery fabric
Nylon clasp (input) - g	12.5	12.5	12.5	Flows / Fabric, fibre, floorcover, foam / Nylon fibre & rope / Import Swiss polyamide resin chip & solution dye spin SDN6/6 bulk continuous (BCF) fibre
Polyester label (input) - g	0.1	0.1	0.1	Flows / Fabric, fibre, floorcover, foam / Polyester fabric / Dye treat polyester upholstery fabric
Polyethylene glue (input) - g	0.1	0.1	0.1	Flows / Buildings products / Membranes & flashing / Glue high density polyethylene 19gsm profile or damp proof membrane DPM
Packaging materials used [cardboard box] (input) - g	616	816	816	Flows / Forest Products / Paperboard & Cardboard / Oxygen bleach cardboard 98 % PCR
Detergent (input) - g	4.5	–	–	Flows / Chemicals / Detergent soaps / Heavy duty detergent concentrate - GLO
Energy for washing (input) - kWh	0.75	–	–	Flows / Elementary flows / Resource / in water / Energy, waste heat, in water
Fresh water for machine washing (input) - litres	38	–	–	Flows / Elementary flows / Emission to water / Surface water / Water (fresh)
Wastewater for machine washing (output) - litres	38	–	–	Flows / Elementary flows / Emission to water / Fresh water / Waste water
Energy for designing (input) - kWh	0.05	0.05	0.05	Flows / Elementary flows / Emission to air / Unspecified / Energy, primary, unused, from wind power
Energy for cutting (input) - kWh	0.05	0.05	0.05	Flows / Elementary flows / Emission to air / Unspecified / Energy, primary, unused, from wind power
Energy for sewing (input) - kWh	0.1061	0.1061	0.1061	Flows / Elementary flows / Emission to air / Unspecified / Energy, primary, unused, from wind power
Road transport in Turkey (input) - km	163.43	398.33	398.33	Flows / Elementary Flows / Emission to Air / High population density / Petrol
Road transport in the UK (input) - km	18.7	18.7	18.7	Flows / Elementary Flows / Emission to Air / High population density / Petrol
Air transport from Turkey to the UK (input) - km	2735	2735	2735	Flows / Elementary Flows / Emission to Air / High population density / Petrol

2.3. Life cycle inventory (LCI)

LCA is a well-known and internationally standardised methodology for calculating the environmental emissions of a product or a process at several life cycle stages (Dong et al., 2024; Kokare et al., 2023). It affects marketing strategies and policy changes by effectively assessing the environmental impacts of products, processes, industries and the economy (Bajdur et al., 2023). LCA is a widely used method for assessing the environmental impact of fashion and requires precise and reliable data to ensure accurate results in fashion studies (Bianco et al., 2023; Shou and Domenech, 2022). In the manufacturing stage, the 'cradle-to-gate' approach was followed to reach accurate and reliable data. All the data for life cycle assessments used details relating to various manufacturing processes of U-PVC, C-PA and C-PES bags. These were classified and named in this paper as P1-P6. The following sections discuss life cycle inventory (LCI) - material sourcing, cleaning process, manufacturing process and transport.

2.3.1. Material sourcing

It was found that the collected end-of-life PVC flex banners worn out a little, and this creates an important opportunity to produce upcycled bags using these materials. End-of-life PVC flex banners were sourced from a recycling centre in Turkey. The authorities of the recycling centre were contacted for the supply of end-of-life PVC flex banners, and these flex banners in several thicknesses were used in the production of upcycled bags within the scope of the research. The material analysis and closer examination revealed that the collected end-of-life PVC flex banners were produced by laminating PVC resin on the polyester fabric produced by the weaving method.

The collected end-of-life PVC flex banners exhibited varying surface thicknesses. The thinnest surface measured 0.3 mm, while the thickest measured 1.5 mm. Additionally, the fabric weights for U-PVC, C-PA, and C-PES bags were identified as 300 g/m^2, 620 g/m^2, and 600 g/m^2,

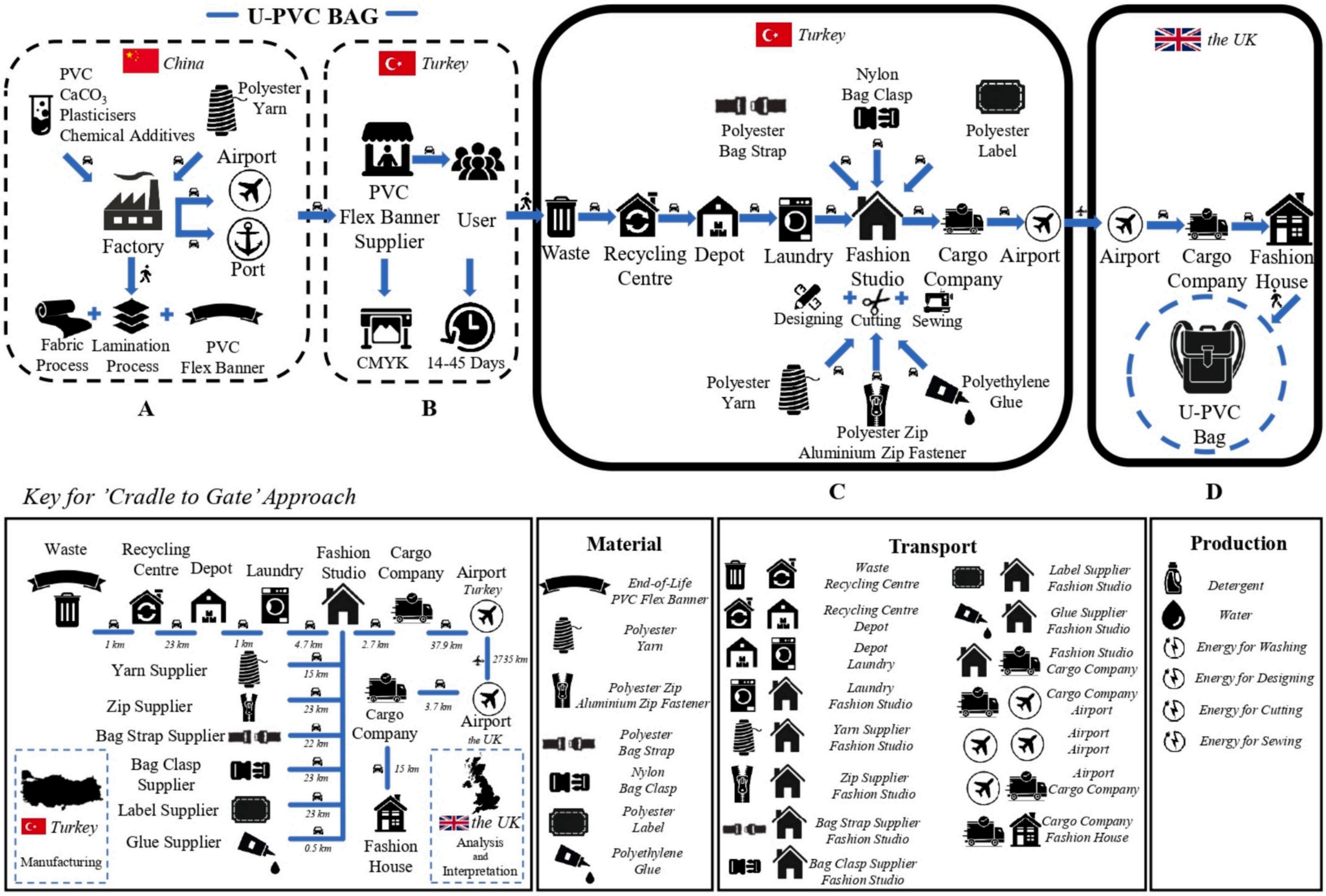

Fig. 1(a). System boundary of the LCA for U-PVC bag.

respectively. The primary material (fabric) used to produce U-PVC bags contained a higher material composition than C-PA and C-PES bags.

Other textile materials were used in the production of U-PVC bags. All these textile materials, which were PES yarn, PES zip, Al zip fastener, PES strap, PA clasp, PES label and PE glue, were purchased from the suppliers in Turkey to produce U-PVC bags. All of the purchased materials were supplied in cardboard boxes of different sizes from the fabric and other material suppliers. Thus, cardboard boxes were used in the supply of materials and the details of the cardboard boxes consumed are presented in Table 5 as packaging materials. In the scenarios for both C-PA bags and C-PES bags, it is assumed that the same other textile materials preferred in the production of U-PVC bags were used in the production of C-PA bags and C-PES bags. All materials consumed for these products are presented in Table 3.

2.3.2. Cleaning process

The end-of-life PVC flex banners used for advertising or marketing purposes in outdoor areas were unclean. The reason for washing the end-of-life PVC flex banners before processing for upcycling is that flex banners were unclean, with residues, and were muddy and soiled; it could pose serious health issues and be unsafe to handle. Hence, it was decided to rinse by hand using hose pipes to remove heavy soil and later, it was washed in the domestic washing machine. In previous research, such plastic materials were also washed before upcycling (Muller, 2001; Xu and Gu, 2015). The end-of-life PVC flex banners collected from the recycling centres were washed at 30 °C with a domestic washing machine with a capacity of 6 kg for one hour. This washing process consumed 4.5 g of detergent, 38 l of water and 0.75 kWh of electricity. No cleaning steps are required for C-PA and C-PES bags as nylon and polyester fabrics were relatively new. The electricity, detergent, and water resources consumed in this cleaning process increase the environmental impact to a certain extent; however, it does not impact the overall sustainability initiative we implemented in the project.

2.3.3. Manufacturing process

The production of U-PVC bags was carried out in Turkey. The patterns of the bags designed during the manufacturing process were placed on the cleaned end-of-life PVC flex banners and cut manually with a utility knife. No electric cutting device was used during the cutting process. The cut PVC flex banner pieces and other textile materials were sewn with an electrically industrial sewing machine. 'Juki DDL-8700-7 Electronic Industrial Sewing Machine' was used in the sewing process of these bags. An average of 0.1016 kWh of electricity was consumed during the sewing process of six U-PVC bags. In the scenarios regarding the sewing processes of C-PA and C-PES bags, the amount of electricity consumed is assumed to be the same as the amount of energy consumed in U-PVC bags.

2.3.4. Transport

Road and air transport were preferred methods in the manufacturing process of U-PVC bags. All road transport operations were conducted entirely within the borders of Turkey and the UK. For the production of U-PVC bags, the transportation data indicates an average of 182.13 km travelled (163.43 km in Turkey and 18.70 km in the UK) and a fuel consumption of 12.32 l (standard unleaded petrol). In comparison, for C-PA and C-PES bags, the corresponding figures are 417.03 km travelled (398.33 km in Turkey and 18.70 km in the UK) and 28.29 l of fuel consumed. The average air distance for transporting all three types of

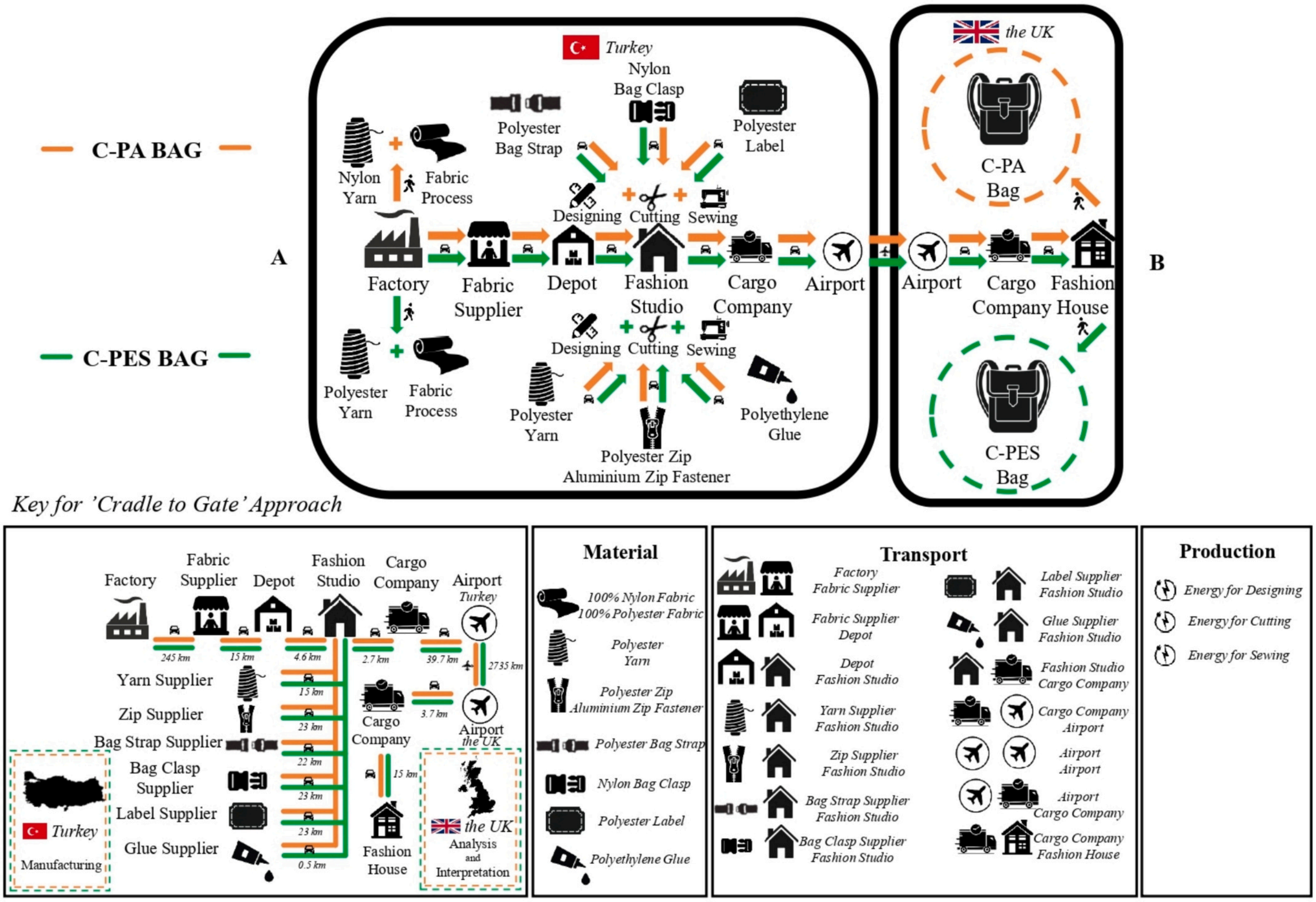

Fig. 1(b). System boundaries of the LCA for C-PA and C-PES bags.

bags is 2735 km, along with 32,820 l of fuel consumed (jet fuel). The transport routes were determined using the shortest path principle, and the distances (both road and air) were calculated accordingly. In this context, the use of fossil fuels, which are significant contributors to CO_2 emissions today (Muthuraj and Mekonnen, 2018; Perera, 2017; Podder et al., 2023), is lower for U-PVC bags due to the reduced distance travelled and fuel consumption. The distances and fuel consumed for U-PVC, C-PA, and C-PES bags are summarized in Table 4.

2.4. Background systems and required data

For modelling the manufacturing processes of U-PVC, C-PA and PES bags, the background systems in the database of OzLCI2019 in openLCA 2.2.0 software were used. This database was preferred because of the rich fabric data it contains (openLCA, 2024). The data were created within the database according to the country specified within the system boundary (Turkey or the UK). Table 5 summarises all the background systems and the required data (average for each product type) from the database of OzLCI2019 used in the research. In some cases where background system details were unavailable, the following processes were added to the database based on data provided or collected from the literature.

3. Life cycle assessment (LCA)

This part of the research includes sections 'life cycle impact assessment', 'carbon footprint calculation' and 'life cycle cost analysis', which present the environmental and economic impacts of U-PVC, C-PA and C-PES bags. Section 3.1. shows the environmental impact assessment for three scenarios and compares the environmental impacts of U-PVC, C-PA and C-PES bags. Moreover, section 3.1.1. presents the calculated carbon values of these scenarios. Section 3.2. presents an analysis of the manufacturing costs of U-PVC, C-PA and C-PES bags, highlighting the advantages and disadvantages of the three bags in terms of cost.

3.1. Life cycle impact assessment (LCIA)

To assess the environmental impact of U-PVC, C-PA and C-PES bags more accurately, a comparative analysis was made between three scenarios and the average of the data (inputs/outputs) for six bags was calculated. Based on this data presented in Table 5, the three scenarios evaluated are summarized as follows.

- U-PVC Bags: These were made of end-of-life PVC flex banners. It was cleaned in a domestic washing machine at 30 °C with detergent. Sewn with an industrial sewing machine using other textile materials (PES yarn, PES zip, Al zip fastener, PES strap, PA clasp, PES label, and PE glue).
- C-PA Bags: These were assumed to be made of 100 % PA woven fabric (600 D nylon Cordura ripstop woven fabric). It is sewn with an industrial sewing machine using other textile materials (PES yarn, PES zip, Al zip fastener, PES strap, PA clasp, PES label, and PE glue).
- C-PES Bags: These were assumed to be made of 100 % PES woven fabric (20 oz. and 600 D thick waterproof outdoor canvas fabric). Sewn with an industrial sewing machine using other textile materials (PES yarn, PES zip, Al zip fastener, PES strap, PA clasp, PES label, and PE glue).

Table 6
Selected midpoint impact indicators for U-PVC, C-PA and C-PES bags openLCA 2.2.0 software.

Impact category	Impact Acronym	Unit	U-PVC bag	C-PA bag	C-PES bag
Agricultural land occupation	ALOP	m^2a	2.87780	2.38035	2.88257
Climate change	GWP	kg $CO_{2\ eq}$	1.42408	6.52616	1.37005
Fossil depletion	ADPF	kg oil $_{eq}$	0.38297	1.54123	1.19307
Freshwater ecotoxicity	ETP	kg 1,4-DB $_{eq}$	0.00608	0.06235	0.00991
Freshwater eutrophication	FEP	kg P $_{eq}$	3.43099E-06	0.00016	4.1183E-06
Human toxicity	HTP	kg 1,4-DB $_{eq}$	0.44587	0.93638	0.35833
Ionising radiation	IRP	kBq U235 $_{eq}$	–	–	–
Marine ecotoxicity	MAEP	kg 1,4-DB $_{eq}$	0.00185	0.02417	0.00392
Marine eutrophication	MEP	kg N $_{eq}$	0.00033	0.00590	0.00036
Metal depletion	MDP	kg Fe $_{eq}$	0.58042	0.19655	0.13267
Natural land transformation	NLT	m^2	–	–	–
Ozone depletion	ODP	kg CFC-11$_{eq}$	6.77022E-07	9.36861E-07	7.68695E-07
Particulate matter formation	PM	kg PM10 $_{eq}$	0.00317	0.00786	0.00376
Photochemical oxidant formation	PCOP	kg NMVOC	0.00630	0.01694	0.00657
Terrestrial acidification	TAP	kg $SO_{2\ eq}$	0.01308	0.03279	0.01609
Terrestrial ecotoxicity	TETP	kg 1,4-DB $_{eq}$	0.00021	0.00205	0.00024
Urban land occupation	ULOP	m^2a	0.00002	0.00021	0.00004
Water depletion	WDP	m^3	0.04407	0.53179	0.27373

Table 6 presents the environmental impacts (including acronyms, units, and numerical values) of upcycling and fast fashion accessories under three scenarios: (1) U-PVC bags made from end-of-life flex banners, (2) C-PA bags made from 100 % PA fabric, and (3) C-PES bags made from 100 % PES fabric.

Within the LCIA, we analysed 18 impact categories using openLCA 2.2.0 software in this study based on the ReCiPe 2016 Midpoint (H) method. The findings of the study revealed that U-PVC bags had lower environmental impact values than C-PA and C-PES bags in 12 impact categories (fossil depletion, freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, marine eutrophication, ozone depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, terrestrial ecotoxicity, urban and land occupation, and water depletion). In one impact category (agricultural land occupation) C-PA bags and three impact categories (climate change, human toxicity and metal depletion) C-PES bags had the lowest environmental impact values. None of the bags showed any environmental impact values in two impact categories (ionising radiation and natural land transformation); in other words, the results were zero for all bag types in the stated impact categories.

In producing PVC, nylon, and polyester materials, ionising radiation (IRP) levels are negligible. This is because the energy used comes from fossil fuels and electricity rather than nuclear energy, which is associated with ionising radiation. Natural land transformation (NLT) refers to

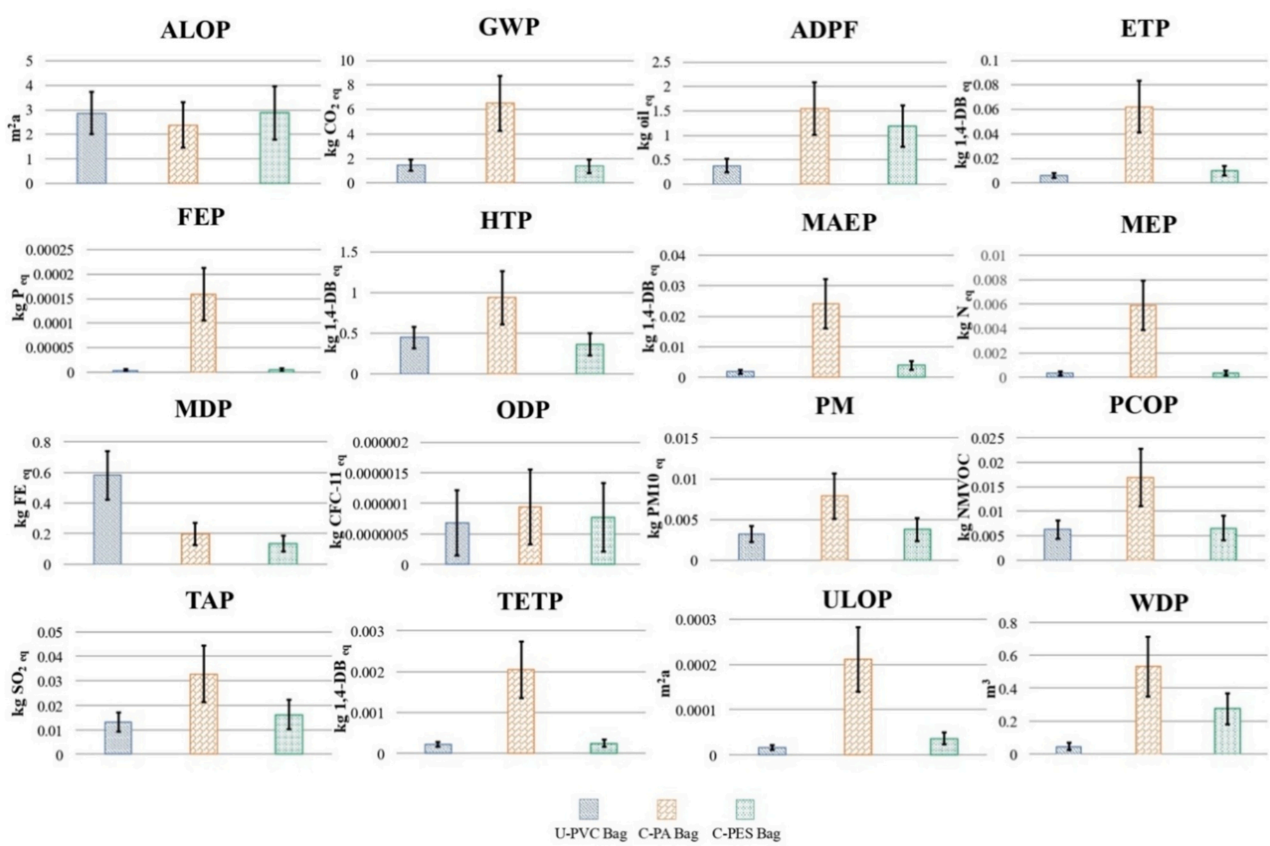

Fig. 2. Comparison of the environmental impacts for the three scenarios.

changes made to land due to human activities, typically for agriculture, industry, urban development, or infrastructure projects (Hooke et al., 2012; Farago et al., 2019). In this project, the impact on natural land transformation remained zero because no significant alterations were made to the land, including its flora and fauna. PVC, nylon, and polyester are synthetic materials primarily used in the textile industry and do not directly alter the natural landscape. Therefore, the natural land transformation (NLT) impact category did not indicate a significant value in the production processes of U-PVC, C-PA, and C-PES bags.

The results also showed that PVC bags had the highest environmental impact value in only one impact category (metal depletion). Moreover, in the three indicators where U-PVC bags were not the lowest (agricultural land occupation, climate change, and human toxicity), the environmental values for U-PVC bags were not the highest. The numerical values of the three scenarios compared among themselves in each impact category are presented in Fig. 2. The impact categories ionising radiation (IRP) and natural land transformation (NLT), which did not have a value for all three scenarios, were not included in this comparison.

Fig. 3 presents the environmental impact breakdown per impact categories of U-PVC bags with C-PA and C-PES bags for three scenarios. While making these comparisons, the environmental impact data of six bags belonging to three scenarios were determined, and the environmental impact data were averaged. In addition, environmental impacts that are related to each other are grouped and analysed together in the study. Thus, the following four environmental impact groups were formed.

Group 1 – land ecosystem: Environmental impact categories reflecting 'land ecosystem' and it covers - agricultural land occupation (ALOP), fossil depletion (ADPF), metal depletion (MDP), terrestrial acidification (TAP), terrestrial ecotoxicity (TETP), and urban land occupation (ULOP). It can be noted from Fig. 3, that U-PVC bags had lower environmental impacts in the impact categories of fossil depletion (ADPF), terrestrial acidification (TAP), terrestrial ecotoxicity (TETP), and urban land occupation (ULOP) compared to C-PA and C-PES bags.

When examining the agricultural land occupation (ALOP) impact category further, land occupation for U-PVC bags was 2.87 m^2a, C-PA bags 2.38 m^2a, and C-PES bags 2.88 m^2a. This shows that land occupation for C-PES bags was marginally higher than for U-PVC bags. Agricultural land use describes the allocation of land for agricultural activities, including the cultivation of crops and livestock, which are crucial to support the food supply chain (Cabernard et al., 2024; Mohamed Junaid et al., 2024). The high environmental impact of U-PVC bags in this impact category is particularly related to the occupancy of depot and storage processes of PVC flex banners, which have short-term use. Nowadays many recycling centres are in rural areas far from the urban areas and PVC flex banners that become waste are temporarily stored in these areas for a long time. The same is true for the factories that produce nylon and polyester fabrics, the primary material for C-PA and C-PES bags. Today, there are almost no factories producing textiles in urban space and their activities are carried out in areas close to agricultural areas away from urban areas. In addition, indirect impacts through PVC, PA and PES raw material production, industrial land use and pollution can also occupy more agricultural land.

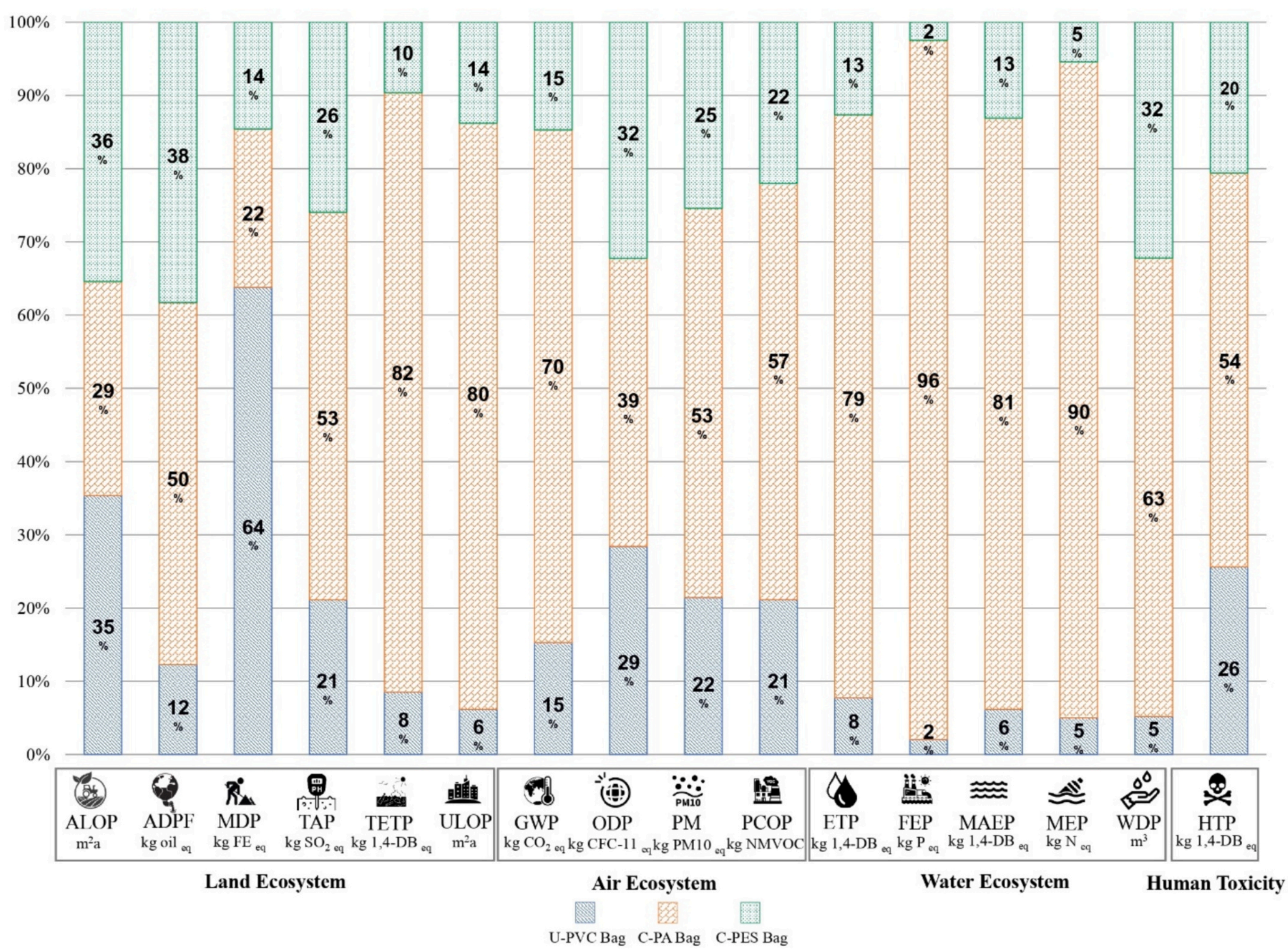

Fig. 3. Environmental impact breakdown per impact category presented in percentage of impact.

Fossil depletion (ADPF) refers to the gradual depletion of fossil fuels in the earth. Fossil fuels are a non-renewable source of energy that is the result of plant decomposition over millions of years (Martins et al., 2019). The fossil depletion impact for U-PVC bags was 0.38 kg oil $_{eq}$, whilst for C-PA and C-PES bags was 1.54 kg oil $_{eq}$, and 1.19 kg oil $_{eq}$ respectively. It can be noticed that the impact of fossil depletion for C-PA bags was four times U-PVC bags and for C-PES bags was three times that of U-PVC bags. PA and PES production in particular causes significant fossil depletion due to its dependence on petrochemical raw materials and fossil fuel-based energy. Nylon and polyester are synthetic fibres derived from petroleum-based resources, mainly crude oil and natural gas (Akter et al., 2022: Nayak et al., 2023), and fossil resources continue to be consumed in the production of PVC flex banners, nylon and polyester fabrics. The consumption of fossil fuel-based resources is harmful to the environment (Wang and Azam, 2024). Addressing these concerns will require research into more sustainable production methods, recycling processes and the development of environmentally friendly alternatives to reduce dependence on non-renewable resources.

Regarding metal depletion (MDP), U-PVC bags had 0.58 kg Fe $_{eq}$, C-PA bags 0.19 kg Fe $_{eq}$, and C-PES bags had 0.13 kg Fe $_{eq}$. The results showed that U-PVC bags had the highest impact values. The metal depletion (MDP) for U-PVC was three times C-PA and for U-PVC was four times C-PES bags. The most obvious reason for this is the extraction and processing of raw materials, especially in the life cycle of PVC resin production. Chlorine, vinyl chloride monomer (VCM), and additives in PVC formulation (stabilisers and plasticisers) in PVC flex banner production have metal-based contents. In addition, the machinery and infrastructure used in the production of PVC flex banners are based on metals such as steel, aluminium and other alloys and cause indirect depletion (Hlisnikova et al., 2020; Marinkovic et al., 2010; Verma et al., 2016; Wang and Qian, 2021). Metal depletion in nylon and polyester fabric is usually related to the use and release of metal-based dyes, pigments or catalysts during the processing of these fabrics (Tang et al., 2021).

There was no major impact of terrestrial acidification (TAP), terrestrial ecotoxicity (TETP), and urban land occupation (ULOP) for all three types of bags. The terrestrial acidification (TAP) and the urban land occupation (ULOP) for C-PA bags were marginally higher than for U-PVC and C-PES bags. Terrestrial acidification arises when the pH of the soil decreases due to the deposition of acidifying substances from the atmosphere, which can affect plant and soil fertility (Azevedo et al., 2013). Especially, nylon fabric production-associated emissions from production, disposal, and the energy-intensive process can cause environmental acidification through the release of sulphur and nitrogen compounds (Campbell et al., 2011; Stojkoski and Kert, 2020). These also arise from human activities such as burning fossil fuels and emissions (Rice and Herman, 2012). Again, U-PVC bags outperformed C-PA and C-PES bags because the burning of fossil fuels and industrial emissions are relatively less compared to nylon and polyester during the production of PVC.

PVC itself is not a primary cause of terrestrial acidification (TAP), the process by which the pH of soils and surrounding ecosystems decreases due to the accumulation of acidic substances from environmental pollution. However, the processes associated with the disposal of PVC flex banners after their production may indirectly affect the ecosystem and cause pollution. In addition, while the direct land usage for nylon production is typically confined to industrial zones, the environmental footprint includes air and water pollution, which can indirectly impact urban land use, such as creating buffer zones or causing shifts in residential and commercial development patterns near these facilities.

Terrestrial ecotoxicity (TETP) refers to the harmful effects of toxic substances on land-based ecosystems, including soil organisms, plants, and animals. It assesses the effects of heavy metals, pesticides, industrial chemicals and pharmaceuticals. Although the production of PVC, nylon and polyester is based on chemicals, it is not based on pollutants such as heavy metals and pesticides, this does not reflect a high environmental impact value for terrestrial ecotoxicity. Again, U-PVC bags performed better than C-PA and C-PES bags because the chemical processes used in the production of PVC are relatively minor compared to nylon and polyester. However, the landfill (especially microplastics) or incineration of plastic and synthetic contents (PVC, nylon, and polyester) increases terrestrial ecotoxicity more than the production process itself (Rai et al., 2023: Rilling and Lehmann, 2020).

Urban and land occupation (ULOP) is about how people use and manage space, how settlements grow, and the challenges and opportunities that arise from land use in different contexts. The urban and land occupation (ULOP) for U-PVC bags was lower than for C-PA and C-PES bags. The overall impact rate for the urban and land occupation is very minor for all three types of bags, with the lowest impact for U-PVC bags. Because PVC production does not cause significant land occupation (Ye et al., 2017).

Group 2 – air ecosystem: Environmental impact categories reflecting 'air ecosystem' and it covers - climate change (GWP), ozone depletion (ODP), particulate matter formation (PM), and photochemical oxidant formation (PCOP). It can be noted from Fig. 3, that U-PVC bags had lower environmental impacts in the impact categories of ozone depletion (ODP), particulate matter formation (PM), and photochemical oxidant formation (PCOP) compared to C-PA and C-PES bags.

The climate change (GWP) is normally expressed in kg CO_2 $_{eq}$, and greenhouse gas emissions (CH_4, or N_2O) other than CO_2 also cause climate change. Climate change is caused by the release of GHG emissions into the air and is one of the most critical environmental indicators (Ecochain, 2024; Tian et al., 2015). When examining the climate change impact category (GWP) further, climate change for U-PVC bags was 1.42 kg CO_2 $_{eq}$, C-PA bags 6.52 kg CO_2 $_{eq}$, and C-PES bags had 1.37 kg CO_2 $_{eq}$. This shows that climate change for impact of climate change on C-PA bags was four times U-PVC and C-PES bags. In addition, it can be noticed that the climate change results of U-PVC and C-PES bags were very close to each other. The high environmental impact of C-PA bags in the climate change category is explained by nylon being a petroleum-based synthetic fabric. In the production of nylon fabrics, high energy is utilised, considerable heat and pressure are generated and N_2O, a potent greenhouse gas, is also released during production (Thaore et al., 2018; Velden et al., 2014). Therefore, C-PA bags have a higher impact on climate change.

There was no major impact of ozone depletion (ODP) for all three types of bags. The ozone depletion (ODP) for C-PA bags was marginally higher than for U-PVC and C-PES bags. Ozone depletion caused by PVC is a complex environmental issue primarily related to the release of chlorine-based compounds during the production, usage, and disposal of PVC materials. When PVC materials are improperly disposed of or incinerated, they release chlorine-based compounds, such as hydrochloric acid and dioxins, into the atmosphere (Al-Harahsheh et al., 2019; Castro et al., 2012). In addition, N_2O generated in nylon and polyester fabric production is a potent greenhouse gas and causes ozone depletion by disrupting the balance of ozone-forming and ozone-depleting reactions in the atmosphere (Velden et al., 2014).

There was no major impact of particulate matter formation (PM) and photochemical oxidant formation (PCOP) for all three types of bags. Photochemical oxidant formation (PCOP) refers to the creation of reactive oxygen species (such as ozone and other oxidizing compounds) in the atmosphere due to chemical reactions triggered by sunlight. It can be noticed that the impact of particulate matter formation (PM) and photochemical oxidant formation (PCOP) for C-PA bags was marginally higher than for U-PVC and C-PES bags. The photochemical oxidant formation for U-PVC bags was lower than for C-PA and C-PES bags.

Particulate matter formation (PM) refers to tiny particles or droplets in the air that can be harmful to health and the environment. This arises from industrial emissions during the production process. The particulate matter formation for all the bags was negligible. Particulates released into the atmosphere, especially during nylon production or processing, can cause air pollution and pose health risks. Furthermore, volatile organic compounds (VOCs) are emitted during the synthesis of precursors such as adipic acid and hexamethylene diamine, which are essential components in nylon production, and cause photochemical oxidant formation (PCOP). These negative factors have a major role in air pollution (Koppmann, 2020; Zhou et al., 2023).

Group 3 – water ecosystem: Environmental impact categories reflecting 'water ecosystem' and it covers - freshwater ecotoxicity (ETP), freshwater eutrophication (FEP), marine ecotoxicity (MAEP), marine eutrophication (MEP), and water depletion (WDP). It can be noted from Fig. 3, that U-PVC bags had lower environmental impacts in all the impact categories of freshwater ecotoxicity (ETP), freshwater eutrophication (FEP), marine ecotoxicity (MAEP), marine eutrophication (MEP) and water depletion (WDP) compared to C-PA and C-PES bags.

Freshwater ecotoxicity (ETP) refers to the harmful effects of chemical pollutants on freshwater ecosystems, including rivers, lakes, and streams. The freshwater toxicity for all the bags was considerably lower, however for nylon bags, it was marginally higher. During nylon manufacturing, emissions of N_2O, volatile organic compounds (VOCs), and other pollutants may occur. N_2O causes indirect water pollution by affecting atmospheric chemistry and potentially leading to acid rain, which harms freshwater systems (Davis et al., 2019).

Freshwater eutrophication (FEP) is the excessive enrichment of lakes, rivers, and other freshwater bodies with nutrients, primarily N (nitrogen) and P (phosphorous). This nutrient overload leads to the rapid growth of algae and aquatic plants, a process known as algal blooms. The freshwater eutrophication impact for U-PVC bags was higher for polyester bags, followed by PVC and nylon bags. Nylon is a synthetic polymer, and it can degrade into microplastics over time. These microplastics can accumulate in aquatic ecosystems, causing harm to organisms by physical ingestion or by leaching harmful additives. Textile applications of nylon and polyester often involve dyeing and finishing processes that introduce chemical pollutants to water systems (Berradi et al., 2019: Manea et al., 2020), on the other hand, PVC production does not involve these processes.

Marine ecotoxicity (MAEP) refers to the harmful effects of pollutants on marine organisms and ecosystems. Heavy metals, pesticides, plastics and industrial chemicals can cause this pollution. Waste dyes and heavy metals used in the production of nylon and polyester can be toxic to aquatic species. In addition, nylon in particular is produced from precursors such as adipic acid and hexamethylenediamine, both of which involve processes that release NOx into the environment. This can cause serious damage to marine ecosystems (Al-Tohamy et al., 2022).

Marine eutrophication (MEP) is the excessive enrichment of coastal and marine waters with nutrients, primarily nitrogen and phosphorus, often due to human activities such as agricultural runoff, wastewater discharge, and industrial pollution. Nylon and polyester are frequently used in the textile industry and can turn into microplastics over time mainly from disposed materials (Welden and Cowie, 2017). This causes nylon and polyester fibre, yarn, or fabric wastes to be more harmful to the marine ecosystem than PVC flex banners.

Water depletion refers (WDP) to the significant reduction of water resources in a given area due to overuse, pollution, and climate change. It impacts groundwater, surface water bodies (such as lakes and rivers), and the hydrological balance essential for ecosystems, agriculture, and human consumption. The water-depletion values for all the bags were low and had the least impact on the environment. However, the production of these raw materials nylon and polyester involves processes that use large quantities of water for cooling, washing, and chemical reactions (Ozturk et al., 2016). Post-polymerisation processes, like pelletizing and fibre spinning, also involve water to clean and cool the fibres. One of the most significant areas of water usage is during the dyeing and finishing of polyester textiles.

Group 4 – human toxicity: The environmental impact category reflects human toxicity, and it only covers – human toxicity (HTP). It can be noted from Fig. 3, that U-PVC bags had the second lowest environmental impacts in the impact category of human toxicity compared to C-PA and C-PES bags.

The impact category of human toxicity (HTP) assesses the impact of toxic substances released into the environment on human toxicity indicators and is divided into non-cancer and cancer-related toxic substances (Ecochain, 2024; Sala et al., 2022). When examining the human toxicity (HTP) impact category further, toxicity was 0.44, 0.93 and 0.35 kg 1,4-DB $_{eq}$, respectively for U-PVC, C-PA, and C-PES bags. This shows that human toxicity for impact for all types was similar. Nylon fibres and fabrics are produced using chemicals such as hexamethylene diamine and adipic acid for nylon-6,6, or caprolactam for nylon-6. These compounds can pose health risks to workers if proper safety measures are not taken. In addition, some chemicals used in nylon fibre and fabric production are irritants to the skin, eyes, and respiratory system, and long-term exposure may increase the risk of cancer. Moreover, nylon is not biodegradable, generating microplastic pollution when it breaks down into smaller fibres (Wang et al., 2019). These microplastics can enter the food chain, potentially impacting human health. Polyester, a widely used synthetic material, is generally considered non-toxic under normal conditions for human use. However, polyester is derived from petroleum-based products through chemical reactions that involve ethylene glycol and terephthalic acid (Gonzalez et al., 2023; Qian et al., 2021). These processes release volatile organic compounds (VOCs) and hazardous air pollutants, which can be harmful to factory workers if proper safety measures are not implemented. PVC is produced using vinyl chloride monomer and phthalates a known carcinogen. Workers in facilities that manufacture polyvinyl chloride are at risk of exposure, which has been associated with liver cancer (angiosarcoma), lung cancer, and other health effects (Pielichowski and Swierz-Motysia, 2006; Sunny et al., 2004). Generally, polyvinyl chloride, nylon, and polyester itself, in its polymerised and finished form, is considered safe for most humans, and it is widely used in the textile industry. For this reason, in terms of human health, occupational health and safety conditions must be fulfilled in producing these polymers or these polymer-based textile products and human contact must be minimised.

3.1.1. Carbon footprint (CF) calculation

This study assessed the carbon footprint (CF) (Department for Energy Security and Net Zero, 2024) for three scenarios: U-PVC, C-PA, and C-PES bags. CF inventory analysis quantifies the production, material, energy, and transport inputs. The emission factors for carbon footprint values were analysed in three categories: material, transport, and production (Peters et al., 2015; Rana et al., 2015b). The formula used to estimate the carbon footprint for all the processes related to material, transport, and production is detailed below, with additional calculations presented in Table 7.

$$CF\ [kg\ CO2\ eq] = \sum AD\ [mass\ or\ volume\ or\ energy\ unit] \times EF$$

where AD is activity data in mass or transport or volume or energy unit; EF emission factor in Kg CO2 equivalent per mass, volume or energy unit

It was observed that U-PVC bags have a lower CF compared to C-PA

Table 7
Carbon footprint parameters and data based on material, transport, and production for U-PVC, C-PA and C-PES bags.

Material (kg)		PVC flex banner	100 % PA fabric	100 % PES fabric	PES yarn	PES zip	AL zip fastener	PES strap	PA clasp	PES label	PE glue	Cardboard box	Transport (km) Road	Air	Production (kWh, m^3, kg) Energy for washing	Energy for designing	Energy for cutting	Energy for sewing	Water	Detergent
U-PVC bag	Consumption	0.28773	–	–	0.0018	0.0158	0.00833	0.0572	0.0125	0.0001	0.0001	0.616	182.13	2735	0.75	0.05	0.05	0.1061	0.038	0.0045
	Fuel efficiency	–	–	–	–	–	–	–	–	–	–	–	14.7	–	–	–	–	–	–	–
	Emission factor	2.93	–	–	3.85	3.85	2.85	3.85	8	3.85	2.96	1.04	2.08	0.2	0.21	0.21	0.21	0.21	0.15	3.16
	kg CO_2 per source	0.84	–	–	0.01	0.06	0.02	0.22	0.1	0.00039	0.0003	0.64064	25.77	547	0.1575	0.0105	0.0105	0.22281	0.0057	0.1422
	kg CO_2 total											574.89								
C-PA bag	Consumption	–	0.65616	–	0.0018	0.0158	0.00833	0.0572	0.0125	0.0001	0.0001	0.816	417.03	2735	–	0.05	0.05	0.1061	–	–
	Fuel efficiency	–	–	–	–	–	–	–	–	–	–	–	14.7	–	–	–	–	–	–	–
	Emission factor	–	8	–	3.85	3.85	2.85	3.85	8	3.85	2.96	1.04	2.08	0.2	–	0.21	0.21	0.21	–	–
	kg CO_2 per source		5.25		0.01	0.06	0.02	0.22	0.1	0.00039	0.0003	0.84864	59.01	547	–	0.0105	0.0105	0.22281	–	–
	kg CO_2 total											612.56								
C-PES bag	Consumption	–	–	0.635	0.0018	0.0158	0.00833	0.0572	0.0125	0.0001	0.0001	0.816	417.03	2735	–	0.05	0.05	0.1061	–	–
	Fuel efficiency	–	–	–	–	–	–	–	–	–	–	–	14.7	–	–	–	–	–	–	–
	Emission factor	–	–	3.85	3.85	3.85	2.85	3.85	8	3.85	2.96	1.04	2.08	0.2	–	0.21	0.21	0.21	–	–
	kg CO_2 per source	–	–	2.44	0.01	0.06	0.02	0.22	0.1	0.00039	0.0003	0.84864	59.01	547	–	0.0105	0.0105	0.22281	–	–
	kg CO_2 total											609.76								

and C-PES bags (Fig. 4). The carbon footprint for U-PVC bags was 574.89 kg $CO_{2\ eq}$, which is slightly lower than that for C-PA bags at 612.56 kg $CO_{2\ eq}$ and C-PES bags at 609.76 kg $CO_{2\ eq}$. When comparing the three types of bags based on material consumption about carbon footprint, U-PVC bags emitted less carbon compared to C-PA and C-PES bags. Nylon and polyester fabrics are widely preferred in the textile industry due to their durability, flexibility, and versatility. However, their carbon footprint during production and life cycle use is higher than that of PVC flex banners. It is important to note that PVC flex banners can pose environmental hazards due to their non-recyclability and improper disposal methods, which significantly contribute to their carbon footprint.

Road transport accounts for a larger share of global emissions due to its extensive use, while air transport has a much higher carbon footprint per kilometre travelled (Kovacikova et al., 2024). In terms of transport-related carbon footprint results, U-PVC bags had the lowest emissions. This is attributed to the longer distance covered (via road transport) between the factories and suppliers of nylon and polyester bags. The carbon footprint associated with electricity usage refers to the GHG emissions linked to the production and consumption of energy. These emissions predominantly arise from burning fossil fuels, such as coal, natural gas, and oil in power plants. In addition, the carbon footprint of a washing machine depends on various factors, including energy efficiency, water usage, the energy source for electricity, and frequency of use (Kim et al., 2015; Shahmohammadi et al., 2018).

C-PA and C-PES bags exhibit a lower carbon footprint during the production process compared to U-PVC bags. This is mainly because end-of-life PVC flex banners, which are the main material for U-PVC bags, require washing before use, as they were stored in recycling plants. Consequently, U-PVC bags consumed energy, detergent, and water during their production process, while C-PA and C-PES bags consumed only energy. The primary reason why U-PVC bags have a lower carbon footprint compared to C-PA and C-PES bags is that U-PVC bags require less main material because of their weight (end-of-life PVC flex banner) and have lower transport emissions, particularly for road transport. The carbon footprint associated with air transportation for all types of bags is similar, around 547 $CO_{2\ eq}$. For U-PVC bags, the carbon footprint generated during washing stages is a total of 0.3054 $CO_{2\ eq}$ (0.1575 $CO_{2\ eq}$ for energy, 0.0057 $CO_{2\ eq}$ for water, and 0.1422 $CO_{2\ eq}$ for detergent), which is minimal and does not significantly impact the overall carbon footprint.

The carbon footprint associated with the cleaning process has been negligible, i.e., 0.3054 $CO_{2\ eq}$ (includes energy, water and detergent consumption). $CO_{2\ eq}$ measures different greenhouse gas emissions on the climate (Climate Partner, 2025). One $CO_{2\ eq}$ has the same impact on global warming as one metric tonne of carbon dioxide. 0.3 kg of $CO_{2\ eq}$ is relatively small, much like driving a gas-powered car for two miles. From the above, it can be inferred that the washing stage has not significantly affected the environmental footprint. In contrast, the carbon footprint from road transport is considerably higher for C-PA and C-PES bags, at 59.01 $CO_{2\ eq}$, compared to just 25.77 $CO_{2\ eq}$ for U-PVC bags. Fig. 4 illustrates an overall carbon footprint, and Table 7 provides a detailed breakdown of the carbon footprint associated with each process.

Wind energy was used in the LCA model for this research. However, this may not apply to global industry averages because transportation in other regions may be based on petrol or diesel-powered engines, contributing to higher carbon emissions and affecting air quality (Tessum et al., 2014). Based on the above, the LCA model aligns with specific regional practices.

Air transport is generally considered a high-cost mode of transportation, especially when compared to other methods like road or rail. Despite these high costs, air transport remains the fastest and most efficient means of covering long distances, especially when transporting goods or passengers across countries or continents.

However, to reduce the cost of transport, public transportation methods such as sea, road and rail transport can be preferred as an alternative to air transport, depending on the region's geographical location.

3.2. Life cycle cost analysis (LCCA)

The initial manufacturing stage of the project involved all processes—materials, transport, and production and was conducted in Turkey. The materials used for the U-PVC, C-PA, and C-PES bags were sourced from various suppliers within Turkey, and the cost data reflected real market scenarios. All purchases were executed in Turkish Lira (TL), with an exchange rate of £1 equating to 42.40 TL. The research also considered the cost of fuel (standard unleaded petrol) for road transport, referencing the selling prices in Turkey and the UK at the time.

Analysis in Fig. 5 indicates that U-PVC bags, produced from end-of-life PVC flex banners, offer significant economic advantages over C-PA and C-PES bags. The average cost of U-PVC bags stands at £49.86, a figure favourably influenced by the main material (end-of-life PVC flex banners) which, being waste material, incurs a minimal second-hand cost of £4.72. In addition, associated costs include other materials (£0.93), cleaning (£7.53), production (£0.02), road transport (£13.09), and air transport (£23.57).

Upon closer examination of U-PVC bags from a resource perspective, transport emerges as a critical factor affecting overall costs. These transport costs are categorized into air and road segments, with air transport from Turkey to the UK significantly raising the U-PVC bag costs. Furthermore, the preference for road transport, necessitated by the diverse locations of material suppliers, also contributes to increased expenses. Detailed insights regarding road and air transport costs are summarized in Table 4. Besides transport, other cost-influential resources include cleaning processes (detergent and water consumption), materials, and production (energy consumption). The cost associated with end-of-life PVC flex banners, despite their second-hand nature, plays a role in the total expenses.

The average production cost for U-PVC bags is £49.86, while C-PA and C-PES bags cost £66.80 and £67.09, respectively. This indicates that U-PVC bags are more economical and less expensive than C-PA and C-PES bags. As shown in Fig. 5, road and air transport account for most of the production and material costs. The road transport costs for U-PVC bags were significantly lower than those for C-PA and C-PES bags. However, the air transport costs for U-PVC bags were higher than those for C-PA and C-PES bags. If materials are sourced locally, costs can be reduced for all bag types. In addition, during upcycling, it is recommended that the carbon footprint be minimised by locally sourcing components and avoiding excessive processes to reduce the carbon footprint arising in this stage.

Furthermore, our research highlights the advantages of upcycling end-of-life PVC flex banners, which have market potential, particularly for outdoor applications, appealing to eco-conscious consumers. Thus, upcycled products made from end-of-life PVC flex banners can also attract the attention of newly established small and medium-sized enterprises and creative industries in the fashion industry (Singh et al., 2019), and they can also create new opportunities for fashion brands and designers (Fletcher and Grose, 2012; Park and Lin, 2020).

However, barriers to market adoption of products made from upcycled materials can stem from several factors related to consumer perceptions and regulatory frameworks. These barriers are generally consumer perceptions (lack of trust in quality, awareness and understanding, higher price point), regulatory and certification frameworks

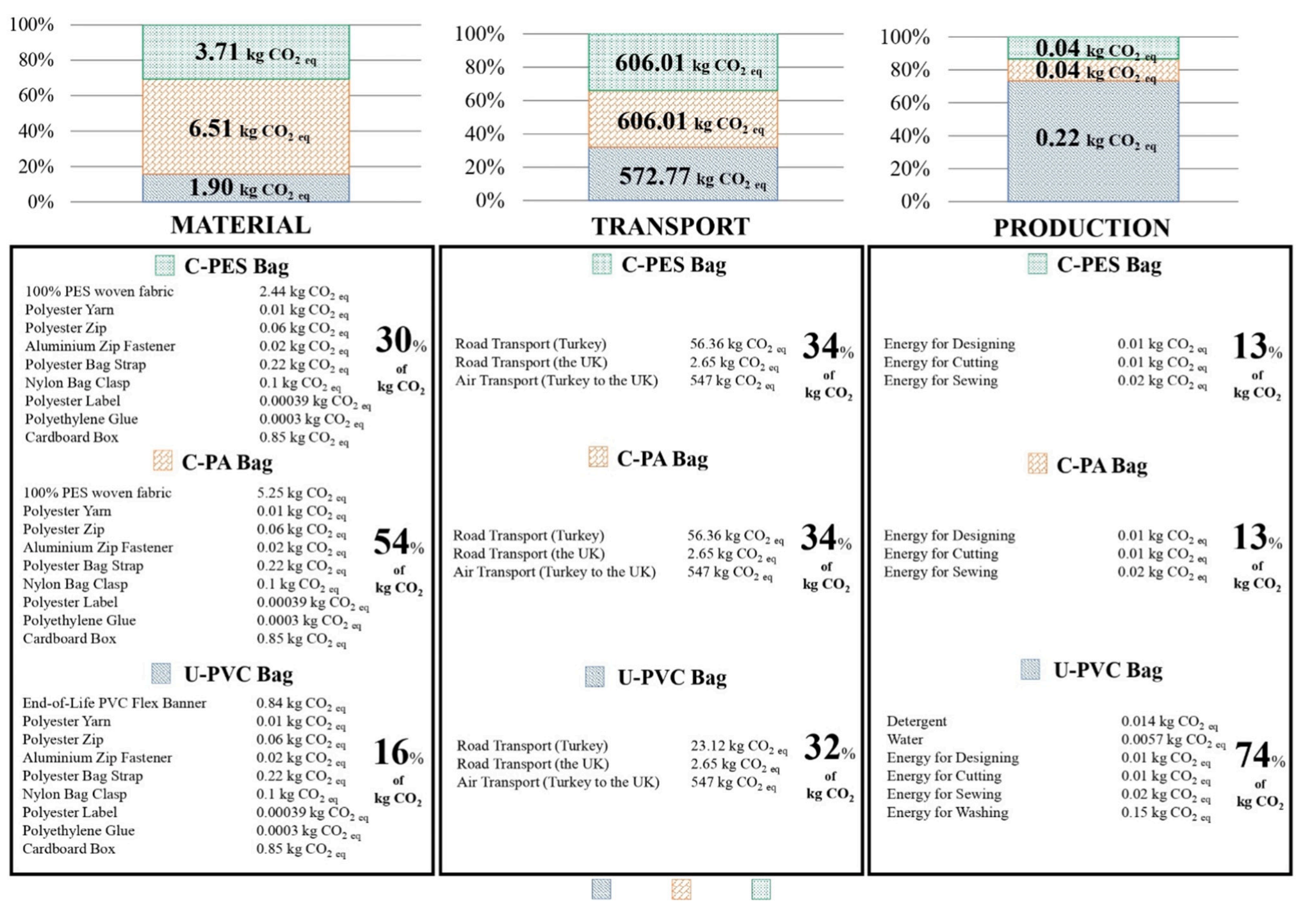

Fig. 4. Carbon footprint results of U-PVC, C-PA and C-PES bags.

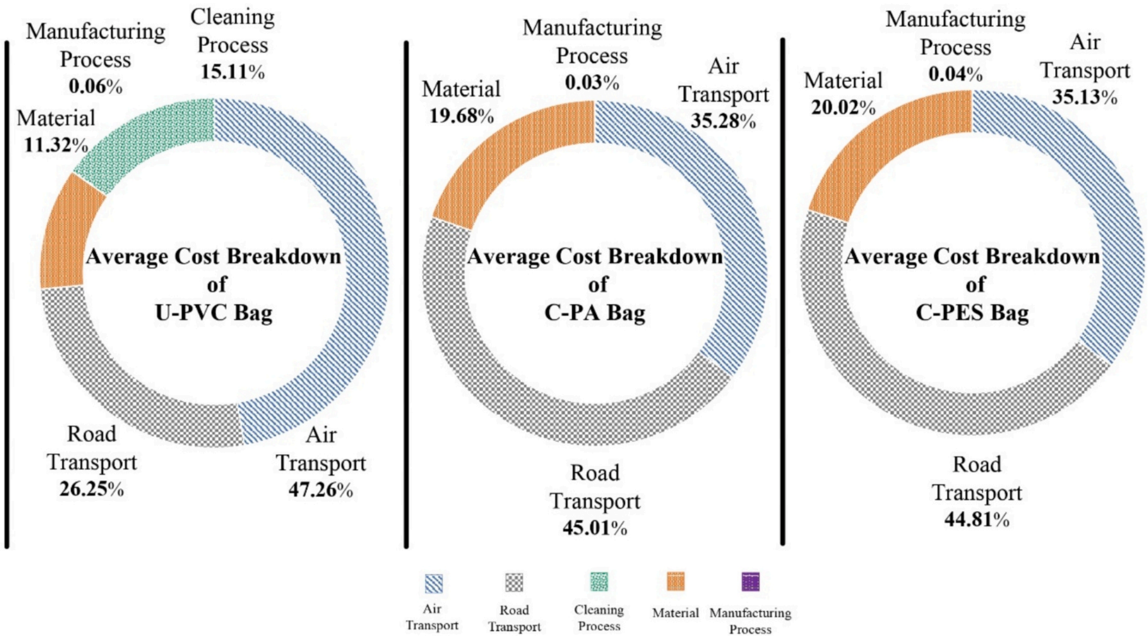

Fig. 5. Average cost breakdown of U-PVC, C-PA and C-PES bags by source,
Note: £1 = 42.07 TL August 2024.

(lack of standardised regulations, limited recognition of sustainability claims, complicated certification), process market adoption challenges (supply chain complexity, consumer behaviours and demands, market fragmentation) cultural factors (attachment to new products, stigma and social norms), technological developments (inadequate upcycling technology, difficulty in material processing). Overcoming these barriers for upcycling fashion brands often requires collaborative efforts between businesses, consumers, governments, and NGOs. Education, regulatory support, and consumer awareness campaigns play vital roles in driving broader market acceptance and adoption of upcycled products.

4. Conclusions and suggestions for future work

The PVC flex banner industry is expected to grow over the next ten years. However, their lifespan is limited, leading to their disposal as waste and contributing significantly to landfill pollution and environmental issues. This research highlights the importance of transforming end-of-life PVC flex banners through upcycling. Upcycling can produce high-value products, effectively extending the life of these materials. Unlike other studies on fashion and textile products that rely on assumption data, our research also involved evaluating life cycle assessments based on a real scenario. We examined the processes involved in upcycling fashion accessories, specifically backpacks and hand-carry bags made from end-of-life PVC flex banners. We compared these with nylon (C-PA) and polyester (C-PES) bags. We used a cradle-to-gate approach in the life cycle assessments, which covers materials and processes from raw material extraction to factory production. The assessments addressed 16 impact categories, including carbon footprint and economic values. This is the first time life cycle assessments were carried out on PVC materials. Therefore, our research addresses the gap in the literature by providing life cycle assessments during the upcycling of end-of-life PVC flex banners and identifying their environmental and carbon impacts for the first time.

This study analysed impact categories within the life cycle impact assessment (LCIA) using openLCA 2.2.0 software based on the ReCiPe 2016 Midpoint (H) method. The findings revealed that U-PVC bags demonstrated lower environmental impact values than C-PA and C-PES bags across 12 impact categories, including fossil depletion, freshwater ecotoxicity (ETP), freshwater eutrophication (FEP), marine ecotoxicity (MAEP), marine eutrophication (MEP), ozone depletion (ODP), particulate matter formation (PM), photochemical oxidant formation (PCOP), terrestrial acidification (TAP), terrestrial ecotoxicity (TETP), urban and land occupation (ULOP), and water depletion (WDP). The above twelve categories relate to land and soil diversity, water and energy consumption, air pollution, and the release of harmful substances into the environment. These impact categories are relevant to the fashion industry because they account for 10 % of global carbon emissions. It strives to decarbonise and accomplish net-zero greenhouse gas emissions by 2050 and maintain global warming below 1.5 °C (United Nations Climate Change, 2023), reduce water usage (Carbon Trust, 2024), reduce clean water pollution and avoid landfill wastes (European Environmental Agency, 2024) and reduce PVC production, and promote the reuse plastics (Ellen MacArthur Foundation, 2024).

Due to the use of metals and alloys in their production, U-PVC bags had a higher impact on metal depletion (MDP) than C-PA and C-PES bags. Conversely, C-PES bags had a greater impact on agricultural land occupation (ALOP) than PA and PVC bags. Regarding the carbon footprint, U-PVC bags emitted 574.89 kg $CO_{2\ eq}$, lower than C-PA bags at 612.56 kg $CO_{2\ eq}$, and C-PES bags at 609.76 kg $CO_{2\ eq}$. This indicates that U-PVC bags have low carbon emissions from reduced transport and types of materials (end-of-life PVC flex banner). Regarding manufacturing costs, the average price for U-PVC bags was £49.86, while C-PA and C-PES bags cost £66.80 and £67.09, respectively. This demonstrates that U-PVC bags are more economical and less expensive than C-PA and C-PES bags. Therefore, our research highlighted the potential opportunity to upcycle end-of-life PVC flex banners as shoulder backpack bags and LCA impact assessment, carbon footprint, and cost-analysis, revealing that upcycling of PVC flex banners is a potential and viable option that can reduce the impact on the environment.

Future research should consider the following suggestions: (a) focus on U-PVC bags produced by the 'cradle-to-cradle' approach, which implements the circular economy and has the least impact on the environment, and (b) explore the production of alternative fashion items (such as apparel and various accessories) from end-of-life PVC flex banners, alongside examining their environmental and economic indicators through life cycle assessment (LCA). In recent years, upcycling has gained prominence in the fashion industry. More fashion brands are anticipated to create upcycled products using other waste plastic materials, including end-of-life PVC flex banners. The research presented is crucial for the industry as it helps to understand how to minimise the environmental impact associated with upcycling end-of-life PVC flex banners. Upcycled fashion items are expected to become integral to the fashion landscape. Effective waste management practices for PVC flex banners are essential to support this trend, ensuring that these materials are directed to brands producing upcycled fashion accessories. This article is anticipated to serve as a methodological reference for future assessments determining the environmental impacts of end-of-life PVC flex banners.

CRediT authorship contribution statement

Kenan Saatcioglu: Writing – review & editing, Visualization, Software, Resources, Investigation, Formal analysis, Data curation. **Prabhuraj D. Venkatraman:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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