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ORIGINAL ARTICLE

Mechanical characterization and sustainability assessment of recycled EVA for footwears

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Abstract

Ethylene vinyl acetate (EVA) is a thermoplastic material largely used in the footwear industry. Indeed, it is employed to produce outsoles and midsoles with high shock absorption. For producing these parts of the shoes, EVA is injected into a heated mold. During this process, gates and runners, which are necessary to allow a correct infill of the mold, are generated and they are treated as scraps and disposed in landfill. In this paper, a method for recovering pre-vulcanized EVA waste is presented and the possibility of developing a recycled product is investigated. EVA waste was shredded and dispersed into virgin EVA with a weight content of 10%. This mixture was employed in an injection molding process to produce samples for characterizing tensile, compression, and abrasion resistances and compare them with those of virgin EVA. At the same time, the environmental sustainability of the recovery process was evaluated through the standard methodology of Life Cycle Assessment (LCA) by comparing the production of recovered outsoles with traditional virgin ones. The LCA was paired with a Life Cycle Costing analysis to quantify possible economic benefits of the innovative system. Even though the resistances are quite lower than the virgin EVA, the recycled one demonstrates remarkable benefits in terms of environmental and cost sustainability, paving the way for a zero-waste system to produce outsoles and, more in general, EVA components.

Keywords Recycling · EVA · Life Cycle Assessment · Life Cycle Costing · Mechanical characterization · Circular economy

1 Introduction

Ethylene vinyl acetate (EVA) is a thermoplastic elastomer largely used to produce footwear. Indeed, due to its remarkable flexibility, abrasion resistance, and lightness, EVA is used to realize outsoles and midsoles for sneakers and other types of shoes. Differently from other materials, such as Thermo Plastic Polyurethane (TPU) and Poly Vinyl Chloride (PVC), EVA is easier to process and allows to produce more performant running shoes with higher shock absorption capabilities [1].

EVA midsoles and outsoles are typically realized through an injection molding process in which EVA pellets are heated and forced to flow in a dedicated mold; the EVA expands and forms a foam rubber [2]. This process can be fully automated and can allow to obtain a very high production rate due to the short processing time (typically in the order of minutes) [3]. The molds used in the injection molding process are typically realized in aluminum alloy and they can be used for the manufacturing of, at least, 10,000 parts. However, in order to guarantee a correct flow of the polymer inside the mold and a uniform filling, gates and runners, namely the channels through which the plastic flows from the injection molding machine into the part cavity, are necessary. Their dimension can vary according to the size and the shape of the parts to produce, but they can represent up to 20% of midsole total weight.

Nowadays, a real recycling process for EVA has not yet been industrially validated and the scraps generated during the injection molding process are used as fillers [4, 5] or disposed in landfill [6]. If a footwear annual production of 24 billion is estimated [7] (most of which contain EVA soles), it is easy to understand the importance of reuse, in a circular economy way, the scraps related to gate and runners [8].

In the scientific literature, several studies were carried out to evaluate the feasibility of alternative recovery systems for EVA crosslinked waste. Lopes et al. [9] employed EVA waste as a filler for natural rubber, styrene-butadiene rubber, and acrylonitrile-butadiene rubber in compression

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molding processes. Two waste percentage contents were testes (10 phr and 20 phr) and footwear outsoles with good mechanical properties were produced. Pavia Junior et al. [6] evaluated the recovery of EVA waste in the forms of injection branches and defective midsole obtained during injection molding processes. In that case, the waste was micronized and added to the virgin material. These studies confirmed the possibility to successfully employ this waste for the production of footwear components with mechanical performance comparable to the virgin ones. However, no analyses were carried out to evaluate the use of ground crosslinked EVA waste in injection molding processes.

Given the high annual production volume of footwear, sustainable production processes of these parts are a global industrial need [8]. Different studies applied the concept of Eco-Design in footwear in order to reduce the ecological impacts of these components during their entire life cycle. Redesign of the parts, sustainability, and risks assessments were conducted [10, 11]. Quantifications and comparison between the environmental footprints of footwear sector products were conducted by means of Life Cycle Assessment analyses. These studies focused on all the life stage of footwear, including material selection (i.e., considering EVA, polyurethane foam, nylon, leather, etc.), production process, and end-of-life options [12, 13]. LCA analyses on safety footwear components were also carried out [14, 15]. However, scientific literature lacks of sustainability studies concerning the use of EVA waste, in a circular economy perspective, in footwear applications. In fact, few LCA studies were conducted on ethylene vinyl acetate waste and they were focused on civil engineering applications [5, 16]. Moreover, no specific LCA study on footwear outsoles was found; this lack of knowledge highlights the needs of understanding the environmental impacts related to the recycling of EVA waste. Similarly, an analysis of the costs related to the recycling and reuse of EVA waste for the manufacturing of new soles must be conducted to understand the industrial feasibility of the entire process.

In this context, the aim of this paper is to evaluate the mechanical properties and the environmental and cost performances of a sole produced by dispersing pre-vulcanized EVA waste, coming from gate and runners but could be also obtained from end-of-life soles, into virgin EVA. Tensile, compression and abrasion tests were performed, and the results were compared to those obtained by virgin EVA samples. Life cycle methodology, according to the ISO 14040 and 14044 standards, was used to calculate the environmental and cost sustainability of the soles realized with a part of EVA waste and with virgin EVA; a comparison between them allows to evaluate and quantify the benefits of recycling EVA waste.

2 Material and methods

2.1 Materials

In the present work, two different materials were investigated: a virgin Ethylene Vinyl Acetate material and a compound containing 90% in weight (90%wt) of virgin material and 10% in weight (10%wt) of recovered EVA waste. The virgin EVA is a crosslinkable and expandable compound, with an expansion ration of 1:1.2 (EVA 120S/12G from Fainplast compounds). It is characterized by a density of 0.45 g/cc and a hardness of 51 shore A. The recovered material was obtained by shredding gate, runners, and production scraps and mixing the obtained granules with the virgin ones in a 10–90% ratio. Filler particles are characterized by dimensions between 50 and 200 µm.

2.2 Mechanical tests

2.2.1 Tensile test

Tensile tests were performed according to the ASTM D412 standard, using the MTS 810® universal servo-hydraulic testing machine, in order to compare the strength and the stiffness of the virgin and recycled materials. In order to guarantee the repeatability of the results, five samples for each material were tested. The process parameters imposed for the tensile tests are reported in Table 1.

The tests were carried out by setting a maximum cross-head displacement equal to 95.0 mm; this allows to obtain a deformation of the useful section equal to 9.5 times, a value considered sufficient to evaluate the typical deformation that a sole can encounter during its useful life. The specimens presented a cross-section of 10 × 6.5 mm. The results were plotted in terms of tensile stress vs. tensile strain curves.

2.2.2 Compression test

Compression tests were performed, in accordance with the ASTM D575-91, using the same universal testing machine used for tensile tests, in order to evaluate the effect of the vulcanized fillers dispersed in the recycled material on the compression properties of the sole.

Table 1 Tensile testing parameters

Temperature	Speed	Distance between shoulders	Maximum allowable displacement
Room temperature	10 mm/min	10.0 mm	95.0 mm

The process parameters reported in Table 2 were used to carry out the tests on both the virgin and recycled materials.

In order to simulate a real use of the soles, a cylindrical punch was positioned on their rear part, as can be seen in Fig. 1, and the tests were interrupted after a displacement of the crosshead equal to 10 mm. The results were plotted in terms of punch load vs. punch stroke curves.

2.2.3 Abrasion test

As far as the abrasion test is concerned, the apparatus and the method reported in ASTM D5963 were used. The test was performed by pressing a defined sample of rubber on a rotating drum covered with a specific abrasive sheet made in Corundum (aluminum oxide) with grit size of 60 and specified conditions of contact pressure, sliding distance, and travel speed of the test piece, rotational speed of the drum, and degree of abrasiveness of the abrasive sheet have been defined. The values of the main process parameters are reported in Table 3.

Five samples for both virgin and recycled materials were tested. They were weighted before and after the abrasion tests and the abrasive resistance was defined by calculating the lost mass.

2.3 Image acquisition

The Leica EZ4 D digital stereomicroscope, equipped with the dedicated software "LasEz," was employed to acquire high-quality images of both specimens' surfaces and cut sections in order to assess the quality of the injection molded parts and the dispersion of the recovered material. The abrasion test specimens were analyzed to assess the wear phenomena and to compare the different behavior exhibited by virgin and recovered material.

2.4 Life Cycle Assessment analysis

Life Cycle Assessment (LCA) analysis was carried out to investigate the EVA waste recycling system and quantify its environmental and economic impacts. As a matter of fact, this study originated from the industrial needs of finding a sustainable and cost-effective solution for the treatment of injection branches and defected parts in IM processes. Therefore, it is crucial for the success of the process that it well addresses these needs. In line with the ISO 14040-14044 standard, environmental impacts evaluation was carried out following the Life Cycle Assessment methodology. LCA consists of the following four iterative phases:

Table 2 Process parameters of the compression tests

Temperature	Compression speed	Punch Diameter	Maximum allowable displacement
Room temperature	5 mm/min	30.0 mm	10.0 mm

Fig. 1 Compression test performed on the rear part of the sole

- Goal and scope definition: in this phase, the aim of the study, the functional unit, the considered scenarios and system boundaries are defined.
- Life Cycle Inventory (LCI): all inputs and outputs of the previously defined system boundaries are identified and quantified by exploiting direct and indirect data sources.
- Life Cycle Impact Assessment (LCIA): the LCI inventory data are translated into potential environmental effects considering different impact categories (i.e., Global Warming Potential, Fossil Depletion, etc.). Characterization and weighting factors are considered; typically, this phase is automatically carried out by means of a LCA software (i.e., GaBi, SimaPro, Open LCA).

Table 3 Main process parameters of the abrasion tests

Temperature	Contact pressure	Diameter of drum	Rotational frequency	Length of abrasion path
Room temperature	10 N	150.0 mm	40 rpm	40.0 m

- Results interpretation: results are thoroughly analyzed and critically reviewed. This phase is needed both to verify the reliability of the results and to identify criticalities and possible improvements of the considered systems.

The Life Cycle Costing (LCC) analysis follows a framework similar to that of LCA; in this case, the objective of the methodology is to evaluate the overall cost of a system. It can be paired with the LCA analysis by considering the same functional unit, scenarios, and system boundaries.

2.4.1 Goal and scope definition

Considering the high environmental impacts of polymeric materials and the worldwide demand for footwear products, EVA waste could result into a relevant environmental issue. The goal of the present LCA analysis is to evaluate the environmental sustainability of the innovative recovery process for crosslinked ethylene vinyl acetate waste obtained during injection molding processes. The production of footwear parts with a percentage content of recovered materials will be compared to virgin production processes considering different impact categories.

In this context, the functional unit is defined as the production a US size 8 shoe outsole (corresponding to a EU size 41) in ethylene vinyl acetate and standard dimensions.

Two different scenarios were considered to represent the production of soles by injection molding with virgin material (Scenario 1) and by using a percentage of recovered EVA (Scenario 2). The scenarios production phases are detailed in the next paragraphs.

- Scenario 1: production of EVA outsoles with virgin material.

The first scenario was modelled considering the current standard injection molding production process that is employed for the production of EVA outsoles. In this case, the EVA crosslinked waste is not recovered and reused but they are directly landfilled. In this paper, the authors will refer to this scenario as the “virgin” one.

In the injection molding process, the material in forms of pellets is fed inside the hopper of the IM machine. A crosslinkable and expandable commercial compound based on EVA, with an expansion ration of 1:1.2, was employed for this study (the EVA 120S/12G from Fainplast compounds). Within the heated cylinder of the machine, the material is moved towards the mold by means of a rotary screw and, due to the effects of heat and friction, it melts. As recommended by the material datasheet, the process was carried out at a temperature of 180°C. The screw then acts as a piston and pushes the molten material into the aluminum mold. Here, the material is molded under controlled temperature and pressure conditions. Before each production cycle, the mold is coated with a silicon-based release agent to prevent the adhesion of the sole to the mold surfaces. The crosslinking occurs in about 6–7 min and, as the part is sufficiently cooled down, it is removed from the mold. Simple manual operations, such as sprue and excess material removal, conclude the process and the cycle can start again. Material scraps and defective parts are transported and disposed in landfills.

- Scenario 2: production of EVA outsoles with 10% of recovered material.

Scenario 2 considers the production of a shoe outsole constituted by 90% of virgin material and by 10% of recovered EVA waste. The latter are obtained as injection branches and defected parts from previous injection molding processes.

One of the goals of the study was to reuse the waste material without making major modifications to the standard process and without compromising the mechanical properties of the molded parts. Hence, Scenario 2 is analogous to the first one with the exception of the raw materials used. The EVA waste obtained during the production of virgin parts are reprocessed and recovered in order to reuse them in IM processes; this prevents them to be sent to landfill disposal and reduced the use of virgin EVA pellets. The waste was finely grounded by means of a dedicated machine with an hourly productivity of about 120. The scraps are then mixed with virgin pellets with a 1 to 9 weight rate and the compound is employed for IM processes.

The present analysis is defined as “from cradle to gate” as it considers all the inputs and outputs related to the functional unit from the extraction of the raw materials to the injection molding process of the EVA outsoles. More in details, the following production phases were considered for the environmental assessment of the two scenarios:

- Production of virgin EVA pellets
- Raw material transport (for both the EVA and the consumables)
- Mold production and transport
- Recovery process for the EVA waste (only for Scenario 2)
- Injection molding process (considering energy consumption and consumables)
- End of Life (EoL) for the EVA waste
- Aluminim mold recycling

The service life and the EoL of the outsole were considered out of the system boundaries; in fact, these phases would have the same environmental impacts for the two scenarios and they would not influence the comparative analysis. The production phases of the machines used (e.g., the injection molding machine and the grinding machine) were not considered in this study. Since their service life is much longer than the time horizon considered for the functional unit, their contribution to the results would be negligible. This approach is widely employed in LCA studies.

2.4.2 Life Cycle Inventory

The Life Cycle Inventory phase was conducted considering both primary and secondary data. Data were gathered considering direct measurements, scientific literature analysis, estimates, and a commercial LCA database (Ecoinvent). As far as possible, data were directly measured during the production processes represented by Scenario 1 and Scenario 2. This category includes data related to materials and energy consumption, and the final weights of the mold and countermold. The weight of the silicon-based release agent used for each molding cycle was evaluated through a comparison with a literature LCA analysis [14]. The recycling process of the tools was modelled by setting a recycling rate of aluminum equal to 80% [17] and road transport. The environmental benefits of this phase are equal to the opposite of raw aluminum production and they were allocated to the FU considering the molds service life.

The initial weight of the tools (before the milling operations) was evaluated considering the CAD model of the molds. The environmental impacts related to the molds production and transport were allocated to the functional unit by considering their service life. The latter, expressed in number of molding cycle, was estimated considering the industrial experience of the company experts.

Transport distances of raw materials and tools were estimated considering the geographical positions of the involved company (in Center Italy) and its suppliers. In general, the suppliers are local and the transport distances are limited (up to few hundreds km). Road transport emissions were retrieved from the Ecoinvent commercial database. Ecoinvent was also employed to model raw materials (e.g., the ethylene vinyl acetate, the release agent, the raw aluminum), and the electric energy production considering the Italian energy mix. Life Cycle inventory data are summarized in Table 4.

After the LCI phase, the input and output data were translated into potential environmental impacts according to different impact categories (Life Cycle Impact Assessment Phase). The software SimaPro, equipped by default with the Ecoinvent database, was employed for the modelling and the LCIA of the two scenarios. Different impact categories were considered for the impact assessment to have a complete view of the possible environmental effects of the two scenarios [18]:

- Cumulative Energy Demand (CED): it quantifies all direct and indirect energy consumptions related to the FU, from fossil, nuclear, and renewable sources. It is expressed in MJ [19].
- Global Warming Potential (GWP): it evaluates the effects of the scenarios in terms of climate change and it is expressed in kg CO_2eq. The methodology proposed by the International Panel on Climate Change (IPCC) with a time horizon of 100 years was considered [20].
- ReCiPe: it evaluated 18 environmental impact categories at midpoint level. These categories focus on specific aspects such as "marine eutrophication" and "fossil sources depletion." They can be gathered together into three damage categories (to human health, to the ecosystem, and to the availability of natural resources) at the endpoint level. The endpoint categories are expressed in Ecopoints [21].

Table 4 Life Cycle Inventory data for the two considered scenarios.

	Scenario 1 (Virgin)	Scenario 2 (Recovered)
Material		
Outsole weight (g)	191.98	185.68
Recovered material weight (g)	/	18.5
Waste weight (g)	30	30
Silicon based release agent (g)	3	3
Mold		
Mold cavity	2	2
Mold and countermold final weight (kg)	35	35
Mold and countermold initial weight (kg)	45.5	45.5
Molds service life (cycles)	12000	12000
Molds supplier distance (km)	100	100
Energy consumption		
Injection molding cycle (kWh/part)	0.591	
Grinding machine (kWh/kg)		0.375

2.4.3 Life Cycle Costing

A cost assessment was performed to pair the environmental assessment with economic considerations. The same functional unit and scenarios defined for the LCA were considered for the Life Cycle Costing analysis and a parametric approach was employed [22]. Several parameters, identified as cost drivers, were used to evaluate the cost of unitary activities within the system boundaries. Simple mathematical formula allowed to assess the cost of each phase that were added together to get the FU total cost. The parameters concerned, for example, physical properties (i.e., material mass), the number of inputs-outputs, labor, and energy.

The goal of the LCC was to determine whether or not the EVA recovery system can provide economic benefits and to quantify them. The inventory analysis was based on the costs effectively incurred by the involved company. The materials cost was calculated considering the weight of the materials used and their cost per kg. The electric energy cost was calculated considering the cost of 1 kWh, the energy consumption of the machines per hour, and their productivity. The depreciation costs of the machines were calculated considering their purchase cost, their service life (in years), their productivity, their average uptime, and the time needed for the production of the functional unit. Similar evaluations were conducted for the monthly maintenance costs. Analogously to the LCA analysis, the molds cost was allocated to the functional unit considering their purchase cost and the number of parts that they can produce before substitution is required. Table 5 summarizes the main cost analysis inventory data.

Table 5 Main inventory data for the Life Cycle Costing analysis

Life Cycle Inventory data		
Virgin EVA	5	€/kg
Recovered material	1.3	€/kg
Labor	1.5	€/outsole
Mold cost	2500	€/mold
Injection molding machine (1 unit)	20000	€/unit
Maintenance	1500	€/month
Number of units	6	
Injection machine service life	5	years
Injection molding productivity	34848	parts/month
1 kWh	0.17	€

3 Results and discussion

3.1 Surface images analysis and mechanical characterization

Figure 2 presents digital stereo microscope images of the recycled and virgin EVA specimens. Both the morphology of cut surfaces and surfaces subjected to the abrasion test are reported.

For both the cut surfaces (Fig. 2A and B), a typical closed cells structure can be identified [23]; it is noted that as far as the virgin EVA section is concerned, the closed cells have spherical shapes and uniform distribution with a diameter dimension of about 20–35 µm. The presence of the recycled material causes significant modifications in the foam structure, generating closed cells of different shapes and dimensions; the size of the cells is increased with respect to the virgin alternative, with dimensions of about 80–150 µm. This structure degradation is well documented in scientific literature studies concerning foam composites in which the filler particles determine irregular cells nucleation and propagation [24, 25]. This phenomenon can also cause mechanical

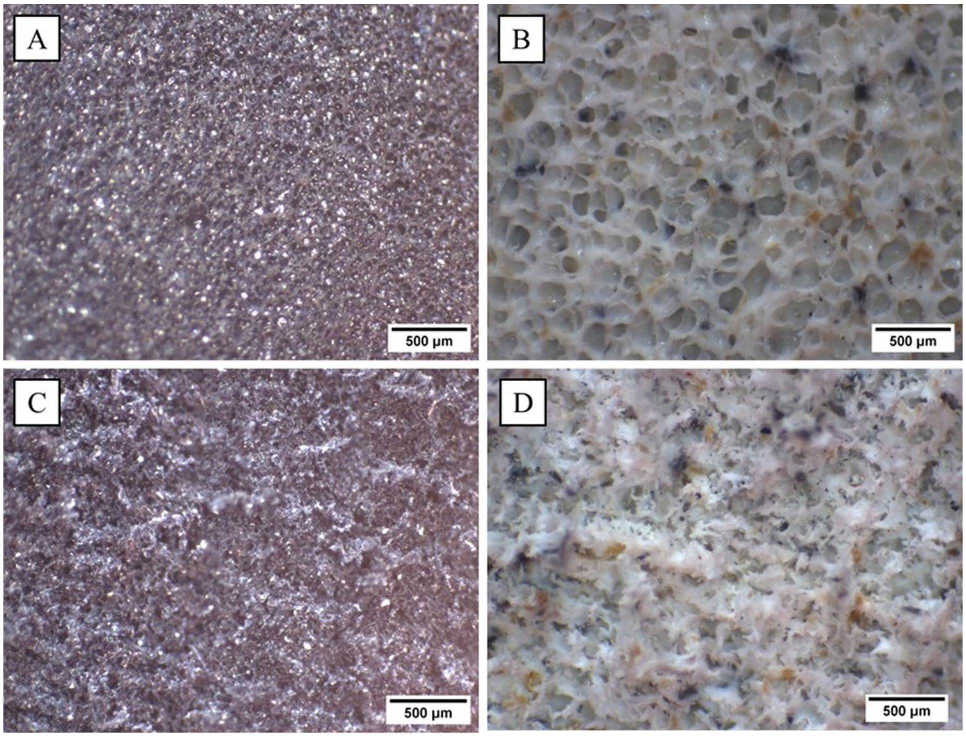


Fig. 2 Digital stereo microscope images of the virgin and recycled EVA specimens with 35× magnification: **A** virgin EVA and **B** recycled EVA cut surfaces; **C** virgin EVA and **D** recycled EVA surfaces subjected to the abrasion test

properties loss [26], in line with what was observed in the mechanical characterization results.

The worn surfaces (Fig. 2C and D) show high material deformation caused by the abrasion test. The deformation is more pronounced for the virgin specimen while, in line with scientific literature [23], the composite material worn surface appears more smooth and it is easier to identify the foam cells structure.

Figure 3 shows typical tensile stress vs. tensile strain curves obtained by performing tensile tests on the virgin and recycled EVA. As reported in the previous section of the paper, the test was interrupted at a displacement equal to 95 mm in order to obtain a deformation of the useful section equal to 9.5.

The virgin and recycled EVA materials exhibit a similar mechanical behavior, characterized by an increase in tensile stress with strain until the deformation limit value equal to 9.5, defined in this work. However, it can be observed that, for a given strain value, the virgin material shows a tensile stress value higher than the recycled EVA. Such discrepancy tends to increase with increasing strain value. At a strain value of 9.5, the virgin EVA reaches a mean tensile strength value of 3.63 MPa, with a standard deviation of 0.12, while the recycled EVA exhibits a mean value of 3.33 MPa, with a standard deviation of 0.10. Such results demonstrate that, by dispersing the pre-vulcanized EVA in the virgin material, a reduction in the tensile strength equal to 8% is obtained, that is recycled EVA acts as a filler and tends to decrease the deformability of the virgin EVA, as reported also in [9].

The compression tests were performed on the rear part of the produced soles both using virgin and recycled EVA materials. Figure 4 shows the comparison between the typical punch load vs. punch stroke curves of virgin and recycled EVA soles.

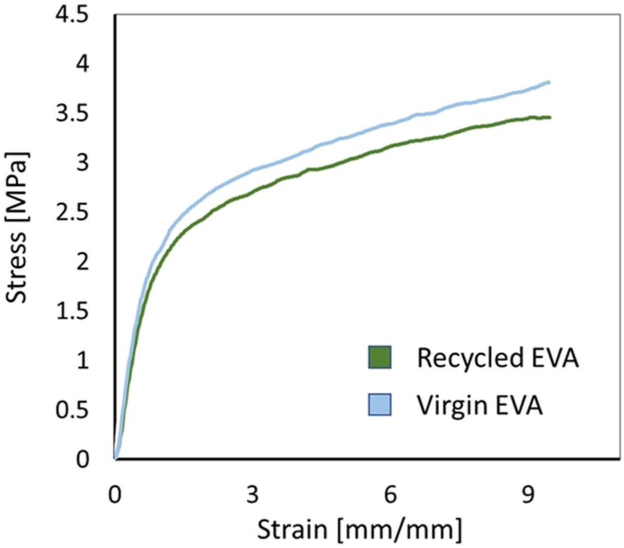


Fig. 3 Typical tensile stress vs. tensile strain curves of virgin and recycled EVA materials

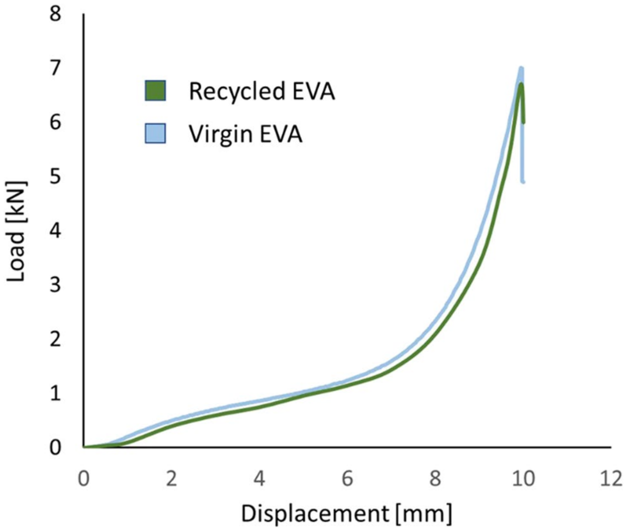


Fig. 4 Typical punch load vs. punch stroke curves obtained by the compression tests on virgin and recycled EVA soles

As can be seen, the virgin and recycled EVA soles demonstrate a very similar compressive behavior, even though, for a given stroke, the recycled material exhibits a slight lower stiffness than the virgin material. As far as the maximum load is concerned, the virgin EVA exhibits a value of 7.0 ± 0.3 KN while the recycled EVA a value of 6.7 ± 0.4 KN. This result can be attributed to modifications in the foam structure of recycled EVA. Indeed, the differences in molecular weight and composition compared to the virgin EVA affect the foaming process, leading to a different foam structure. This results in changes in the foam density, cell size, and cell distribution, which affect the mechanical properties of the EVA.

The abrasion test allows to understand the effect of recycled EVA particles on the wear resistance of soles. Figure 5 shows the average percentage mass loss after the abrasion tests for both the virgin and recycled EVA samples.

It is worth notice that the recycled EVA results in a higher quantity of mass loss after the abrasion tests. This result can be attributed to the weak connection between the recycled particles to the virgin material that, during the relative motion with the abrasive sheet, are expelled from the samples, leaving holes, and decreasing the after-test mass.

3.2 Life Cycle Impact Assessment

Figure 6 reports the results of the Life Cycle Impact Assessment phase in terms of Cumulative Energy Demand and Global Warming Potential. The impact values for each considered phase are reported in Table 6. The overall trend is

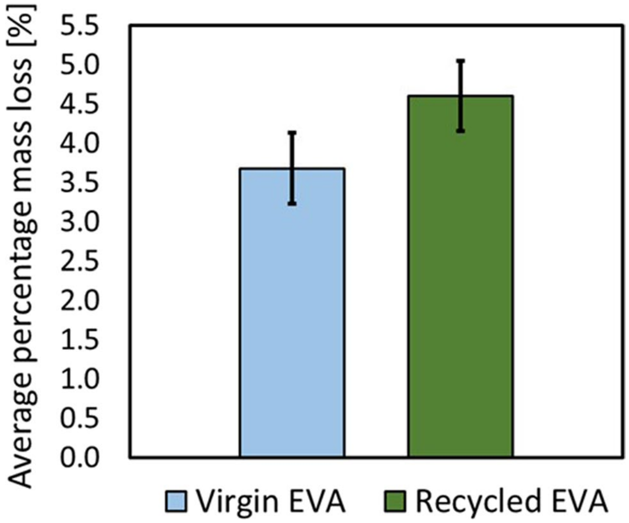
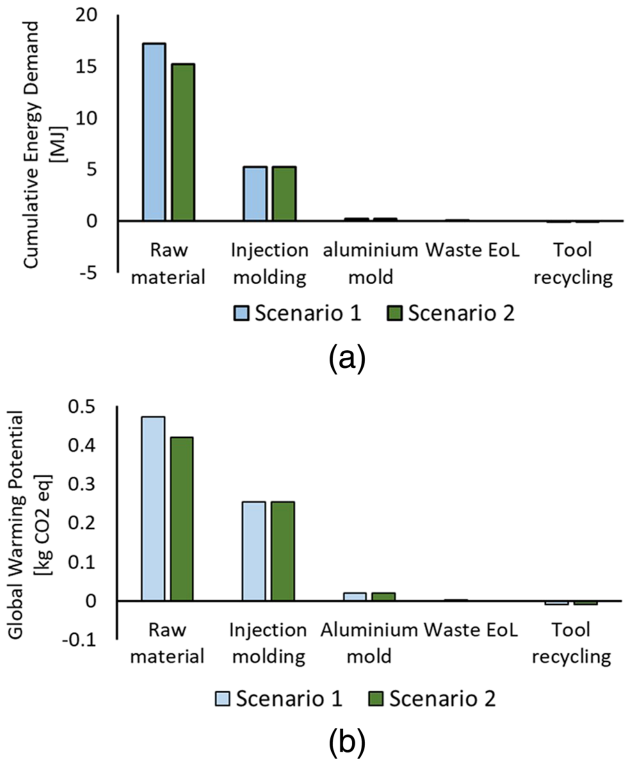


Fig. 5 Comparison between the virgin and recycled EVA material after abrasion tests



(a)

(b)

Fig. 6 LCIA results in terms of **a** Cumulative Energy Demand and **b** Global Warming Potential

Table 6 LCIA results in terms of CED and GWP

	IPCC GWP 100a		Cumulative Energy Demand	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
	kg CO2 eq		MJ	
Total	0.741	0.685	22.608	20.565
Materials	0.474	0.421	17.240	15.205
Injection molding	0.253	0.253	5.239	5.239
Mold	0.020	0.020	0.222	0.222
Waste EoL	0.003		0.008	
Mold recycling	−0.009	−0.009	−0.101	−0.101

the same for the two impact indicators and recovered material scenario showed the best environmental behavior. More specifically, Scenario 2 provides a reduction in environmental impacts equal to 9% for CED and 7.6% for GWP. Raw materials production and transport represent a major contribution on the impacts of the two scenarios: depending on the impact indicator and the considered scenario, they determine between 61 and 76% of the total footprint of the production processes. For Scenario 1, the “raw material” phase accounts for the impacts of the raw ethylene vinyl acetate compound production and its transport while for Scenario 2, it also accounts for the EVA waste recovery process. The environmental benefits related to Scenario 2 are almost exclusively attributed to the substitution of virgin EVA with the grounded waste. The recovery process is very simple, and all its impacts are determined by the energy consumption of the grinding machine. Due to the high production rate of the latter, low-energy consumption is associated with the recovered waste. Overall, the EVA scraps used in Scenario 2 have a total carbon footprint of only 0.0066 kg CO_2 eq and they account for about 1.6% of the total impacts of the production process. This a remarkable result considering that the EVA waste account for 10% in weight of the raw material used and it used as a substitute for a high impact virgin material. The grinding recovery process could strongly improve the sustainability of injected molded parts with an impacts reduction of about 2 kg CO_2 eq per kg of recovered EVA used in the molding mix.

Landfill disposal was considered the end of life option for the waste generated during the injection molding process of Scenario 1 (0.03 kg of crosslinked EVA). This phase is negligible for what concerns CED and GWP impact indicators. As far as Scenario 2 is concerned, no impacts related to the disposal of EVA waste were taken into account. As a matter of fact, Scenario 2 is based on the idea of creating a circular economy model for EVA waste, eliminating the need for unsustainable EoL options. The other production phases are the same for the two scenarios.

The injection molding phase is the most relevant after the material production. It contributes between 23 and 37% on the total impacts of the two scenarios according to CED and GWP. Its impacts are mainly determined by the energy consumption required by the IM machine (for heating and clamping) while the contribution of the release agent is negligible.

Mold production and transport are impactful phases; however, those impacts are allocated to a high number of parts as a single set of tools (constituted by a mold and a countermold) can be used for about 12,000 cycles. So, overall, the impacts of the aluminum mold affect the final results by less than 3%. For the same reason, the recycling phase of the tools brings negligible environmental benefits.

Finally, Figs. 7 and 8 report the results obtained by means of the ReCiPe methodology in terms of the 18 midpoint categories and the 3 endpoint damage categories. In order to improve the graph readability, the midpoint categories were normalized, i.e., each value was divided by the highest value obtained for that specific impact category in the two scenarios. In this way, the highest value is always equal to 100% and the lowest impact alternative is expressed as a fraction of the first one. Scenario 2 showed the lowest environmental impacts for every midpoint category, with an average reduction with respect to Scenario 1 equal to 12.5%. The impacts reduction ranged from 2.3% for the Stratospheric ozone depletion to 80% for the Marine eutrophication impact category; for the former, in both scenarios, the impacts are mainly determined by the electric energy consumption of the injection molding phase (about 68%). Hence, since this phase is kept unchanged between the two scenarios, the benefits related to the virgin material substitution are less evident in percentage terms. In the case of marine eutrophication, the recovery alternative provides a reduction in impacts equal to 80% with respect to the virgin production process.

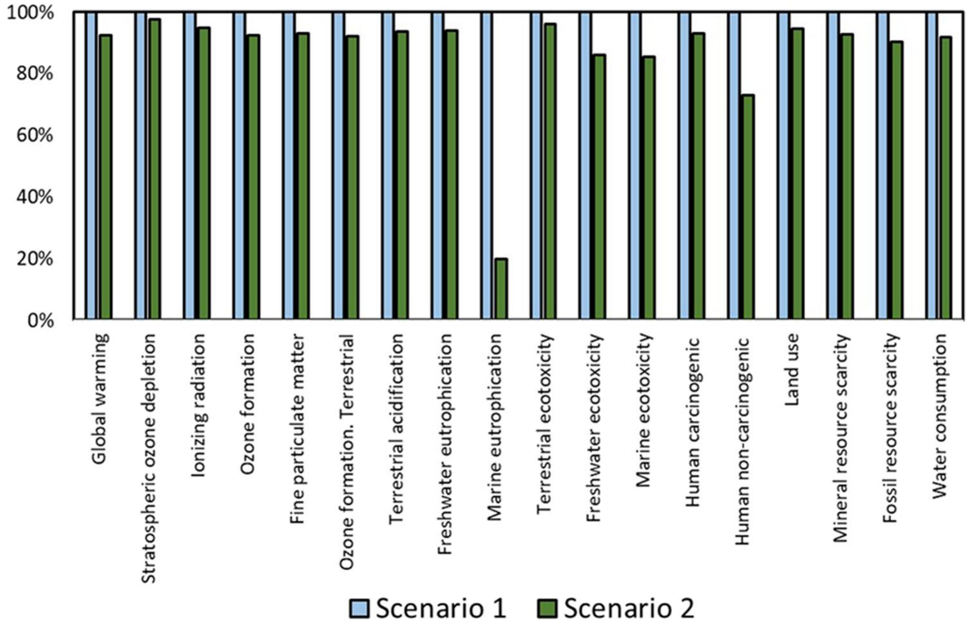


Fig. 7 LCIA results for the 18 categories of the ReCiPe methodology

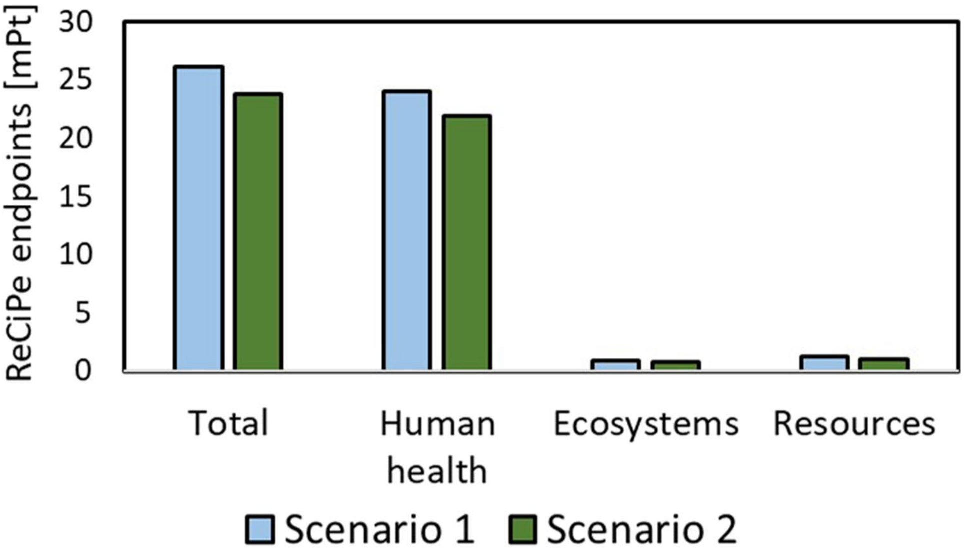


Fig. 8 Results for the damage categories of the ReCiPe methodology

In Scenario 1, this category value is primarily determined by the landfill disposal of the EVA waste (79%); the reuse of the scraps prevents them to be sent to landfill so it drastically lowers the impacts of Scenario 2. Moreover, the virgin EVA production causes the second highest contribution so its substitution with low-impacts recycled material further improved the sustainability of the production process. Regarding the other impact categories trends, they are in line with was observed for the Cumulative Energy Demand and Global Warming Potential indicators, with the raw material production determining the majority of environmental impacts. This is also supported by the endpoint categories results, in which all the midpoint categories results are gathered together and show an overall impacts reduction equal to 9%. One again, the three categories show uniform results with an almost uniform impacts percentage reduction.

The environmental benefits of plastic materials recycling are well documented in scientific literature Life Cycle Assessment analyses even though they strongly depend on the specific case study and the considered materials [27, 28]. For example, impacts reduction in terms of GWP up to 42.8% associated with recycled polypropylene for injection molding processes was observed by previous literature [29]. Similar values could be achieved by increasing the percentage of recycled material in the injection molding blend, further improving the sustainability of EVA components. Moreover, if impacts reduction per kg of recovered materials is considered, the present study is associated with even higher benefits with respect to present literature (−2.1 kg CO_2 eq per kg of recovered material) [27] due to the low-energy consumption of the recovery process.

3.3 Cost comparison

Table 7 summarizes the results of the economic analysis of the production of the outsole in the two considered scenarios. The total costs are expressed in terms of cost contribution of raw material, mold, injection molding machine depreciation, maintenance, labor, and energy consumption. The costs are referred to optimized production volumes, considering an optimal allocation of the costs of the tools. As for the environmental impact analysis, the two scenarios are very similar and they differ only for the costs related to the raw materials. Costs related to labor, mold, maintenance, machine depreciation, and molding cycle energy consumption are the same for the two alternatives.

Table 7 LCC analysis results for the two scenarios

	Scenario 1	Scenario 2
Raw material	0.96 €	0.86 €
Mold	0.10 €	0.10 €
Injection molding machine	0.11 €	0.11 €
Maintenance	0.09 €	0.09 €
Labor	1.50 €	1.50 €
Energy consumption	0.10 €	0.10 €
Total	2.76 €	2.66 €

Overall, the recovered EVA waste is a much cheaper material than the virgin one (1.5 €/kg vs 5 €/kg) so Scenario 2 resulted the cheapest scenario. The reuse of the IM scraps can provide a cost reduction equal to 0.10 €, corresponding at about 4% of the total production cost (2.76€ vs 2.66 €).

Figure 9 shows the results of the analysis in terms of percentage contributions for the two production processes. The purchase cost of raw materials is definitely a major cost item for the company and it contributes for 33% of the total costs of Scenario 1 (0.96 €). Hence, it is crucial to avoid material waste and to obtain a 100% valorization of the purchased materials.

Labor cost is the greatest contributor to the systems costs and it determines more than 50% of the costs in the two scenarios. Despite the fact that the IM process is highly automated, the supervision of an operator is always required to monitor the production. Further improvement of the production process could focus on this issue. The other cost item (molds, maintenance, energy consumption, depreciation) are the same in the two scenarios and determine a lower percentage contribution on the final results, with costs per part ranging from 0.09 € to 0.11€.

4 Conclusions

The paper aims at studying the mechanical, environmental, and cost performances of a material obtained by recycled EVA, used for the soles of footwear, and at comparing them with those given by the virgin EVA material in order to understand the feasibility of the recycling process. The EVA waste, generated from gates and runners shredding, was dispersed in virgin EVA in a 10–90% ratio. Dedicated samples and soles were produced through injection molding process. Tensile, compression, and abrasion tests were carried out on both virgin and recycled EVA samples in order to obtain the mechanical properties of the two materials investigated. Furthermore, the life cycle methodology was used to calculate the environmental and cost sustainability of the soles realized with virgin and recycled EVA.

The main conclusions can be summarized as follows:

- The presence of recycled particles dispersed in the virgin EVA leads to a slight reduction of the mechanical performances as compared to those obtained by the virgin material. Such results can be attributed to the weak connection of the pre-vulcanized EVA waste fillers to the virgin material.

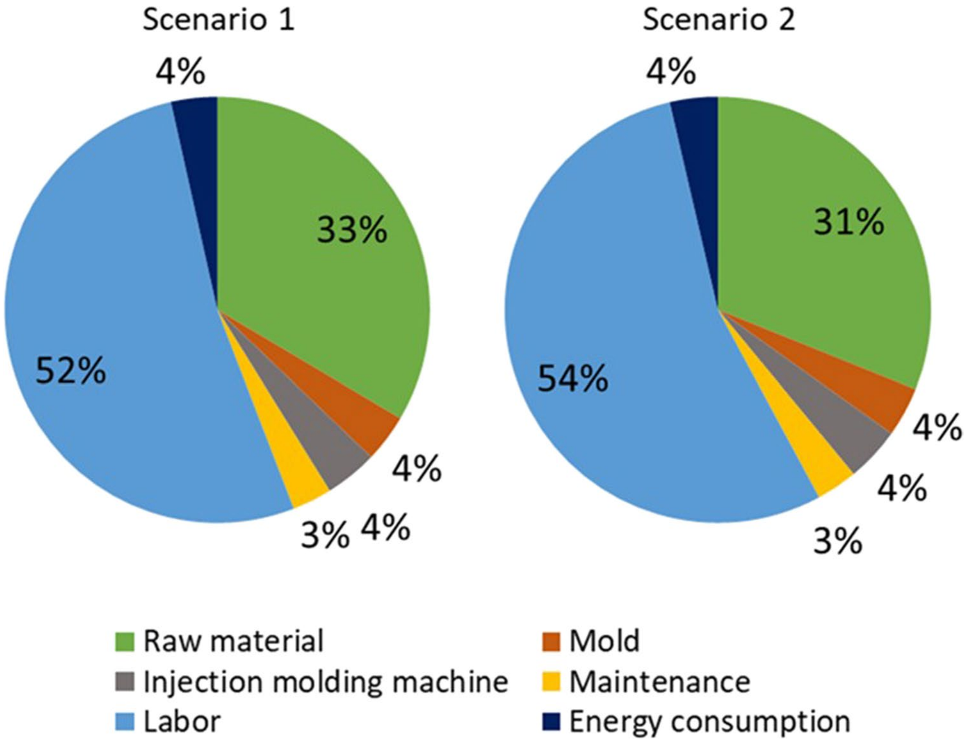


Fig. 9 Percentage contributions on the total production costs of the oursole in the two scenarios

- The slight decrease of the mechanical properties of the recycled EVA compared to the virgin material justifies the use of EVA waste for commercial purposes.
- By substituting a part of virgin EVA with the recycled material, it is possible to sensibly increase the environmental sustainability and decrease the cost of a sole. Indeed, using a quantity of 10% of recycled EVA, a reduction of 9% for CED and 7.6% for GWP indicators is obtained in comparison with a 100% virgin EVA sole. As far as the costs during the life cycle is concerned, a reduction of about 4% can be gained.

The results confirm that the reuse of EVA waste as fillers in the production of EVA soles can be a suitable method to almost maintain similar mechanical properties than virgin materials, but with a sensible reduction in the environmental impacts and in the costs.

Future work will be focused on the evaluation of other mass dispersion of EVA waste in order to find the best compromise between the reduction of mechanical properties and the enhancements in terms of sustainability and cost performance.

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Author contribution Iacopo Bianchi: software, writing, conceptualization, investigation. Archimede Forcellese: supervision, reviewing. Michela Simoncini: writing—reviewing and editing, investigation. Alessio Vita: methodology, investigation, formal analysis, visualization. All authors read and approved the final version of the manuscript.

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Declarations

Conflict of interest The authors declare no competing interests.

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