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Environmental impact assessment of sound absorbing nonwovens based on chicken feathers waste

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ABSTRACT

Chicken feathers (CFs) are currently a biogenic solid waste generated on a large scale and around the world. Its valorization could provide a great opportunity to manufacture environmentally friendly materials and increase the profit of poultry processors. The aim of this study was to fabricate sound absorbing nonwoven materials using CFs wastes to evaluate both the environmental impact of their fabrication processes using Life Cycle Assessment (LCA) methodology and the acoustic performance and to compare the results with a conventional insulating material such as stone wool (SW). The study showed that it was possible to fabricate CFs-wool nonwovens incorporating up to 50% w/w of CFs. The new material showed similar acoustic properties to those of SW, even behaving better for frequencies below 2200 Hz. LCA study showed that the environmental impacts decrease when the amount of CFs increases in those nonwoven materials containing CFs-wool, except for abiotic depletion and eutrophication impact categories. However, despite the synthetic nature of the SW, SW only presented worse environmental performance than the CFs based nonwoven materials for few impact categories (depletion of abiotic resources, human toxicity and photo-oxidant formation) due to the negative contribution caused by the incorporation of wool (W) into the nonwoven materials.

1. Introduction

An estimated 100 million tons of chickens were raised in 2017 around the world (AVEC, 2017), and the data from FAO states that chicken world production has almost doubled in the last twenty-five years (Food and Agriculture Organization of the United Nations, 2019). The intensive production and consumption results in huge amount of animal by-products not suitable for human nutrition (Gobierno de España - Ministerio de Agricultura y Pesca Alimentación y Medio Ambiente, 2018). Among these animal by-products, chicken feathers (CFs) represent around 5–7% of the total chicken weight (Instituto Markin, 2009; Carrillo et al., 2012). These CFs constitute a waste that are mainly buried in landfills and/or burned in incinerators. The conversion of CFs to animal food, the only possible way in which this residue is used nowadays, is strictly controlled due to the bovine spongiform encephalopathy outbreaks (Fundación Española para el Desarrollo de la Nutrición Animal (FEDNA), 2012; REAL DECRETO, 2000). Moreover, the most common treatment, which is the incineration method, leads to the generation of greenhouse gases (Bessa et al., 2017).

Due to the increasing awareness of the environmental impact and health issues of chemical materials (World Health Organization, 2016), the trend to valorize natural raw materials is growing. A good example of this trend is the interest in valorising CFs, as well as other natural by-products. Following this tendency, some proposals directed to obtain value-added products as biocomposites (Colom et al., 2016), biosorbents (Rosa et al., 2008), filter media (Jin et al., 2013), insulation materials (Reddy and Yang, 2013) and tissue engineering scaffolds (George et al., 2003) have emerged.

Regarding the insulation materials option, it is important to note that the sound insulation products that are available nowadays are not necessarily recycled, and sometimes imply pollutant production processes or require high consumption of resources (Asdrubali et al., 2012; EURIMA, 2018). For example, building acoustic insulation is commonly realized using fibrous and porous materials obtained from petrochemicals (urethane foams) or from natural sources that requires the consumption of high energy for their manufacture (glass and SW). Consequently, the use of natural or recycled materials could reduce the environmental impact that those materials can cause, promoting the

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introduction of the sustainability concept in building design. Among the sound-absorbing materials made with natural resources or by-products that have been proposed during the last years (coir, kenaf, bamboo, W, etc.), CFs is currently under study and its development is at an early stage (Kusno et al., 2019; Dieckmann et al., 2018; Asdrubali et al., 2015a). This biogenic waste that could result in a route of obtaining environmental friendly acoustic insulation materials since a waste from poultry industry is valorised and the final acoustic product could perform well in terms of biodegradability or compostability. CFs are made of hydrophobic keratin, a protein with an environmental durability similar to nylon. The diameter of the CFs fibres (excluding the central part of the feather, the quill) is generally smaller than that of the W fibres. That physicochemical structure is responsible for the properties of CFs: light weight, moderate biodegradability, high specific modulus and tensile strength (Staron and Marcin Banach, 2011). In addition, keratin has also good acoustic performance (Zhang et al., 2018) since the quill of the CFs is formed by a porous macrostructure that can promote sound absorption by trapping air in its inner part (Huda and Yang, 2008). Consequently, their application to the production of porous and non-porous sound insulation materials is an alternative of valorisation worth to explore that could consume the huge amount of CFs produced annually. In fact, this route of valorisation has already been explored, demonstrating the viability of manufacturing nonwoven materials from CFs by using thermal bonding with binding materials (Dieckmann et al., 2018), air laid (Dieckmann et al., 2018) or compaction (Kusno et al., 2019) methods. In all these three cases, the resulted materials demonstrate comparable, or in some cases better, sound absorbing properties than conventional acoustic insulation materials. Besides, it is important to take into account that CFs are comparable to sheep W, in terms of light weight, recyclability and biodegradability, so the combination of both materials could be an alternative for developing new insulation products. These resulted products would also be a low cost alternative since in Europe sheep are raised fundamentally to obtain meat, and these breeds W is generally considered a by-product that has to be eliminated according to animal by-products and derived products not intended for human consumption European regulation (The European Parliament and the Council of the European Union, 2009) by incineration, composting or disposal in a landfill, as well as CFs.

Alternatively to nonwoven materials, others authors have demonstrated that CFs used in combination with thermoplastic matrices, such as high density polyethylene [Liu et al., 2012; Barone and Schmidt, 2004, ethyl vinyl acetate (Soheilmoghaddam et al., 2017) and polypropylene (Huda and Yang, 2009; Barone et al., 2005; John and Thomas, 2008; Yalcin et al., 2013; Soheilmoghaddam et al., 2017), result in biocomposites panels with good sound dampening properties, which perform better than cellulose based composites. However, when CFs were mixed with polymers to fabricate rigid biocomposite panels, in general, the obtained materials exhibit limited acoustic absorption properties (Asdrubali et al., 2015b; Ricciardi et al., 2014). On the contrary, when fibres are consolidated in the form of nonwoven, the sound absorption efficacy improves significantly as it was reported by (Patnaik et al., 2015) who prepare nonwovens using a keratin based fibre with properties similar to CFs, i.e. W, in combination with recycled polyester fibres.

From author's acknowledgment, the proposal of using CFs for the development of nonwoven insulation materials with acoustics properties comparable to commercial products, i.e. SW, represents an advance in the search of new routes of valorisation of biogenic CFs waste. So, the aim of this work was to fabricate a new nonwoven acoustic insulation material using conventional textile machinery, characterize their acoustic properties and evaluate the environmental impacts related with their manufacturing process at laboratory scale by means of Life Cycle Assessment (LCA) methodology.

2. Methodology

2.1. Material preparation and acoustic characterization

CFs were supplied by a slaughterhouse located in Catalonia (Spain). CFs as provided by the slaughterhouse are unstable, unsafe and biodegradable. A pre-treatment is mandatory to stabilize and sanitize the waste (Griffith-Patent US, 2002). CFs were first frozen at −20 °C and subsequently washed in a washing machine at 35 °C with a 3300 ppm H_2O_2 solution (hydrogen peroxide 35% weight solution, Chem-Lab NV, Belgium), in a 5/1 (v/w) liquor ratio for 50 min. After that, CFs were dried in an air oven at 60 °C for 24 h. After such process, the appearance of CFs was significantly improved not only in terms of smelling and general look but also in the content of microorganisms. This methodology has been developed and published previously (Casadesús et al., 2018).

CFs fibers previously pretreated as described above were separated from the quill using a Shirley opener (Platt Bros & Co Ltd, North West England, UK). In order to ensure the fibers orientation and their correct separation and cleaning, five passages were performed. After some experiments using a carding machine, the results show that CFs fibers were not long enough to directly obtain a nonwoven material. In order to improve the cohesion, W fibers were added. W is also a keratinaceous fiber with similar characteristics. The used W is categorized as type 2 (Arrebola Molina et al., 2018) and it is already skirted and washed. CFs fibers were mixed with W in a carding machine (Platt Bros & Co Ltd, North West England, UK) in order to promote the fiber alignment and web formation. The obtained nonwoven was quite thick, without need of the cross-lapping step. The single layer of nonwoven was consolidated by means of a needle-punching machine (DILO OUG-II-6, Germany) with two needle-boards separated 12 mm. The stitch depth was 8 mm, and the needle type used was SNF 15 × 18 × 36 RB30 (Ventura et al., 2014). Nonwovens containing 0% (CFs0W100), 10% (CFs10W90), 25% (CFs25W75) and 50% (CFs50W50) of CFs and the corresponding amount of W fibers were manufactured (Fig. A1, see Appendix).

Compositions including more than 50% of CFs were not possible using this method because of the lack of cohesion of the web.

After preparation, the density, weight and thickness of nonwoven materials were determined following UNE-EN ISO 12127:1998 (AENOR, 1998) methodology.

The sound absorption coefficients (α) of the nonwoven materials were determined using the two-microphone impedance tube (Brüel & Kjaer 4206, Denmark) and following the ISO 10534-2 standard (AENOR, 2002). Cylindrical samples with diameters of 29 mm were prepared by cutting the material and then submitted to a plane sound wave. The sound pressures were measured at the same time in two microphone positions and the relationship between the acoustic energy that is absorbed by the material and the total incident energy resulted in the normal incidence sound absorption coefficient. The α coefficient was determined for frequencies in the range of 500–6200 Hz. The influence of the thickness in the sound absorption was measured by preparing samples with a different number of nonwoven layers, located one above the other without any bonding within them.

Measurements of two different specimens extracted from each prepared material were carried out and the average curve of α was reported. As the difference between the duplicates was minimal, this information was not reported since the error bars would overlap with the line of the curve. From the α average curve, the Noise Reduction Coefficient (NRC) was calculated as the arithmetic average of α determined at 500, 1000 and 2000 Hz (Seddeq, 2009) based on ASTM C 423 (ASTM subcomitee, 2018). SW, a product commonly used as insulator in the market, was chosen as a reference, in order to compare the performance of the new materials (Kusno et al. (2017)). The

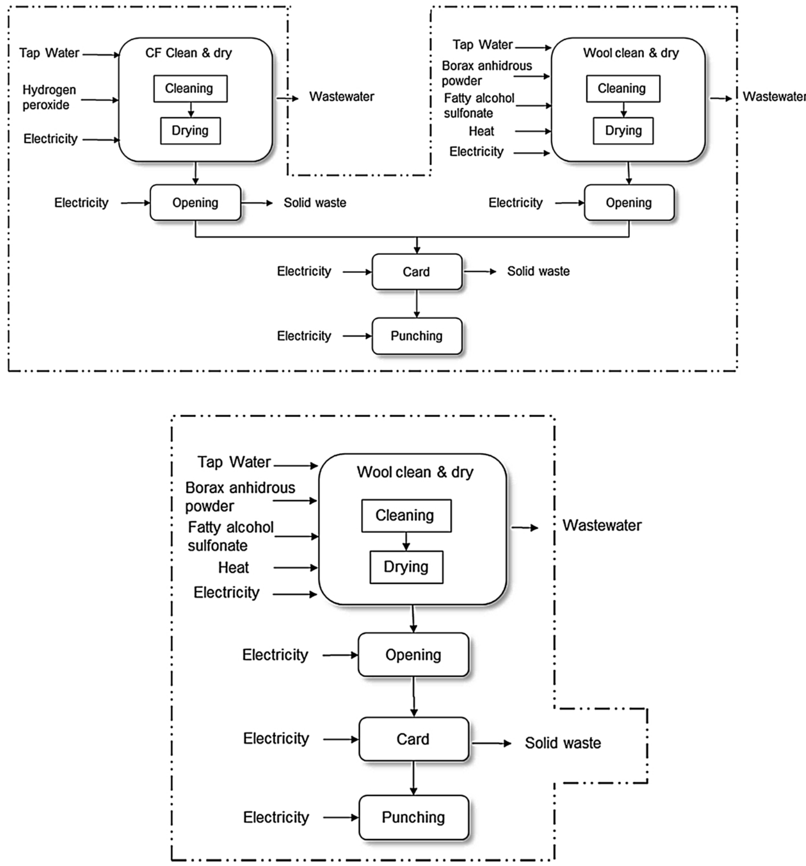

Fig. 1. System boundaries between product system and environment for acoustic insulating materials made with CFs (above) and W (below).

thickness, weight and density of the chosen commercial SW (Arena Isover) were determined by measuring five specimens of the sample.

2.2. Environmental analysis

Environmental analysis was carried out following the four basic phases of the life cycle assessment (LCA) methodology according to ISO 14040 (AENOR, 2006a) and ISO 14044 (AENOR, 2006b): goal and scope definition, Life cycle inventory, Life cycle impact assessment and interpretation. SimaPro 8.03 software, developed by Pré Consultants, was used as a tool to the LCA, using the CML-IA (baseline) method (v3.4) midpoint approach. SimaPro is a software widely used by the scientific community for LCA studies. The CML-IA method is one of the most commonly used methodology to LCA studies and the baseline considers the most common impact categories used in LCA. Also, it aims to provide best practice for midpoint indicators, operationalizing the ISO 14040 series of Standards.

2.2.1. Goal and scope definition, functional unit and system boundaries

The main goal of the LCA study was to assess and compare the nonwoven materials prepared with CFs and W (CFs0W100, CFs10W90, CFs25W75 and CFs50W50) with a conventional SW insulation material in order to evaluate the environmental performance of the new developed materials.

Due to the lack of data regarding to the installation, maintenance, and end-of-life stages, and being the materials a prototype, Cradle-to-Gate approach was considered the most appropriate, so the use and end of life product stages are out of the scope of the study.

The functional unit (FU) is a central element of a LCA. It provides the reference for the normalization of the other data in the product. A meaningful and valid comparison of different products is not possible without a functional unit (European Commission - Joint Research Centre - Institute for Environment and Sustainability (2010)). The European Commission-Joint Research Centre states that the quantitative definition of a product functional unit should refer to technical standards whenever possible and appropriate (European Commission - Joint Research Centre - Institute for Environment and Sustainability (2010)). As pointed by Berardi et al., in case of thermal insulating materials, it is common to use as a functional unit the quantity of material necessary to obtain a given thermal resistance (Berardi and Iannace, 2015). In this case, the environmental impacts are indirectly determined according to the material performance. Conversely, no standard functional unit has been introduced so far in the field of acoustic studies (Asdrubali et al., 2016) and there are only few studies concerning acoustic materials in which the acoustic properties are considered in the definition of the functional unit (Ricciardi et al., 2017; Buratti et al., 2016). To conduct a comparative study of the performance of acoustic insulation materials it seems more appropriate to include the effect of their sound absorption properties (Pedroso et al., 2017) by using the corresponding NRC values.

Based on the aforementioned premises, for the sake of comparability, two functional units were defined and the corresponding LCA study has been carried out. In the former case, the surface (m^2) of an acoustic panel with a sound absorption unit (uA) of 1 metric Sabin was selected as a functional unit (FU = 1 uA). In the second case, a surface-based functional unit was selected, so the FU corresponds to 1 m^2 of acoustic material surface (FU = 1 m^2)

On the one hand, the first FU definition (FU = 1 uA) takes into account the acoustic performance of the different materials in order to make a suitable comparison. So, FU has been calculated using the Eq. (1), where *S* is the surface (m^2); *A* is the sound absorption in metric Sabins (in this case equal to 1 unit), and *NRC* is the Noise Reduction Coefficient:

$$S = A/NRC \qquad (1)$$

The mass of each material needed to perform evenly can be calculated using Eq. (2), where M is the mass (kg), δ is the density (kg/m^3), d is the thickness (m) and S is the surface (m^2) calculated by Eq. (1):

$$M = \delta \cdot S \cdot d \tag{2}$$

Combining **Eqs.** (1) and (2) and considering A = 1 uA, it is possible to express the equivalent mass of each material with the equal sound absorption performance (Eq. (3)):

$$M = \delta \cdot d \cdot \left(\frac{1}{NRC}\right) \tag{3}$$

On the second hand, the additional surface-based FU (FU = 1 m^2) does not consider the acoustic performance of the different materials and only provides information about the amount of material required to obtain a panel with a surface 1 m^2 taken into account only the different density of each material. The mass of each material required to fabricate a 1 m^2 panel has been calculated by using the Eq. (2).

The system boundaries between the product system and the environment for acoustic insulating materials fabricated with a mixture of CFs and W and, alternatively, using 100% of W, are shown in Fig. 1.

As it is shown in the Fig. 1, CFs and W need to be cleaned and dried before opening process to obtain fibres and, consequently, the process will produce wastewater. Nevertheless, such wastewater was considered out of the boundaries of the system due to its low load of pollutants (Molins et al., 2017).

Regarding the issue of allocation rules, the environmental impacts attributed to animal rising were disregarded by the following reasons. On the one hand, according to the Ministry of Agriculture and Fisheries, Food and Environment of Spain, CFs wastes are animal by-products "with little or no commercial value or economic and without viable destination" (Gobierno de España - Ministerio de Agricultura y Pesca Alimentación y Medio Ambiente, 2018). For this reason, the authors have considered that there is not any causal or economic relationship between the raising of poultry (non-functional flow) and the CFs (co-products). All the flows needed for the chickens fattening, as well as the chemicals used for the de-feathering step in the skinning process are only imputable to the chicken meat (Molins et al., 2017). Consequently, those environmental impacts were excluded since they are strictly attributed to chicken meat production. On the other hand, W market has shrunk in several European regions and, nowadays, it is often incinerated as a waste (Berardi and Iannace, 2015). Therefore, similarly to the case of CFs, it has been considered that there is not any causal or economic relationship between the raising of sheep (non-functional flow) and the W (co-products) and, again, those flows needed for fattening, as well as for shearing, are only imputable to meat production. Thus, environmental impacts strictly attributed to sheep meat production were also excluded.

It was considered that, due to its high calorific value, all the solid wastes generated in opening and card processes go to incineration with electricity recovery, modelled based on the methodology documented by Doka. Accordingly, the calculation tool for waste disposal was based on Ecoinvent LCI database v2.1 (Ecoinvent, 2019), with October 2008 corrections (Doka, 2013). The upper and lower heating values are reported in Table 1 and were established using the Dulog's formula according the elemental composition of CFs and W (Marculescu and Stan, 2011; Zahn et al., 1997; Simpson and Crawshaw, 2002), also shown in Table 1.

Table 1
Elemental composition and upper and lower heating values of CFs and W.

	CFs	W
Upper heating value (MJ/kg)	31.3	23.1
Lower heating value (MJ/kg)	29.3	21.6
Chemical composition		
Oxygen (% wt without O from H_2O)	13.5	22-25
Hydrogen (% wt without O from H_2O)	8.6	6.5-7.5
Carbon (% wt all biogenic)	61.5	50-52
Sulfur (% wt)	4.9	3-4
Nitrogen (% wt)	8.8	16-17
Chlorine (% wt)	2.6	–

The background Life Cycle Inventory (LCI) data for the energy and material inputs come from Ecoinvent v3.3 data base (Ecoinvent. 2016) and these sources are shown in Table 2.

The primary data used in this study was obtained from laboratory scale processes carried out following the protocol described in Section 2.1.

2.2.2. Selected impact assessment method

SimaPro 8 software was used to perform the LCA, following the CML-IA baseline 3.04 midpoint approach, excluding infrastructure processes and long-term emissions.

The selected impact categories to assess and compare the different new nonwoven materials made with CFs and W and the conventional SW acoustic panel belong to the CML-IA baseline indicators at "midpoint level" approach, developed at the Institute of Environmental Sciences of Leiden University (PRé, 2018). A short explanation of each IC and the used indicator or characterization factor is presented to provide a basic knowledge of the terms:

- "Abiotic depletion" is related to the extraction of minerals and fossil fuels due to inputs in the system. The Abiotic Depletion Factor is determined for each extracted mineral (kg Sb equivalents/kg extraction units) or fossil fuel used (MJ units) based on concentration reserves and rate of de-accumulation.
- "Climate change" is related to emissions of greenhouse gases to air. The characterization model developed by the Intergovernmental Panel on Climate Change was selected and data are expressed as Global Warming Potential for time horizon 100 years (GWP100a), in kg carbon dioxide/kg emission units.
- "Stratospheric Ozone depletion" causes that a larger fraction of UV-B radiation reaches the earth surface. This IC is output-related and at global scale. The characterization model developed by the World Meteorological Organization defines ozone depletion potential of different gases with the normalized unit kg CFC-11 equivalent/ kg emission.
- "Human toxicity" concerns effects of toxic substances on the human environment, although Health risks of exposure in the working environment are not included. The characterization factor, Human Toxicity Potential, is calculated with USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon. For each toxic substance, Human Toxicity Potential is expressed as 1,4-dichlorobenzene equivalents/kg emission.
- "Fresh-water aquatic ecotoxicity" refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil. Eco-toxicity Potential is calculated with USES-LCA, describing fate, exposure and effects of toxic substances and measures are expressed as 1,4-dichlorobenzene equivalents/kg emission.
- "Marine ecotoxicity" refers to impacts of toxic substances on marine ecosystems (see description of fresh water toxicity).
- "Terrestrial ecotoxicity". This category refers to impacts of toxic substances on terrestrial ecosystems (see description of fresh water toxicity).
- "Photochemical oxidation" evaluates the formation of reactive substances (mainly ozone) which are injurious to human health and ecosystems and which may damage crops. This problem is also indicated as "summer smog" and should not be confused with "winter smog", being the last outside the scope of this category. The indicator Photochemical Ozone Creation Potential for emission of substances to air is calculated with the UNECE Trajectory model and expressed in kg ethylene equivalents/kg emission.
- "Acidification" considers acidifying substances that cause a wide range of impacts on soil, groundwater, surface water, organisms,

Table 2
Primary and background data sources.

Input/process	Data source
Tap water: Tap water (Europe without Switzerland)/tap water production, conventional treatment/Alloc Def, U	(Ecoinvent. 2016)
Hydrogen peroxide: Hydrogen peroxide, without water, in 50% solution state (GLO)/market for/Alloc Def, U	(Ecoinvent. 2016)
Electricity: Electricity, low voltage (ES) market for/Alloc Def, U	(Treyer et al 2016)
Borax anhydrous powder: Borax, anhydrous, powder (GLO) /market for/ Alloc Def, U	(Ecoinvent. 2016)
Fatty alcohol sulfonate: Fatty alcohol sulfate (RER)/ market for/Alloc Def, U	(Ecoinvent. 2016)
Heat: Natural gas, low pressure (CH)/ market for/ Alloc Def, U[1]	(Ecoinvent. 2016)
SW (CH)/SW production/Alloc Def, U	(Ecoinvent. 2016)

[1] 9000 kCal/m^3 of Low calorific value has been supposed.

ecosystems and materials (i.e. buildings). Acidification Potential for emissions to air is calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances. Acidification Potential is expressed as kg SO_2 equivalents/kg emission. The method was extended for compounds such as HNO_3, H_2SO_4, SO_3, HCl, HF, H_3PO_4, H_2S and NO.

- "Eutrophication", also known as nitrification, includes all those impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to air, water and soil. The indicator Nutrification potential is based on the stoichiometric Heijungs procedure (Heijungs et al., 1992), and expressed as kg $PO_4{}^{3-}$ equivalents/kg emission.

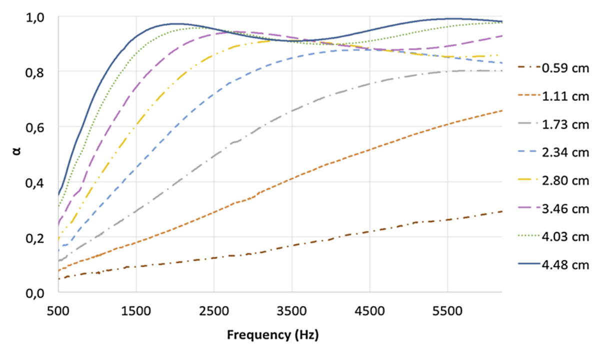

Fig. 2. α values for different thicknesses (in cm) of the CFs50W50 sample.

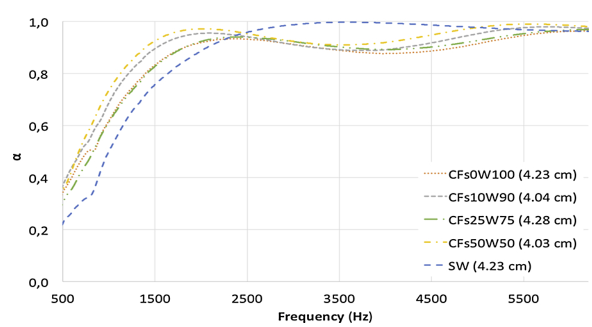

Fig. 3. α results for samples in a 4.20–4.48 cm thickness range.

3. Results and discussion

3.1. Characterization of the nonwoven materials based on chicken feathers

Physical and acoustic properties of CFs-W nonwoven materials of different composition were compared with the properties of a commercial material used for sound absorption (Kusno et al., 2017) such as SW. The density, weight and thickness of the resulted CFs-W nonwovens and SW are shown in Table 3, showing that the density of the CFs-W composites was always higher compared with SW regardless the percentage of CFs used. Nevertheless, it is worthy to note that the density decreases when the amount of CFs increases resulting in lighter materials.

Sound absorption performance was determined by measuring α in the range of frequencies from 500 to 6200 Hz either for 1 or several layers of the material (Fig. 2) and for different composition of CFs (Fig. 3). The results observed corroborated that all the materials behave as a porous insulating material where the sound energy penetrate the material hitting the surface and converting itself to heat energy. In addition, the frequency absorption profile is in agreement with typical porous materials (Doka, 2013), i.e. SW or fiberglass, where α increases proportionally to the frequency up to a maximum. Likewise, Fig. 2 shows that sound absorption is highly dependent on sample thickness since, as expected, α increases with the thickness of the material. When thickness values are higher than 4.0 cm, α reached values above 0.95 at 2000 Hz which is considered an adequate performance of the material in comparative terms with commercial acoustic insulators.

Fig. 3 shows the acoustic characterization of four nonwoven samples containing CFs and/or W with comparable thickness (range of 4.20–4.48 cm) and compares these samples with commercially available SW (4.4 cm thick). Nonwoven materials performed better than SW below 2200 Hz, worse in the 2200–5200 Hz range and similarly for frequencies higher than 5200 Hz. Moreover, comparing the performance of the CFs nonwoven materials with other recycled materials, such as textile recycled fibers or paper waste (Buratti et al., 2016), it was observed that CFs based materials give higher α values.

Absorption profiles for samples with similar thickness were very similar. The NRC parameter was calculated in order to characterize the nonwoven materials and the reference materials (Table 4), but also to compare their characteristics to the ones of other similar materials (Yang et al., 2012; Jayamani and Hamdan, 2013; Fouladi et al., 2013). A higher NRC value was systematically achieved by nonwoven materials despite their density was slightly higher than that of SW.

Table 3
Density, weight and thickness of the fabricated CFs-W nonwovens and commercial SW.

Sample code	Density (kg/m^3)	Weight (g/cm^2)	Thickness of 1 layer (cm)
CFs0W100	27 ± 4	0.018 ± 0.001	0.66 ± 0.05
CFs10W90	23 ± 1.5	0.017 ± 0.002	0.57 ± 0.06
CFs25W75	23 ± 4	0.017 ± 0.002	0.59 ± 0.02
CFs50W50	20 ± 3	0.013 ± 0.001	0.64 ± 0.03
SW	17 ± 0.7	0.076 ± 0.005	4.4 ± 0.2

Table 4
NRC and experimental density for nonwoven materials and reference material.

Sample code	NRC	Density (kg/m^3)
CFs0W100	0.65 ± 0.021	27 ± 3.679
CFs10W90	0.60 ± 0.021	22 ± 1.525
CFs25W75	0.60 ± 0.021	23 ± 4.002
CFs50W50	0.65 ± 0.022	20 ± 2.822
SW	0.55 ± 0.037	17 ± 0.690

Table 5
Thickness and equivalent mass of tested materials for each FU considered compared to SW.

Sample code	Thickness (cm)	FU = 1uA		FU = 1 m^2	
		Surface (m^2)	Equivalent mass (kg)	Surface (m^2)	Equivalent mass (kg)
CFs0W100	4.2	1.6	1.8	1	1.2
CFs10W90	4.0	1.7	1.5	1	0.9
CFs25W75	4.3	1.6	1.6	1	1.0
CFs50W50	4.0	1.6	1.3	1	0.8
SW	4.4	1.9	1.4	1	0.8

Further evidence of the effective sound absorption of CFs/W nonwovens is given by comparing the NRC obtained for a number of different types of natural fibres. It is found that NRCs of ramie, jute and flax are as high as 0.6, 0.65 and 0.65 for samples of 40 mm of thickness (Marculescu and Stan, 2011), which are comparable to the obtained for CFs based samples.

3.2. Life cycle assessment results

3.2.1. Functional unit calculation

As mentioned previously two functional units have been defined for the LCA study. For each of these units, i.e. FU = 1 Absorption Unit (1 uA) and FU = 1 m^2, the equivalent mass (in kg) has been calculated by using Eqs. (3 and 2), respectively, for an acoustic panel of a thickness similar to that of commercial SW. The corresponding values are reported in Table 5.

3.2.2. Life cycle inventory

The Life Cycle Inventory (LCI) comprises the data collection and the adequate calculations to quantify the inputs and outputs of the studied systems, reported to the functional unit. Table 6 shows the LCI flows for the analysed materials and for the two functional units considered.

Regarding to the LCI data shown in Table 6 the following considerations apply: i) most of the data were obtained from the processes carried out in the laboratory with the exception of data related to W cleaning and drying processes, which was obtained from Murphy et al. (Murphy and Norton, 2008); ii) the LCI background data for energy, heat and material inputs (i. e., tap water, hydrogen peroxide, borax anhydrous powder and fatty alcohol sulfonate) come from Ecoinvent v3.3 database (Wernet et al., 2016); iii) data related to the manufacture of SW acoustic panel come from Ecoinvent v3.3 database (Kellenberger et al., 2007). Melting, fiber forming and collecting, hardening and curing furnace, and internal processes were considered as well as transport of raw materials and energy carrier for furnace. Administration, packing and infrastructure were not included; iv) Related to the cleaning and drying CFs processes: the amount of tap water and hydrogen peroxide of the CFs pre-treatment process has been determined by experiments carry out in our laboratory in order to have completely sanitized feathers. The CFs cleaning process was carried out in a conventional washing machine with 5 kg capacity working 102 min at 35 °C. The electricity consumed was measured using a wattmeter (12Wh/kg$_{in}$). The cleaning and drying process yield were determined obtaining values of 96% and 71% respectively. The energy requirements for drying the CFs at 60 °C after cleaning and before nonwoven manufacture have been deducted from the enthalpy balances.

$$Q = m_{dry\ CF}*(h_{CF,out} - h_{CF,in}) + \Sigma m_{dry\ air}*(h_{air,\ out} - h_{air,in}) \tag{4}$$

$$h_{CF} = (C_{CF} + XC_{H20})T \tag{5}$$

$$h_{air} = (C_{aire} + YC_{steam})T + Y\Delta H_v \tag{6}$$

Where:

$m_{dry\ CF}$: mass of dry CFs (kg)
$h_{CF,out}$: enthalpy of CFs at out conditions
$h_{CF,in}$: enthalpy of CFs at in conditions

Table 6
LCI for acoustic insulating nonwoven materials made with W and CFs (10, 25 or 50%), and with 100% of W.

Input	Unit	CFs10W90		CFs25W75		CFs50W50		CFs0w100	
		Amount (FU = 1m^2)	Amount (FU = 1uA)	Amount (FU = 1m^2)	Amount (FU = 1uA)	Amount (FU = 1m^2)	Amount (FU = 1uA)	Amount (FU = 1m^2)	Amount (FU = 1uA)
CFs clean and dry									
Tap water (Cleaning)	L	1.709	2.849	4.314	6.903	7.847	12.752		
Hydrogen peroxide (Cleaning)	kg	0.006	0.010	0.015	0.024	0.027	0.044		
Electricity (Cleaning)	kJ	8.795	14.659	22.201	35.522	40.380	65.618		
Electricity (Drying)	kJ	186.188	310.313	469.989	751.982	854.818	1389.079		
CFs opening									
Electricity	kWh	0.026	0.043	0.066	0.105	0.119	0.194		
Output waste (100% CFs)	kg	0.046	0.077	0.177	0.1872	0.213	0.3458		
W clean and dry									
Tap water	L	5.950	9.917	1.611	2.578	3.039	4.938	8.739	10.196
Borax anhydrous powder	kg	0.071	0.118	0.019	0.031	0.036	0.059	0.104	0.121
Fatty alcohol sulfonate	kg	0.008	0.014	0.002	0.004	0.004	0.007	0.012	0.014
Heat	kWh	0.767	1.278	0.208	0.332	0.392	0.636	1.126	1.314
Electricity	kWh	0.240	0.400	0.065	0.104	0.123	0.199	0.353	0.411
W opening									
Electricity	kWh	0.233	0.389	0.226	0.361	0.119	0.194	0.343	0.400
Card									
Electricity	kWh	0.675	1.125	0.600	0.960	0.426	0.692	0.612	0.714
Output waste[1]	kg	0.027	0.045	0.040	0.064	0.048	0.078	0.024	0.028
Punching									
Electricity	kWh	0.927	1.545	0.830	1.328	0.808	1.313	0.852	0.994

[1] The composition of waste varying depending of the composition of the nonwoven materials.

$m_{dry\ air}$: mass of dry air (kg)
$h_{air,out}$: enthalpy of air at out conditions
$h_{air,in}$: enthalpy of air at in conditions
C_{CF}: Specific heat of CFs (kJ/kg K)
X: water content of CFs (kg water/kg dry CFs)
C_{H20}: Specific heat of water (kJ/kg K)
T: Temperature (K)
C_{air}: Specific heat of air (kJ/kg ºC)
Y: Humidity Ratio (kg water/kg dry air)
C_{steam}: Specific heat of steam (kJ/kg K)
ΔH_v: latent heat of water (kJ/kg);

v) the energy consumption related to opening CFs and W was calculated taking into account the machine power and the process time (5.04 KW and 0.04 h/kg in). The amount of output waste was estimated considering a 33% mass losses for CFs and a 0% for W; vi) the energy consumptions for card and needle-punching processes were calculated from machines power (12.52 kW and 17.3 kW, respectively) and the process time, which varies between 0.04 h/kg_{in} for 100% W nonwovens to 0.06 h/kg_{in} for mixtures of CFs and W. The amount of output waste at card process was 2% for W and 10% for CFs. Incineration of these wastes was considered to model the emissions and electricity recovery based on the methodology documented by Doka (Asdrubali et al., 2016).

3.2.3. Life cycle impact assessment and interpretation

Life Cycle Impact Assessment (LCIA) is the phase in an LCA where the inputs and outputs of elementary flows that have been collected and reported in the inventory are translated into impact indicator results. SimaPro 8 software was used to perform the LCIA, following the CML-IA baseline 3.04 midpoint approach, excluding infrastructure processes and long-term emissions.

In Fig. 4 the environmental impacts are shown for all the investigated materials, connected to the application as a sound insulation material (FU = 1 uA) and to the production of 1 m^2 of panel (FU = 1 m^2). In the Fig. 4, the 100% of each impact category was allocated to the sample with the highest value while the percentages for the other samples were calculated in relation to the highest one. Likewise, the absolute values of each corresponding environmental impact are shown in the Appendix (Tables A1 and A2).

Taking as a reference the functional unit connected to the application of the materials as an absorber panel (FU = 1uA), it can be observed that all the impact categories are higher compared with the obtained for the production of 1 m^2 of panel since the equivalent mass is higher in the former. Nevertheless, the trend described by both functional units is similar since the material and energy balances affecting the LCA analysis are almost proportional to the calculated equivalent mass which in the case of FU = 1 uA was significantly higher by the effect of the NRC parameter.

It can be noticed that, regardless the functional unit, the SW material determines the lowest environmental impacts, except for the following three categories: Abiotic Depletion, Human Toxicity and Photochemical Oxidation. This result was at some extend expected, since many differences could be, at first, ascribed to the synthetic origin of SW. Conversely, environmental impacts related to Ecotoxicity (in fresh water, marine aquatic environments and terrestrial environments) were low or even negligible for SW but of high importance for the developed CFs based nonwovens. Similar values (understood as less than 20% of difference between materials) were found for some impact categories such as Global Warming, Acidification and Eutrophication.

It is worth to mention that, differently to what one may expect before a deep analysis, synthetic SW exhibited lower values than nonwovens made of natural fibres for 7/11 of the environmental impacts of the CML. Moreover, it is important to note that the acidification impact category was about 100% for both SW and CFs10W90 nonwoven material.

The reasons behind the three aforementioned impact categories with high values for SW can be explained taking on account several considerations (Althaus et al., 2017; Schmidt et al., 2004a, b). Abiotic Depletion high values were mainly due to the formaldehyde used in the manufacture of the material and because of the necessary metals to produce formaldehyde from methanol. Human Toxicity noticeable values (5-folds higher than values for nonwoven materials) can be associated to toxic substances used in the SW manufacture (i.e. phenol), and the fuel used for the melting process, in this case, coke. Similarly, the formation of photo-oxidant substances (Photochemical oxidation) was also caused by the use of phenol, formaldehyde and coke in the production of SW.

Focusing the analysis in the nonwovens and considering all the impact categories, it can be said that W is, at least, as polluting as CFs, since for those impact categories where CFs show higher values, differences with W values are very low (i.e. Eutrophication). On the contrary, there are some impact categories with high values for W (i.e.

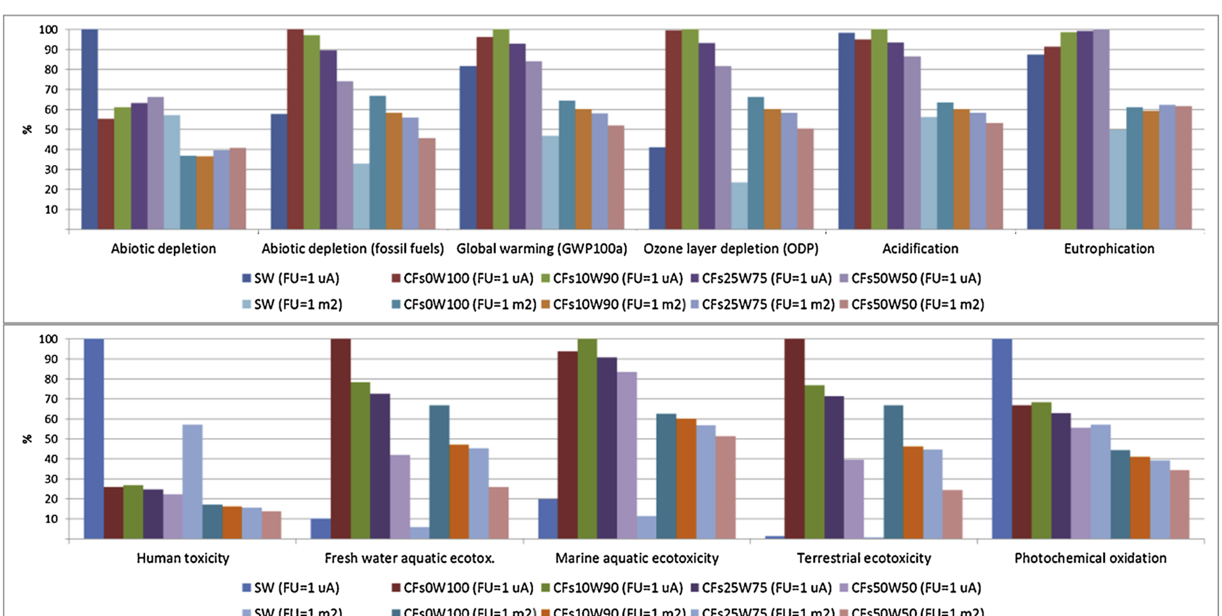

Fig. 4. Environmental impacts (relative values) of the CFs based materials and SW for the two functional units.

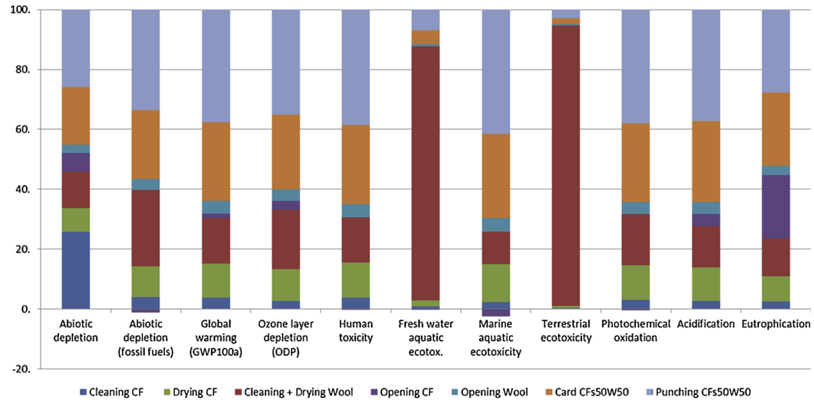

Fig. 5. Process steps affecting each environmental impact for CFs50W50 nonwoven materials.

Table 7
Sensitivity impact assessments: expecting values and coefficient of variation (CV) for CFs50W50 and SW acoustic panels.

		CFs50W50 (FU = 1 uA)		SW (FU = 1 uA)	
Impact Category	Unit	Expected results (95 %)	CV (%) *	Expected results (95 %)	CV (%) *
Abiotic depletion	kg Sb eq	1.36E-07	14	2.12E-07	30
Abiotic depletion (fossil fuels)	MJ	2.03E+01	17	1.65E+01	12
Global warming (GWP100a)	kg CO_2 eq	1.46E+00	8	1.50E+00	9
Ozone layer depletion (ODP)	kg CFC-11 eq	2.10E-07	18	1.10E-07	20
Human toxicity	kg 1,4-DB eq	3.00E-01	38	8.83E-01	65
Fresh water aquatic ecotox.	kg 1,4-DB eq	3.08E-01	34	2.89E-01	49
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.82E+03	31	1.22E+03	61
Terrestrial ecotoxicity	kg 1,4-DB eq	1.88E-02	25	7.15E-04	17
Photochemical oxidation	kg C_2H_4 eq	3.85E-04	9	7.30E-04	13
Acidification	kg SO_2 eq	1.00E-02	10	1.21E-02	7
Eutrophication	kg PO_4^{3-} eq	2.28E-03	37	1.78E-03	34

* 95% confidence level.

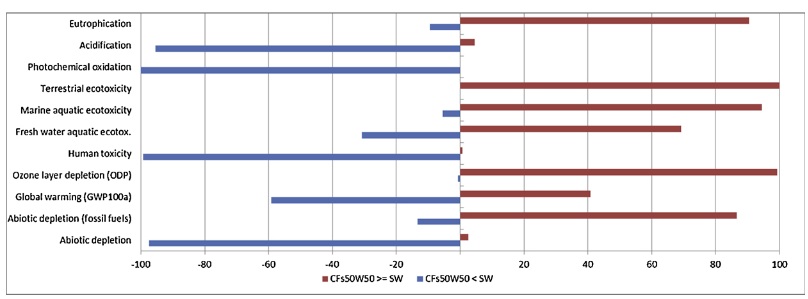

Fig. 6. Comparative Monte Carlo analysis for CFs50W50 and SW acoustic panels.

Fresh Water aquatic Ecotoxicity and Terrestrial Ecotoxitiy but also for Abiotic Depletion due to fossil fuel and Ozone Layer Depletion). These latter impacts are mainly associated with the chemicals used for cleaning W, and mostly, with the energy consumption related also with the card and needle-punching machines and with the drying process applied after washing, as it can be noticed in Fig. 5. In addition, cleaning and drying W step process also determines the Ecotoxicity impact (fresh water and terrestrial). Note that, as the W content in the material decreases, the impacts are also reduced. For instance, due to the reduced amount of W in the CFs50W50 nonwoven, its Global Warming Potential equals that of SW.

Taking as a reference the sound absorption unit (FU = 1uA) and the Global warming impact (GWP100a), CFs nonwovens are better acoustic absorption solution than rice husk, cork scraps, end-life granulated tires and waste paper pressed and glued based materials (Buratti et al., 2018). In this sense, the average GWP100a of CFs based materials is 1,7 kg CO_{2eq} while that of the alternative materials are approximately 3, 10, 11 and 15 kg CO_{2eq}, respectively. These results highlight the potential for manufacturing environmental friendly acoustic products using CFs due to the advantages of processing this waste and to the good behaviour in sound absorption in comparison with other alternative recycled materials.

3.2.4. Sensitivity analysis

As it has been observed in the Fig. 5, the card and punching processes present a great contribution in most of the environmental categories considered, mainly due to the energy consumption. For these reasons a sensitivity analysis was carried out varying the energy consumption of these processes, showing only the values for the acoustic panel of higher CFs content. Taken into account the minimum and maximum energy consumption values for the processes mentioned, a triangular distribution was considered.

Thus, the energy consumption related to the card and punching processes have been varied between 0.51 to 0.75 kW h/kg_{out} and

0.71–1.03 kW h/kg$_{out}$ respectively, been this values the minimum and maximum energy values consumed for the different non-woven materials manufactured.

A Monte Carlo simulation has been made in order to determine the distribution of each studied environmental impact category. The resulting distribution functions allow us to stablish an expected value and a Coefficient of variation (CV; 95% confidence level) for all the impact categories considered. A 700 fixed number of runs was used according to the predefined probability distributions.

Table 7 shows these statistical results for CFs50W50 and SW showing overlapping distributions. In order to determinate if there are a 'real' difference between both acoustic panels, Fig. 6 shows the distribution difference between CFs50W50 and SW for each impact category. If the difference is positive (red bars), CFs50W50 has a higher or equal impact than SW, if the outcome is negative (blue bar), the opposite is true.

It can be observed that CFs50W50 presents a better environmental performance for Acidification, Photochemical oxidation, Human toxicity and Abiotic depletion impact categories, and slightly better performance for Global Warming potential.

4. Conclusions

CFs based nonwovens were fabricated and characterized to explore their ability to be used as new environmentally friendly acoustic materials. It was possible to fabricate CFs-W nonwoven materials with acoustic properties similar to SW, behaving even better for frequencies below 2200 Hz. According to these results, nonwovens incorporating CFs waste and W up to 50% were found to be an alternative to the current porous acoustic absorbents.

Despite its synthetic nature, the SW reference material only presented worse environmental performance than the CFs based nonwovens for few impact categories: Depletion of abiotic resources, Human Toxicity and Photo-oxidant formation. The reason for this quite surprising result is that the energy consumptions of W processing, including drying, carding and needle-punching, determines a high environmental impact for the CFs-W composites. Nonetheless, it is noteworthy to mention that the processing techniques used to implement the nonwoven materials are far from being optimal since there are based on data from laboratory scale. The same is valid for the energy consumption associated to such processes. Consequently, the found environmental impacts can be understood as the worst-case scenario and they are expected to reach lower levels than those reflected in our study at an industrial production scale.

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Appendix A

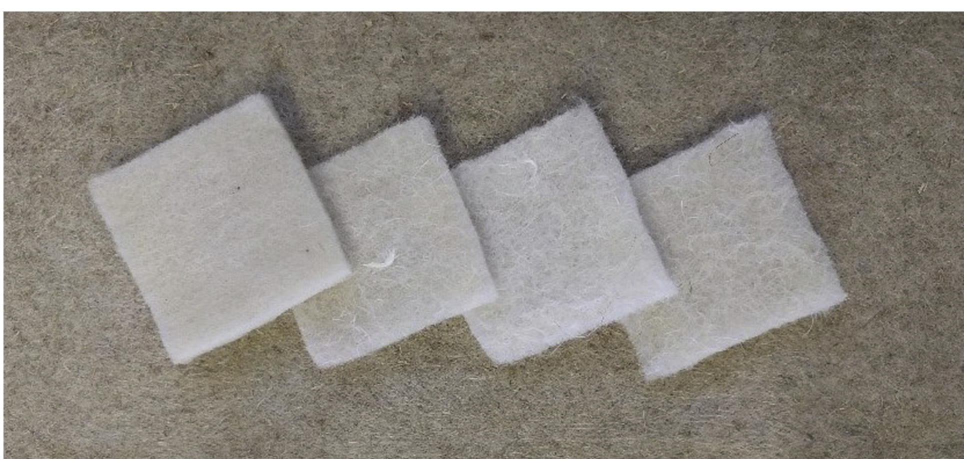

Fig. A1. Appearance of needle punched samples. From left to right: CFs0W100, CFs10W90, CFs25W75 and CFs50W50.

Table A1
Absolute values of the environmental impacts for different samples and two FU (continued on Table A2).

Impact Category	Unit	SW (FU = 1 uA)	SW (FU = 1 m^2)	CFs0W100 (FU = 1 uA)	CFs0W100 (FU = 1 m^2)	CFs10W90 (FU = 1 uA)	CFs10W90 (FU = 1 m^2)
Abiotic depletion	kg Sb eq	2.13E-07	1.22E-07	1.17E-07	7.82E-08	1.29E-07	7.77E-08
Abiotic depletion (fossil fuels)	MJ	1.66E+01	9.49E+00	2.89E+01	1.93E+01	2.80E+01	1.68E+01
Global warming (GWP100a)	kg CO_2 eq	1.50E+00	8.59E-01	1.77E+00	1.18E+00	1.84E+00	1.11E+00
Ozone layer depletion (ODP)	kg CFC-11 eq	1.10E-07	6.30E-08	2.68E-07	1.79E-07	2.70E-07	1.62E-07
Human toxicity	kg 1,4-DB eq	7.71E-01	4.41E-01	1.98E-01	1.32E-01	2.06E-01	1.23E-01
Fresh water aquatic ecotox.	kg 1,4-DB eq	1.17E-02	6.66E-03	1.15E-01	7.67E-02	8.99E-02	5.40E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq	2.72E+02	1.55E+02	1.29E+03	8.59E+02	1.38E+03	8.26E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	6.25E-04	3.57E-04	4.76E-02	3.17E-02	3.65E-02	2.19E-02
Photochemical oxidation	kg C_2H_4 eq	7.37E-04	4.21E-04	4.91E-04	3.27E-04	5.03E-04	3.02E-04
Acidification	kg SO_2 eq	1.21E-02	6.91E-03	1.17E-02	7.79E-03	1.23E-02	7.39E-03
Eutrophication	kg PO_4^{3-} eq	8.47E-04	4.84E-04	8.86E-04	5.91E-04	9.56E-04	5.74E-04

Table A2
Absolute values of the environmental impacts for different samples and two FU (continuation).

Impact Category	Unit	CFs25W75 (FU = 1 uA)	CFs25W75 (FU = 1 m^2)	CFs50W50 (FU = 1 uA)	CFs50W50 (FU = 1 m2)
Abiotic depletion	kg Sb eq	1.34E-07	8.37E-08	1.41E-07	8.66E-08
Abiotic depletion (fossil fuels)	MJ	2.58E+01	1.61E+01	2.14E+01	1.32E+01
Global warming (GWP100a)	kg CO_2 eq	1.71E+00	1.07E+00	1.55E+00	9.53E-01
Ozone layer depletion (ODP)	kg CFC-11 eq	2.51E-07	1.57E-07	2.20E-07	1.36E-07
Human toxicity	kg 1,4-DB eq	1.89E-01	1.18E-01	1.71E-01	1.05E-01
Fresh water aquatic ecotox.	kg 1,4-DB eq	8.35E-02	5.22E-02	4.83E-02	2.97E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.25E+03	7.81E+02	1.15E+03	7.06E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	3.39E-02	2.12E-02	1.88E-02	1.16E-02
Photochemical oxidation	kg C_2H_4 eq	4.62E-04	2.89E-04	4.09E-04	2.52E-04
Acidification	kg SO_2 eq	1.15E-02	7.18E-03	1.06E-02	6.54E-03
Eutrophication	kg PO_4^{3-} eq	9.63E-04	6.02E-04	9.70E-04	5.97E-04

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