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Recovery of electronic wastes as fillers for electromagnetic shielding in building components: an LCA study.

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Abstract: The present study reports the development of sandwich panels for building walls having electromagnetic interference (EMI) shielding abilities. Conductive polymer composites (CPCs) have started being employed as EMI shielding materials. In this paper we propose the use of a conductive polymer composite flat sheet made of high-density polyethylene (HDPE) recovered from municipal solid wastes (MSW) used as polymeric matrix, “doped” with dispersed metal fillers recycled from e-wastes. Test results proved that the recycled metal fillers enhance the electrical conductivity and enable EMI shielding. Different sandwich panels were discussed in the context of building applications, using identical HDPE/metal-filler EMI sheets, but different thermal insulation material (polystyrene and glass wool). The life cycle assessment (LCA) methodology was applied to evaluate the environmental impact generated during the following steps: a) recycling of thermoplastic materials from MSW; b) recovering of metallic components from waste PCB; c) re-use of the recovered components into sandwich panels with electromagnetic shielding properties for buildings. The goal of the LCA was to perform a comparative analysis of the composite sandwich structures manufactured to be used as EMI shielding in buildings applications in order to assist the materials selection and eco-design. By means of the LCA results it was possible to manufacture a building component with good EMI shielding properties and reduced environmental impacts.

Keywords: electromagnetic shielding; waste recovery; thermal insulation; recycling; polymer; metallic filler.

Notation

BDS	Broadband Dielectric Spectrometer
BFR	Brominated Flame Retardants
dB	decibel
CML	Leiden University Institute of Environmental Sciences
CPC	Conductive Polymer Composites
EM	ElectroMagnetic
EMI	ElectroMagnetic Interference
f.u.	LCA functional unit
GWP	Global Warming Potential
HDPE	High-Density PolyEthylene
ISO	International Organization for Standards
LCA	Life Cycle Assessment
MSW	Municipal Solid Wastes
PCB	Printed Circuit Boards
ReCiPe	Reduced Energy Consumption in Plastics Engineering
RoHS	Restriction of Hazardous Substances
SE	Shielding Effectiveness
S (Ω^{-1}, ℧)	Siemens is the derived unit for electrical conductance, susceptance and admittance that are reciprocals of resistance.
SEM	Scanning Electrom Microscopy
TMO	Transition Metal Oxides
WEEE	Waste Electrical and Electronic Equipment
w/o	weight percentage

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1. Introduction

Over the last 50 years, the increase in population and industrialization has increased the demand for electrical and electronic equipment (EEE) such as cell phones, printers, televisions, and personal computers with the increasing of societal living standards [1]. But when it comes to the disposal of such electronic devices, many concerns arise due to the content of some toxic metals which have severe human health and environmental effects if they are not disposed of carefully [2,3]. Therefore, such electronic wastes (e-waste or WEEE) require a proper management both for environmental protection and economic savings, considering that most metals are valuable materials if they are recovered and reused. Developed countries differ from developing countries in respect to e-waste as in developing countries threats from inadequate handling are greater, formal recycling systems are lacking and recycling legislations are either weak or absent [4]. Many studies exist in this topic as reported in a comprehensive literature review conducted by Ikhlayel in 2018 [5]. Here the author recommends the application of a systematic integrated e-waste management (IEWM) for developing countries as a necessary alternative to the existing approach. The European Directive on WEEE (European Union, 2012) aims at reducing the disposal of wastes and promotes efficient use of resources by reuse, recycling and other forms of recovery of such waste.

However, the integration of the materials, components and structures does not make for ease of recovery of the metals, polymers, ceramics, etc.

1.1 Novelty of the work

The study we present hereafter fits very well into this contest as we propose a possible recovery solution for metal components from e-waste and their reuse in the production of an innovative composite material where the use of recovered metals brings both benefits of enhancing the final properties and reducing the environmental burdens. We studied and tested a possible process to recover metals from printed circuit boards (PCB) and reuse them in the production of conductive metal-thermoplastic panels that are proved to act as ElectroMagnetic Interference (EMI) shielding materials [6]. ElectroMagnetic Interference (EMI) shielding materials prevent penetration or leaking of electromagnetic radiation from enclosures [7]. The rapid development of the electrical industry has led to EMI becoming a serious problem in modern society. EMI not only causes operational malfunction of electronic instruments but can be harmful for humans under certain circumstances. Many diseases such as leukaemia, miscarriages, breast cancer, are correlated to continuous exposure to ElectroMagnetic (EM) fields. Effective shielding is of primary importance to protect the indoor and outdoor environments from unwanted electromagnetic waves. It is particularly needed for the buildings containing power transformers, mobile communications and other electronic facilities [8]. Research studies on new materials solutions with good electromagnetic interference shielding effectiveness are very current [9-11].

Recently, conductive polymer composites (CPCs) have started being employed as EMI shielding materials owing to their low cost, strong resistance to corrosion, lightweight and good processability in comparison with conventional metals. The electrical conductivity (σ) of polymers can be enhanced by the addition of conductive fillers developing CPCs with EMI shielding properties. The maximum fraction of conductive fillers was reported to be 10 wt%; greater concentrations can lead to poor dispersion of particles and increase the viscosity of the polymer [12,13].

In the present study we propose the use of HDPE recovered from MSW as polymer matrix to produce a conductive polymer composite flat sheet by addition of dispersed powder rich in metals, recovered from waste PCB boards. Recovering and reusing HDPE from MSW is a realistic practice due to the good resistance of this thermoplastic material. For example, studies on the addition of asphaltenes in HDPE have shown that introduction of up to 4% of filler to the polyethylene matrix does not significantly change the physical-mechanical properties [14].

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1.2 Why LCA

LCA methodology was applied to evaluate the environmental impact of the materials under study. We selected the LCA method as it is recognized as the most effective tool in line with the recent Circular Economy (CE) [15] principles, referring to the challenges of resource scarcity, environmental impact or economic development, to promote a transition from a “Cradle to Grave” approach which means from materials extraction, manufacture use and waste production to a “Cradle to Cradle” approach in a “closed loop”, where the wastes produced become itself nutrient for the next cycle.

Circular Economy Facilitates UN Sustainable Development Goals. The practice of recycling waste materials and reusing them in new products encounters the principles of circular economy towards the SDG goals [16].

As this paper covers different topics it was necessary to arrange them into a clear structure, as follows: section 2 describes the LCA methodology and the application to the present case study; section 3 presents the experimental program including testing results and data collection for the life cycle inventory analysis; section 4 provides the life cycle impact assessment results and discussion and section 5 reports the conclusions.

2. LCA methodology

LCA was applied according to the ISO standards 14040-44:2006 [17,18] that define the following phases: 1) Goal and scope definition; 2) Life Cycle Inventory (LCI) analysis; 3) Life Cycle Impact Assessment (LCIA); 4) Life Cycle Interpretation. In particular, all data collected and used for the LCI were loaded into SimaPro v.8.3 [19] accessing the Ecoinvent database v.2.2. The ISO standard allows the use of impact category indicators that distinguished into two levels: the “mid-point” level and the “endpoint” level. In general, indicators that are chosen close to the inventory result have a lower uncertainty, as only a small part of the environmental mechanism needs to be modeled, while indicators near endpoint level can have significant uncertainties. However, indicators at endpoint level are much easier to understand and interpret by decision makers than indicators at midpoint. In this study we used the CML2000 mid-point level indicator and the Recipe H/A endpoint level indicator. It is important to point out that the LCA provides a model that is a simplification of a complex reality. The present application can be considered a good approach for of eco-design as it gives information on materials selection and process optimization to improve existing products and the development of new products. In this way, an LCA study can be performed to assess the environmental impact e.g.: of a company-internal product improvement, product development or technical innovations.

2.1. Scope & goal definition

In this phase it is needed to identify the objectives of the study and the system boundaries in order to avoid omitting relevant parts of the system to be investigated.

The goal of the present LCA was to perform a comparative analysis of the composite sandwich structures manufactured to be used as EMI shielding in buildings applications in order to assist the materials selection and eco-design.

Moreover, at this stage of the assessment, the Functional Unit (FU) is required to be chosen.

2.2. Functional unit and system boundaries

Cradle-to-gate analyses for two different EMI shielding systems were carried out. The functional unit is defined as the material assembly used for the production of one sandwich with dimensions 700 mm square by 2.5 mm thick with EMI shielding properties. According to the ISO 14040-44, an inventory analysis was carried out for each system under investigation to quantify the environmentally significant inputs and outputs by means of mass and energy balance.

As shown in fig. 1, the system boundaries include the following processes:

- Recovery of HDPE from MSW;
- Recovery of metallic components from PCB waste;
- Production of the metal-modified composite through extrusion and injection moulding;
- Assembly of the sandwich shielding panels for building applications.

Figure 1. System boundaries: recovery of HDPE from MSW; recovery of metallic components from PCB waste; processing of the metal-HDPE sheet through extrusion; production of EM shielding panels for buildings.

2.3. Life Cycle Inventory Analysis

Primary data, literature data and Ecoinvent v2.2 database were used as following:

- HDPE from MSW: primary data were collected from the company All Green AS;
- Metal-powders from PCB: inventory data were taken from the Ecoinvent database and at laboratory scale;
- Metal-HDPE flat sheet production: primary data were collected at laboratory scale;
- EMI shielding sandwich panels: inventory data were collected at laboratory scale. Two different panels were produced.

3. Experimental

3.1. Metallic components recovered from wasted

PCB usually consist of glass fibres in an epoxy resin matrix with various microscale metal features, posing a significant challenge to separate them during recycling. The thermoset polymers used in PCB do not melt even with the application of extreme heat. Further, brominated flame retardants (BFR) in resins, make combustion difficult and such disposal can generate toxic gases. Therefore, PCB pose a great recycling issue [20] so some form of re-use is preferable for discarded personal computers, etc.

Nevertheless, the metal content is very high (about 70% weight, as reported in www.wrap.org) and this makes PCB wastes a rich metal source. Furthermore, after the RoHS directive in 2006 [21] the use of lead (Pb) in solder has decreased. If cadmium and lead contents exceed the limits allowed under legislations, the PCB can be classified as hazardous waste as they can potentially cause significant contamination of soil, groundwater and surface water by heavy metals (lead and cadmium) if the boards and components are not correctly disposed of [22-25]. Locking the non-volatile/non-leachable wastes in (clearly labelled) building products is preferable to disposable in moist landfill where the toxic material could escape to the ecosystem.

New lead-free solders mainly composed of Sn 95.5%, Ag 3.8%, Cu 0.7%; Sn 96.1%, Ag 2.6%, are now in practice [26].

The present study is considering a lead-free PCB sample with high content of iron oxide. The metallic parts of PCB were manually separated from the plastic component and were ground using a SPEX mill, 8000M series. The milling time was 4 h, using a rotation speed of 875 cycles/min. Metal-plastic powders at a size ranging between 100-200 μm were obtained. Fig. 2 shows the different processing steps.

Figure 2. The process steps to obtain the metal-powder from PCB

For the Life cycle Inventory Analysis, the following data were collected:

- Materials: (1 m^2 of waste PCB, weighing 3.08kg).
- Milling: the electricity used for grinding was calculated.
- Metal-particles obtained: (2.7 kg of metallic powder and 0.38kg of other waste).

The metal distribution of the recovered powder was analysed using a Scanning Electron Microscope (SEM) at magnitude of 5000x coupled with an X-ray diffraction spectrum and reported in Fig. 3. An elemental analysis was also carried out by means of an X-ray fluorescence spectrometer (WDXRF S8 Tiger Bruker) to check the metallic distribution in the PCB powder. Results are reported in table1.

Figure 3. (a) SEM image for magnitude 5000x and
(b) X-ray diffraction spectrum of the metal-powders.

Table1. Elemental analysis. Distribution of the metallic content in the PCB powder by means of an X-ray fluorescence spectrometer (WDXRF S8 Tiger Bruker) test.

Formula	Molecular weight	Concentration (%)	Pick with highest intensity	Signal intensity	Statistic error (%)
CaO	20	26,26	Ca KA1-HR-Tr	25,2	0,625
Fe_2O_3	26	16,72	Fe KA1-HR-Tr	15,72	0,409
CuO	29	14,95	Cu KA1-HR-Tr	13,9	0,657
SiO_2	14	13,69	Si KA1-HR-Tr	12,7	1,61
SnO_2	50	8,95	Sn KA1-HR-Tr	7,93	0,865
BaO	56	4,39	Ba LA1-HR-Tr	3,39	2,73
Br	35	3,10	Br KA1-HR-Tr	3,105	0,504
ZnO	30	3,61	Zn KA1-HR-Tr	2,61	0,652
MnO	25	2,88	Mn KA1-HR-Tr	1,88	1,27
NiO	28	12,57	Ni KA1-HR-Tr	1,57	2,06
ZrO_2	40	0,89	Zr KA1-HR-Tr	0,532	1,22
SrO	38	0,61	Sr KA1-HR-Tr	0,605	1,24
Ag	47	0,38	Ag KA1-HR-Tr	0,38	8,77

3.2. Polymer recovered from MSW

The recycling process of HDPE (performed by SC All Green SRL (Romania), is schematically illustrated in fig. 4. The electricity consumption data, required for the inventory analysis, is in table 2.

Figure 4. Schematic representation of the HDPE recycling process.

For the LCA, the functional unit (f.u.) chosen was the mass of mixed plastics from MSW processed during 1 batch (350 kg) for the duration of 1 h. All the required inventory data was collected according to the chosen f.u. and listed in table 3.

The dielectric analysis will the subject of a future paper.

3.3.1. Life Cycle Inventory for the metal-particle modified HDPE panel production

Primary data were collected at laboratory scale. The functional unit was one 700 mm square by 2.5 mm thick panel with materials data reported in table 4.

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Table 2. Calculation of the electricity demand for each step of the process. The power of each device is expressed in kW/h.

No	Type	kW/h
1	Belt conveyor	0.5
2	Dispositive to remove the label	17.2
3	Belt Conveyor with Metal Detector	0.5
4	Crushing	18.5
5	Screw absorption device	3
6	Decontamination container with screw	5.5
7	Friction Device	7.5
8	Washing tank (I)	3
9	Washing tank (II)	3
10	Dewatering by centrifugation	15
11	Drying device (I)	3
12	Drying device (II)	3
	Total electricity consumption	**79.7**

Table 3. Life Cycle Inventory data of the process to recover HDPE from MSW at the plant.

Item	Quantity	Assumptions
Waste plastic mix	350kg (250kg of HDPE)	All the plastic is recovered. Only recovery of HDPE is considered with 100% allocation
Electricity consumption	79,7 kW	Calculated for the processing duration of 1 h
Water consumption	12,045 m^3	The water is destined to wastewater treatment after use
Non-recovered mat	5kg	Waste production
Transportation	<40km	The waste collection from the municipal area

Figure 6. Evolution of the dielectric constant eps': **a**) As a function of frequency for different temperatures; **b)** At 1.00E+07 Hz for different % of metal micro-fillers recovered from the PCB wastes.

Table 4. Preparation of the CPC panel.

Input	Quantity
HDPE from MSW	0.775 kg
Metallic powder from PCB	0.1 kg
Injection moulding	0.875 kg

3.4. The suggested EMI shields

3.4.1. EMI shielding effectiveness

Shielding effectiveness (SE) measures the capability for the material to attenuate the intensity of EM waves [27]. The EMI shielding mechanism depends on the absorption of the EM energy, the material surface reflection and the multiple internal reflections of the EM radiation. For adequate shielding behaviour, the shielding material must have electrical conductivity in the range 10^{-4} to 10^{1} S/m [28,29].

In this work, two sandwich material assemblies were produced and tested: Shield type 1, illustrated in fig. 7(a-d), consists of the metal-particle modified HDPE sheet (thickness 2.5mm), glass wool (thickness 95mm) as thermal insulating material, adhesive and an aluminium foil (thickness: 20μm) to enhance the EMI shielding ability. Shield type 2 consists of the same metal-particle modified HDPE sheet (thickness 2.5mm), a polystyrene sheet (thickness 50mm) as thermal insulating material, adhesive and aluminium foil (thickness: 20μm) to enhance the EMI shielding ability.

In all cases, the metallic particles provide the EMI shielding ability due to the increased electrical conductivity of the studied sandwich components.

Figure 7. *(1)* Schematic representation of the Shield type 1: a) CPC sheet; b) Glass wool; c) adhesive; d) aluminium foil. *(2)* Snapshots from the fabrication of the EM shield type 1.

The EMI shielding effectiveness of the developed sandwich panels were studied by measuring signal attenuation (decibel, dB) in an anechoic chamber employing an antenna Horn 3115, at a frequency of 10 GHz, according to the standard EN 50147-1.

The optimum attenuation value (-48.3dB) for the Shield type 1, was obtained when the HDPE surface is oriented towards emission. For the Shield type 2, the strongest attenuation value (-42.7dB) was recorded with the HDPE surface oriented towards reception**.** The apparatus used is shown in fig. 8. In both cases, there is additional attenuation within the panel to complement reflection from the aluminium foil.

Figure 8. Apparatus used for the attenuation measurements according to the standard EN 50147-1 on shield effectiveness.

The obtained SE values are within the range of EMI shielding performance reported in the literature. Singh et al., 2014 [30] reported EMI shielding performance of 0.1, 0.5, 1.0, 5 and 10 wt% transition metal oxide (TMO) filled PVA composites prepared by the solvent casting method. Measurements were conducted in the 4-12 GHz (C band<8 GHz<X band) frequency regimes with minimum reflectivities reported in Table 5.

Table 5. EMI shielding effectiveness reported by Singh et al for 10w/o TMO filled PVA[30]

Filler	Formula	Minimum reflectivity (dB)	Frequency (GHz)
Iron (ferric) oxide	Fe_2O_3/PVA	−38.85 dB	10.4 GHz
Zinc oxide	ZnO/PVA	−33.65 dB	10.4 GHz
Zirconium dioxide	ZrO_2/PVA	−24.90 dB	11 GHz
Titanium dioxide	TiO_2/PVA	−32.90 dB	9.76 GHz
Silicon dioxide	SiO_2/PVA	−41.90 dB	10.4 GHz

3.4.2. Life Cycle Inventory of EMI shielding systems.

The Inventory data of the two studied EMI shields are presented in table 6.

Table 6. Inventory data of the two 700 mm square EMI shielding systems: type 1 and type 2.

Materials	Thickness	Weight (g)
Electromagnetic shield type 1		5051
1 metal-composite panel	2.5 mm	875
Glass-wool mat	95 mm	3950
Binder		200
Aluminium sheet (ρ = 2710 kg m^{-3})	20 μm	26
Electromagnetic shield type 2		2520
1 metal-composite panel	2.5 mm	875
Expanded polystyrene (ρ = 20 kg m^{-3})	50 mm	500
Binder		200
Cement		600
Steel grid		350

4. Life cycle impact assessment

4.1 Results

The first LCA run carried was the calculation of the impact during the recycling of mixed plastics derived from MSW. In the network of fig. 9 a schematic output depicts the quantities of materials and electricity required to obtain 1 kg of recycled HDPE. The numbers, expressed as percentage (%), are related to the GWP (Global Warming Potential) impact for each step. The box marked with green lines indicates the avoided impact due to the reuse of HDPE, meaning that most of the impact is compensated by the recovery and re-use of HDPE.

Figure 9. Network of the HDPE recycling process. GWP contributions evaluated through CML 2000. The avoided impacts due to the HDPE recovery is reported in green.

Fig. 10 is a flowchart containing both impact types, generated and avoided, during the recycling process. The created impacts (values above zero, in the upper part of the flowchart) are mainly associated to the electricity consumption during the recycling process (light-blue bars) The avoided impacts (values below zero, in the bottom part of the flowchart) are associated to the materials recovery (HDPE).

In order to calculate the reduction of the impacts due to the recycling process of HDPE a comparative assessment shown in fig. 11 compares recycled and virgin HDPE (obtained from the Ecoinvent database). Single point damages were reported according to the ReciPe endpoint method, where the strongest damage reduction is associated to the resources section: the use of recycled HDPE eliminates the use of virgin raw material.

Figure 10. Impact categories evaluated for the HDPE recycling process.

The network of fig. 12 is a schematic representation of the impact associated to the production of one metal-modified HDPE sheet obtained by using recycled HDPE and metallic powder. GWP contributions, for each step involved, are expressed in percentage (%). The avoided impacts (green

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boxes) are evaluated for the recovery of HDPE (-48,5%) and for the recycling of printed circuit boards (-99,3 %). The positive impacts (created impacts, red boxes) are associated to the recycling processes (the grinding of PCB to obtain the metal powder; the recycling of HDPE) and to the injection moulding process used to develop the metal modified recycled HDPE sheet.

Figure 11. Damage impacts associated to the use of 1 kg of recycled HDPE and 1 kg of virgin HDPE. Method ReciPe Endpoint.

Figure 12. Network of the production of one composite panel containing recycled HDPE and recovered metal powder from PCB. GWP contributions evaluated through CML 2000. The avoided impacts are given in green.

The impacts associated to the EMI shields, type 1 and type 2, are reported in figs 13 and 14. Figure 13 is the network of the processes involved in the production of the EMI shield type 1 showing the GWP contributions evaluated through CML 2000. The major contributions are associated to the metal-HDPE panel (32.4%) and to glass wool met (62%). Figure 14 is the network of the processes involved in the production of the EMI shield type 2. The major contributions are associated to the metal-HDPE panel (47.7%), the polystyrene foam (32.2%) and steel (9.51%).

Figure 13. Network of the processes involved in the production of the EMI shield type 1. GWP contributions evaluated through CML 2000

Figure 14. Network of the processes involved in the production of the EMI shield type 2. GWP contributions evaluated through CML 2000.

Figure 15. Comparative impact results of all categories for EMI shields, type 1 and type 2. Method CML 2000.

Figure 15 reports a comparative analysis of EMI shields type 1 and type 2 by means of the CML2000 characterization method. All impact categories result higher for type 1. The quantitative evaluation of GWP reported in table 7 shows that 6,43 kg CO2 eq are released in the case of type 2 while 9,48 kg CO2 eq are involved for type 1. The major contribution to this result was the use of glass wool mat (5,88 kg CO2) in type 1. Glass wool mat was used in type 1 in order to provide thermal insulation properties to the structure whilst in type 2 polystyrene was used which contributed for 2.07 kg CO_2 eq. However, type 1 performed better in EMI shielding, due to the presence of aluminium foil in the sandwich structure.

4.1.1 Uncertainty

LCA results deal with uncertainty. Quantity uncertainty is present for any data used in the inventory and the impact assessment. In this study characterization factors (CFs) from LCIA methods that are currently provided without uncertainty ranges, are reported. Uncertainty is also induced by the methodological choices e.g.: related to the goal and scope of the study, such as the definition of the functional unit, cut-off rule, allocation rule. In this study no allocation was required and the cut-off rule of 1% was applied. Finally, in this comparative LCA the compared systems use the same background processes and therefore a common propagation of uncertainty from the background is expected.

Table 7. Quantitative contribution of each process for the total impact on GWP of the production of the two EMI shielding systems, type 1 and type 2. Method CML 2000.

Item	**Database**	**Unit**	**EMI type 2**	**EM type1**
Total of all the items		kg CO2 eq	6,43	9,48
HDPE bottles E	Industry data 2.0	kg CO2 eq	2,42	2,42
Polystyrene foam slab, at plant/RER S	Ecoinvent system	kg CO2 eq	2,07	x
Injection moulding/RER S	Ecoinvent system	kg CO2 eq	1,16	1,16
Printed wiring board, through-hole, lead-free surface, at plant/GLO S	Ecoinvent system	kg CO2 eq	0,76	0,76
Steel, low-alloyed, at plant/RER S	Ecoinvent system	kg CO2 eq	0,61	x
Cement, unspecified, at plant/CH S	Ecoinvent system	kg CO2 eq	0,46	x
Adhesive mortar, at plant/CH S	Ecoinvent system	kg CO2 eq	0,22	0,22
Electricity, medium voltage, production RO, at grid/RO S	Ecoinvent system	kg CO2 eq	0,17	0,17
Electricity, low voltage, production RO, at grid/RO S	Ecoinvent system	kg CO2 eq	0,03	0,03
Tap water, at user/RER S	Ecoinvent system	kg CO2 eq	0,01	0,01
Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH S	Ecoinvent system	kg CO2 eq	0,00	0,00
HDPE resin E	Industry data 2.0	kg CO2 eq	-1,48	-1,48
Wastewater treatment, other emissions	LCA Food DK	kg CO2 eq	-	-
Recycled HDPE	PCB waste	kg CO2 eq	-	-
Metal powder	PCB waste	kg CO2 eq	-	-
metal-HDPE panel	PCB waste	kg CO2 eq	-	-
EMI shield type 2	PCB waste	kg CO2 eq	-	x
Glass wool mat, at plant/CH S	Ecoinvent system	kg CO2 eq	x	5,88
EMI shield type1	PCB waste	kg CO2 eq	x	-
Aluminium, primary, at plant/RER S	Ecoinvent system	kg CO2 eq	x	0,31

4.2 Discussion

According to the LCA results, it seems that the EMI shielding sandwich under study needs to be optimised in order to perform adequately as EMI shields with the least environmental impact. One way to achieve this could be the reduction of the amount of glass wool in Shield type 1. A hypothetical evaluation is reported in fig. 16 where a new Sandwich panel (type 3) containing half amount of glass wool is analysed. As can be seen, all kinds of impact are significantly eliminated. EMI shielding properties remain unaffected by the reduction of glass wool, however thermal insulation may be influenced.

Figure 16. Comparative impact results of all categories for EMI shields type 1 and type 2 and a hypothetical type 3 containing half the amount of glass wool. Method CML 2000.

Table 8, taken from literature, reports interesting data for several materials used as insulators for building. Rock wool (assumed to behave similarly to glass wool) has a low thermal conductivity and very low primary energy demand and GWP compared to expanded polystyrene and polyurethane. This means that glass wool in Shield 1 was a good choice. However, the glass wool generated a significant impact because of its increased thickness.

Table 8. LCA results of several insulation materials, from Zabalza et al., 2011[31]

Building product	**Density Kg/m3**	**Thermal conductivity (W/mK)**	**Primary energy demand (MJ-Eq/kg)**	**Global Warming Potential (kg CO2-Eq/kg)**	**Water demand (1/kg)**
EPS foam slab	30	0.0375	105.486	7.336	192.729
Rock wool	60	0.04	26.393	1.511	32.384
Polyurethane rigid foam	30	0.032	103.782	6.788	350.982
Cork slab	150	0.049	51.517	0.807	30.337
Cellulose fibre	50	0.04	10.487	1.831	20.789
Wood wool	180	0.07	20.267	0.124	2.763

The insulating material thickness is a critical parameter to provide thermal resistance in buildings. Table 9 reports the thermal resistance evaluated for the Shield containing polystyrene and the Shield containing glass wool. As the two insulating materials possess similar thermal conductivity, they are expected to provide similar thermal resistance when the thickness is similar. Since in Shield type 1 the thickness of glass wool is approximately double the thickness of polystyrene of Shield type 2, a glass wool panel of half the thickness, i.e. 0.5 m, was tested. This new system (type 3) exhibited weaker thermal resistance than type 2, but the environmental impact was much lower as shown by fig. 16.

The choice of the functional unit is crucial for LCA evaluation as the results may change considerably. In this paper, on one hand, Shield type 2 and 3 employ the same functional unit as they are both EMI shields with similar thermal resistance values i.e. ranging from 12.4 to 13.5 m^{2}k/W. Thereby, the corresponding LCA outputs are comparable. On the other hand, for Shield type 1, the functional unit is defined as an EMI shield with thermal resistance equal to 22.5 m^{2}k/W. In such case, LCA outcomes of Shield 1 are not comparable with the other two Shield cases. Obviously, excluding the thermal properties from the functional unit definition and referring solely to the EMI properties, all three Shield types will be comparable in terms of LCA.

Table 9. Thermal resistance for the insulating materials used in the structure of EMI shields.

	Thermal Conductivity (W/mk)	Thermal resistance (m^{2}k/W)	ess (m)
Polystyrene	0.037	13.5	0.5
Glass wool	0.04	22.5 12.5	0.95 0.5

One disadvantage of using glass wool instead of polystyrene might be the weight as the density of glass wool is higher and for some applications this can be a hurdle. Another solution of environmental-friendly insulating material could be cork instead of glass wool, but in this case, the total cost will increase. It is noteworthy that an earlier LCA proved that cork has very low environmental impact when employed as natural insulating material for building applications [32]. Also, cork performs well in terms of fire resistance [33] but it is a very expensive material and the cost is obviously a factor that cannot be disregarded.

The case study reported in this paper can be considered an addition to the existing literature in this field. A recent review on LCA application in WEEE management from Ismail and Hanafiah, 2019 [34] reports, as consideration from the authors, that different studies evaluated different WEEE management strategies with different objectives along with different research subjects, even for similar research scope. For an example, under the research scope that evaluated final disposal strategies for WEEE (i.e., evaluation of recycling, recovery and disposal strategies for WEEE), the management strategies discussed were unique from one study to another, and this make it difficult to compare, even if similar research subject was selected for comparison [34]. This is still a limit of the LCA method.

4. Conclusions

This study investigated the development of electromagnetic shielding and thermal insulating components for building applications, employing recovered polymers and metal fillers from municipal solid wastes and printed circuit boards, respectively. Two different components were studied in terms of shielding effectiveness (primarily) and thermal insulation (secondarily), built into a sandwich assembly: Sandwich type 1 and Sandwich type 2. The two component types were evaluated in terms of electromagnetic shielding effectiveness and thermal insulating ability whereas the involved materials and processes were evaluated using life cycle assessment.

The sandwich components feature a polymeric sheet made of recycled HDPE, sourced from MSW and modified (doped) with 10w/o metal particles recovered from lead-free waste printed circuit boards. The metal particles are fundamental to the shielding effectiveness of the sandwich components.

Sandwich type 1, containing glass wool, performed better in terms of electromagnetic attenuation and was the preferred choice. However, the LCA comparison revealed a high environmental impact due to the high thickness of the glass wool layer. Since the EMI shielding is not influenced by the thickness of the glass wool, a third system (type 3) fabricated with half the thickness of glass wool was evaluated with LCA. The thermal conductivity for Sandwich type 3 was similar to that of Sandwich type 2, however the overall environmental impacts were significantly reduced.

This study remarks the importance of the choice of the correct functional unit in LCA applications as the results may change considerably.

The paper we present here does not deal with methodological innovation, as we use the standard LCA methodology applied to a case study. Nevertheless, this case study can be considered an example of eco-design useful in the phase of material selection for the manufacture of new products. Data collection for the inventory analysis was included in the experimental section (section 3) in order to remind that the environmental assessment of a product should be used as a characterization method together with the other characterization methods (e.g.: physic-chemical, mechanical, thermal, electrical etc.) to allow a full understanding of the materials under study.

Finally, this paper represents an interesting contribution to the growing literature on WEEE recyclable and reuse processes as increasing the variations of LCA studies provides increasing support to quantify and assess environmental impact of various product systems within the complex WEEE management.

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References

[1] Sunbal Siddique and Abdullah Siddique, 2019. History and Major Types of Pollutants in Electronic Waste Recycling in: Electronic Waste Pollution, editors Muhammad Zaffar Hashmi and Ajit Varma, pp.1-12. https://link.springer.com/book/10.1007%2F978-3-030-26615-8.

[2] Kyere et al. Contamination and Health Risk Assessment of Exposure to Heavy Metals in Soils from Informal E-Waste Recycling Site in Ghana DOI: http://dx.doi.org/10.28991/esj-2018-01162.

[3] Rehman, A; Khan, K.A.; Hamid, T.; Nasir, H.; Ahmad, I.; Alam, M. Effective Utilization of Municipal Solid Waste as Substitute for Natural Resources in Cement Industry Civil Engineering Journal Vol. 6, No. 2, 2020
Doi http://dx.doi.org/10.28991/cej-2020-03091467.

[4] R. Heeks, L. Subramanian, C. Jones. Understanding e-Waste Management in Developing Countries: strategies, Determinants, and Policy Implications in the Indian ICT Sector Inf. Technol. Dev., 21 (2015), pp. 653-667. Doi: 10.1080/02681102.2014.886547.

[5] Mahdi Ikhlayel, 2018. An integrated approach to establish e-waste management systems for developing countries, Journal of Cleaner Production 170, pp 119-130. DOI: 10.1016/j.jclepro.2017.09.137.

[6] Chung D.D.L. Composites get smart. *Mater Today* 2002, *1*, 30–35. https://doi.org/10.1016/S1369-7021(02)05140-4

[7] Guan, H.; Liu, S.; Duan, Y.; Cheng, J. Cement based electromagnetic shielding and absorbing building materials. *Cement & Concrete Composites* 2006, *28,* 468-474. https://doi.org/10.1016/j.cemconcomp.2005.12.004 .

[8] Li, Y.; Chen, C.; Zhang, S.; Ni, Y.; Huang, J. Electrical conductivity and electromagnetic interference shielding characteristics of multi-walled carbon nanotube filled polyacrylate composite films. Applied Surface Science 2008 254,18, 5766-5771. https://doi.org/10.1016/j.apsusc.2008.03.077.

[9] Wang, L.; Shi, X.; Zhang, J.; Zhang, Y.; Gu, J. Lightweight and robust rGO/sugarcane derived hybrid carbon foams with outstanding EMI shielding performance Journal of Materials Science & Technology, 2020, 52:119-126; https://doi.org/10.1016/j.jmst.2020.03.029.

[10] Yang, X., Fan, S., Li, Y., Guo, Y., Li, Y., Ruan, K., Zhang, S., Zhang, J., Kong, J., Gu, J. Synchronously improved electromagnetic interference shielding and thermal conductivity for epoxy nanocomposites by constructing 3D copper nanowires/thermally annealed graphene aerogel framework. Composites Part A, 2020, 128: 105670. https://doi.org/10.1016/j.compositesa.2019.105670

[11] Song, P., Qiu, H., Wang,L., Liu, X., Zhang, Y., Zhang, J., Kong, J., Gu, J. Honeycomb structural rGO-MXene/epoxy nanocomposites for superior electromagnetic interference shielding performance. Sustainable Materials and Technologies, 2020, 24: e00153. https://doi.org/10.1016/j.susmat.2020.e00153

[12] Lin, C.T.; Swanson, B.; Kolody, M.; Sizemore, C.; Bahns, J. Nanograin magnetoresistive manganite coatings for EMI shielding against directed energy pulses. Prog.Org.Coat. 2003, 47, 190.https://doi.org/10.1016/S0300-9440(03)00138-3.

[13] Sankarana, S.; Deshmukha, K.; Ahameda, M.B.; Pashab, S.K.K. Recent advances in electromagnetic interference shielding properties of metal and carbon filler reinforced flexible polymer composites: A review. Composite Part A: Applied science and Manufacturing 2018, 114, 49-71. https://doi.org/10.1016/j.compositesa.2018.08.006.

[14] Y.Y.Borisova, A.M. Minzagirova , A.R. Gilmanova, M.F. Galikhanov, D.N. Borisov, M.R. Yakubov. Heavy Oil Residues: Application as a Low-Cost Filler in Polymeric Materials, Civil Engineering Journal Vol. 5, No. 12, December, 2019, 2554. http://dx.doi.org/10.28991/cej-2019-03091432.

[15] Ellen MacArthur Foundation, World Economic Forum and McKinsey & Company. The New Plastics Economy: Rethinking the Future of Plastics (Ellen MacArthur Foundation, 2016).

[16] W.R. Stahel. Circular Economy, Nature; Vol. 531, Iss. 7595, 2016: 435-438 DOI:10.1038/531435a.

[17] ISO 14040. Environmental Management – Life Cycle Assessment – Principles and Framework 2006. https://doi.org/10.3403/30151316.

[18] ISO 14044. Environmental Management – Life Cycle Assessment – Requirements and Guidelines 2006. https://doi.org/10.5555/iso14044:2006

[19] PRè-Product Ecology Consultants, SimaPro7.2. 2012.

[20] Hino, T.; Agawa, R.; Moriya, Y.; Nishida, M.; Tsugi-Ta, Y.; Araki, T. Techniques to separate metal from waste printed circuit boards from discarded personal computers. *Journal of Matter Cycles Waste Management* 2009, *11*, 42-50. https://doi.org/10.1007/s10163-008-0218-0

[21] Directive on the restriction of certain Hazardous Substances in Electrical and Electronic Equipment, 2006.

[22] Bizzo, W.A.; Figueiredo, R.A.;de Andrade, V.F. Characterization of Printed Circuit Boards for Metal and Energy Recovery after Milling and Mechanical Separation. *Materials* 2014, 7, 4555-4566; https://doi.org/10.3390/ma7064555 .

[23] Ron, A.; Penev, K. Disassembly and recycling of electronic consumer products: An overview. *Technovation* 1995, 15, 363–374. https://doi.org/10.1016/0166-4972(95)96597-M

[24] Xiang, D.; Mou, P.; Wang, J.; Duan, G.; Zhang, H.C. Printed circuit board recycling process and its environmental impact assessment. *Int. J. Adv. Manuf. Technol*. 2007, 34, 1030–1036. https://doi.org/10.1007/s00170-006-0656-6

[25] Lee, C.H.; Chang, C.T.; Fan, K.S.; Chang, T.C. An overview of recycling and treatment of scrap computers. *J. Hazard. Mater. B*, 2004, 114, 93–100. https://doi.org/10.1016/j.jhazmat.2004.07.013

[26] Seeling, K.; Suraski, D. A comparison of tin-silver-cop- per lead-free solder alloys, *AIM Incorporated*, www.aimsolder.com.

[27] Lakshmi, K.; John, H.; Mathew, K.T.; Joseph, R.; George, K.E. Microwave absorption, reflection and EMI shielding of PU–PANI composite. *Acta Materialia* 2009, *57*, 371–375. https://doi.org/10.1016/j.actamat.2008.09.018

[28] Gupta, A.; Choudhary, V. Electrical conductivity and shielding effectiveness of poly (trimethylene terephthalate)/multiwalled carbon nanotube composites. *Journal of Materials Science* 2011, *46*, 6416–6423. https://doi.org/10.1007/s10853-011-5591-8.

[29] Kulkarni, G.; Velhal, N.; Phadtare, V.; Puri, V. Enhanced electromagnetic interference shielding effectiveness of chemical vapor deposited MWCNTs in Xband region. *Journal of Materials Science: Mater Electron* 2017, *28* , 10, 72127220. https://doi.org/10.1007/s10854-017-6402-z.

[30] Singh, R.; Kulkarni, S.G. Nanocomposites based on transition metal oxides in polyvinyl alcohol for EMI shielding application. *Polym Bull* 2014, *71*, 2, 497– 513. https://doi.org/10.1007/s00289-013-1073-2

[31] Zabalza, I.; Valero, A.; Aranda, A. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment* 2011, *46*, 1133-1140. https://doi.org/10.1016/j.buildenv.2010.12.002

[32] La Rosa, A.D.; Gagliano, A.; Summerscales, J.; Latteri, A.; Cozzo G., Cicala, G., Environmental impacts and thermal insulation performance of innovative composite solutions for building applications. *Construction and Building Materials* 2014, 55, 406–414. https://doi.org/10.1016/j.conbuildmat.2014.01.054

[33] Di Modica, P.; La Rosa, A.D.; Cicala, G.; Kotsikos, G.; Gibson, G. Fire Resistance and Fire Reaction of Bio-Composite Sandwiches for Building Construction. In: *ICNF 2015*, 2nd International Conference on Natural Fibres, Ponta Delgada, Azores, Portugal. 2015 https://eprint.ncl.ac.uk/file_store/production/218798/5CE700FF-EB12-449DB3E0-32F7996BAC39.pdf.

[34] Ismail, H; Hanafiah, M.M. An overview of LCA application in WEEE management: Current practices, progress and challenges Journal of Cleaner Production 232 (2019) 79- 93. https://doi.org/10.1016/j.jclepro.2019.05.329

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on 05 October 2020 with DOI: 10.1016/j.jclepro.2020.124593.

Figures

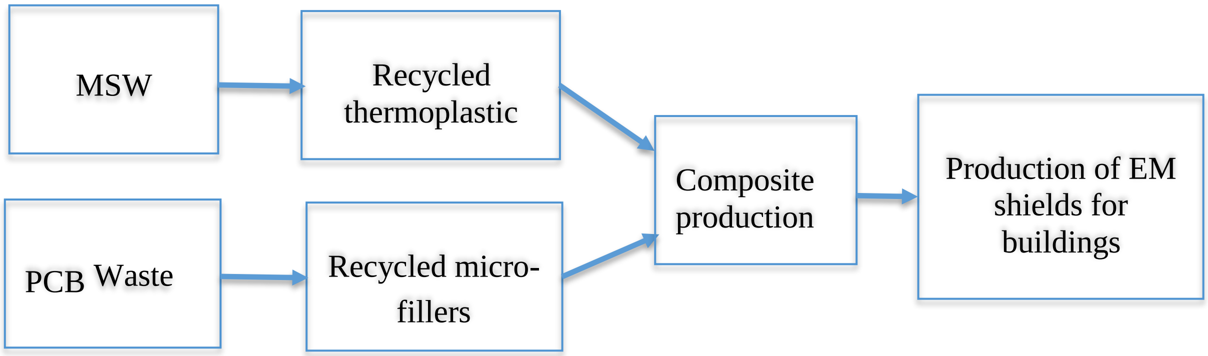
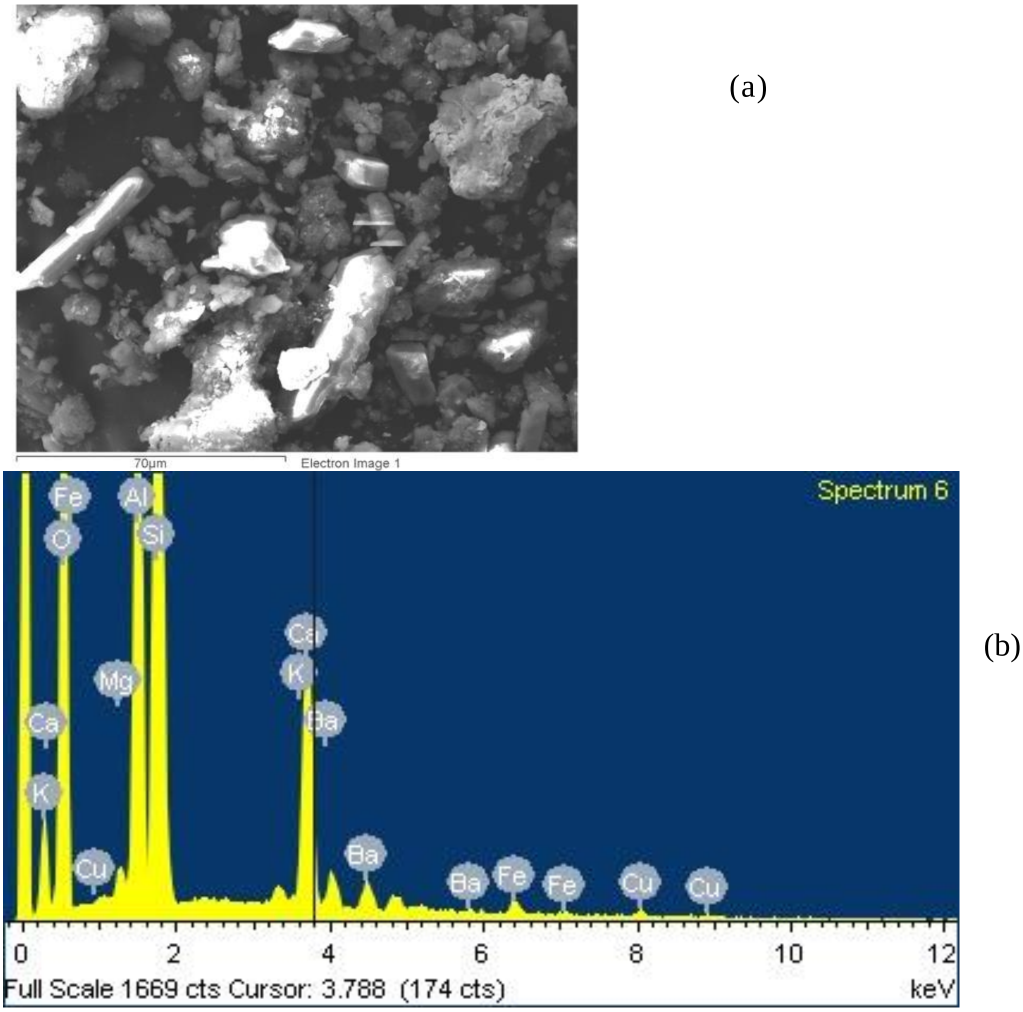


Figure 1

Figure 2



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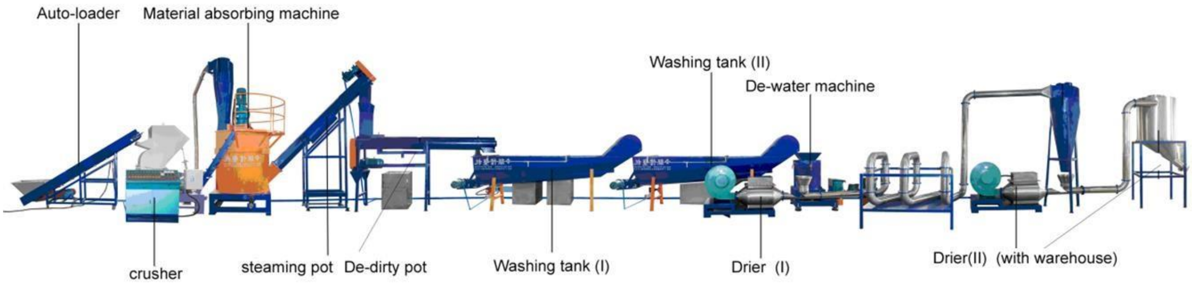

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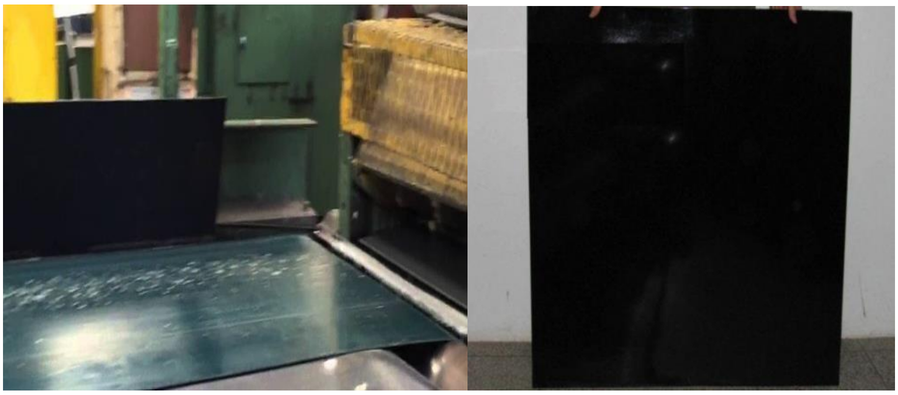

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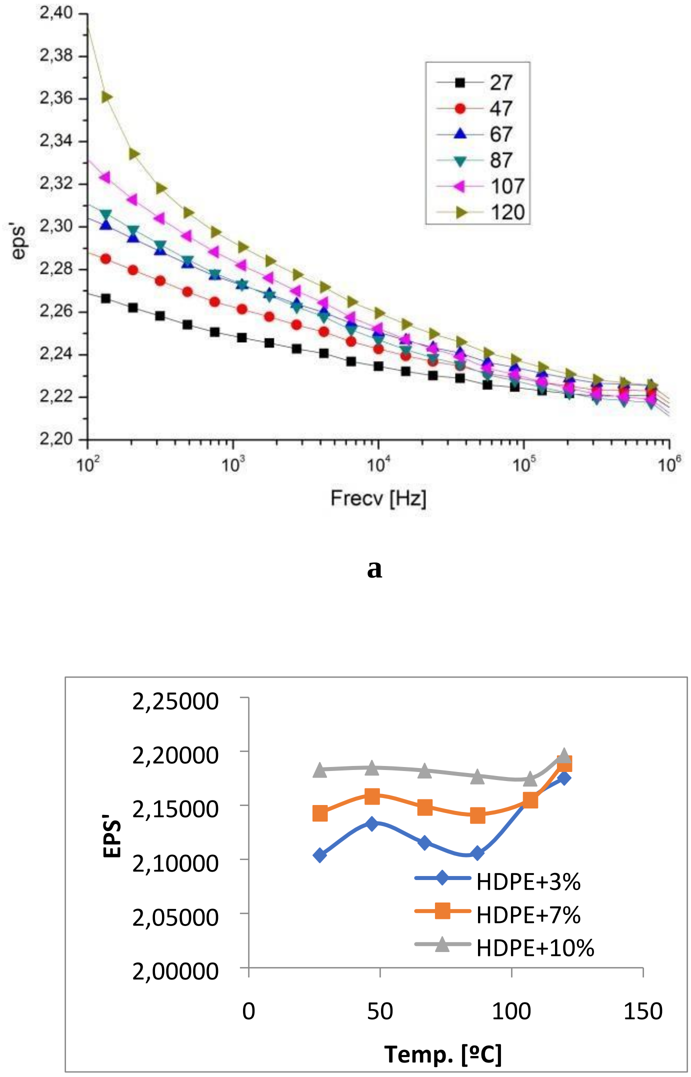
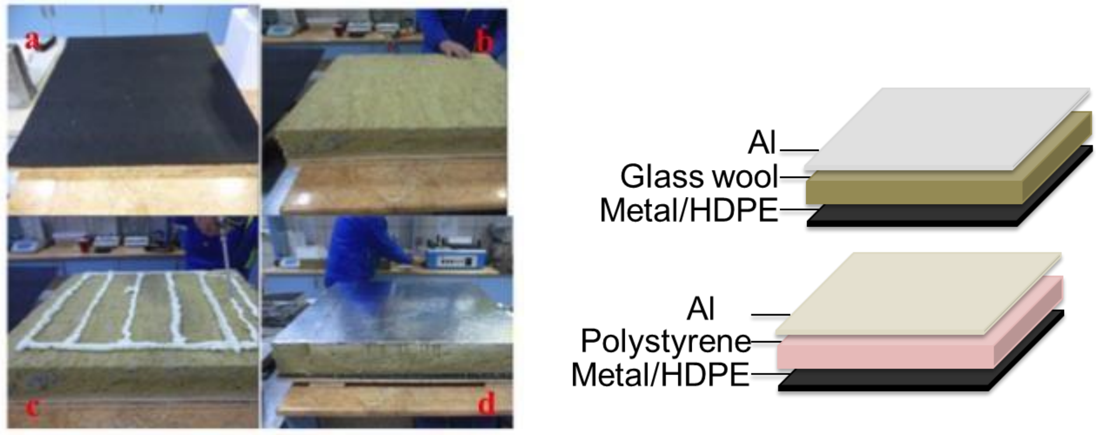


a

b

Figure 6



(2)

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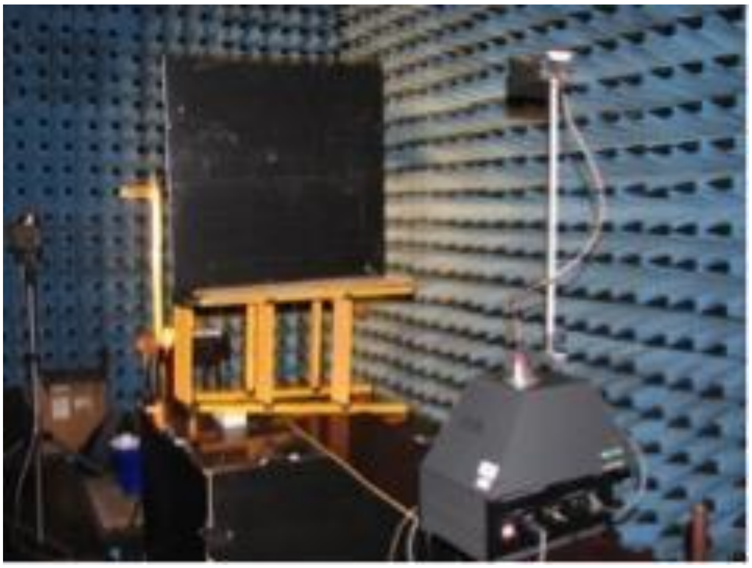
Figure 7



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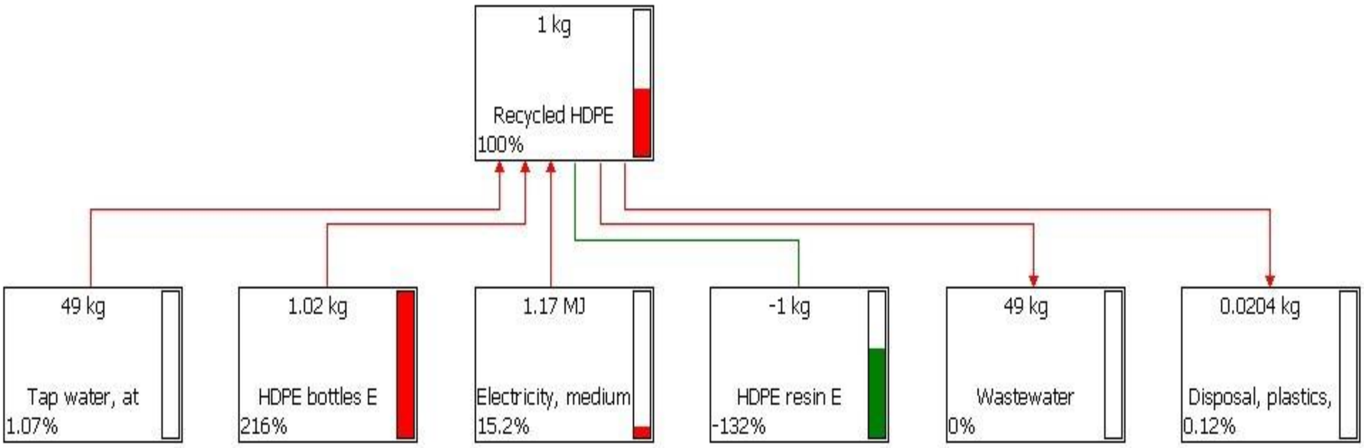

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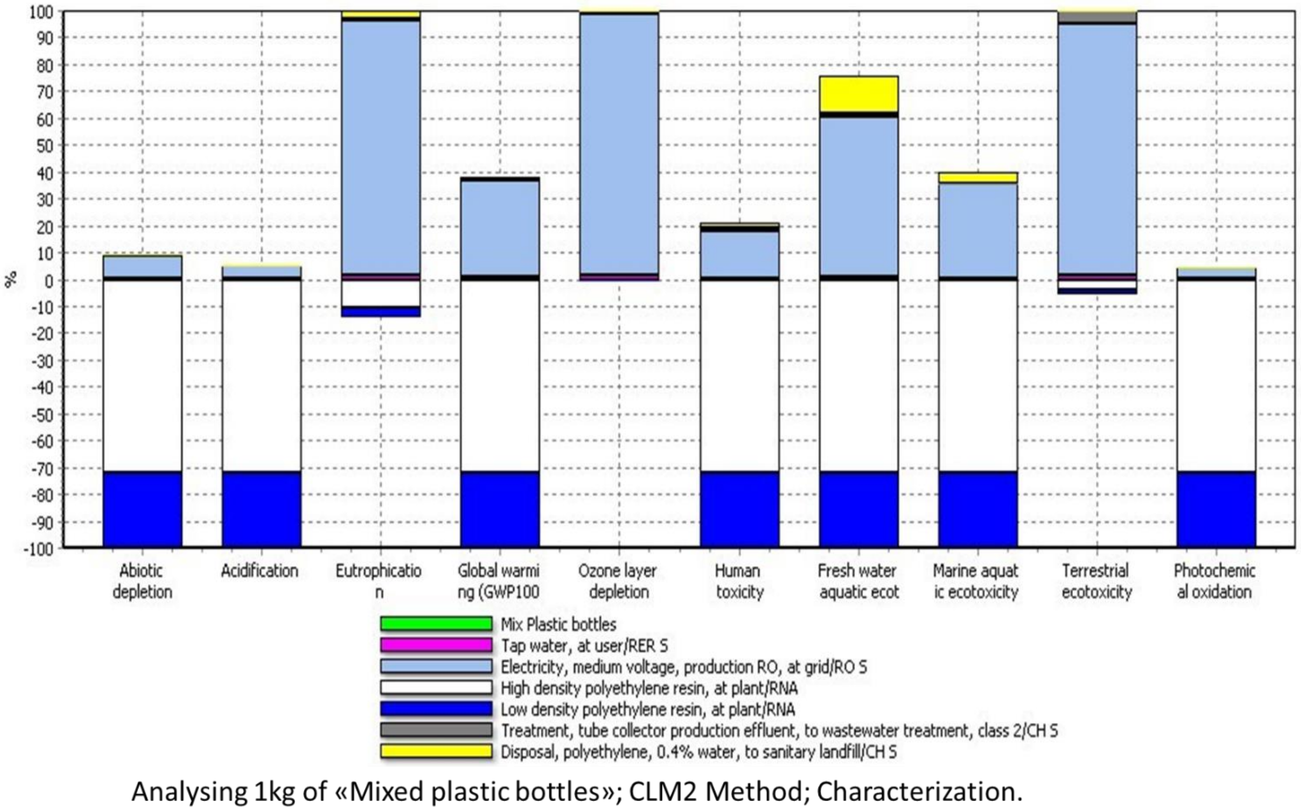

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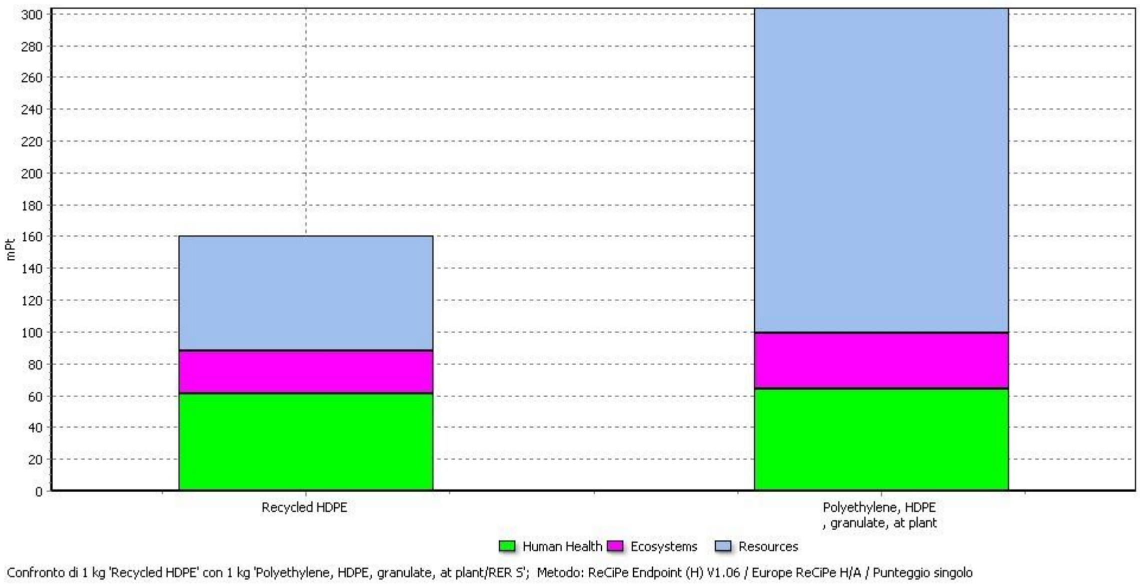

Figure 11

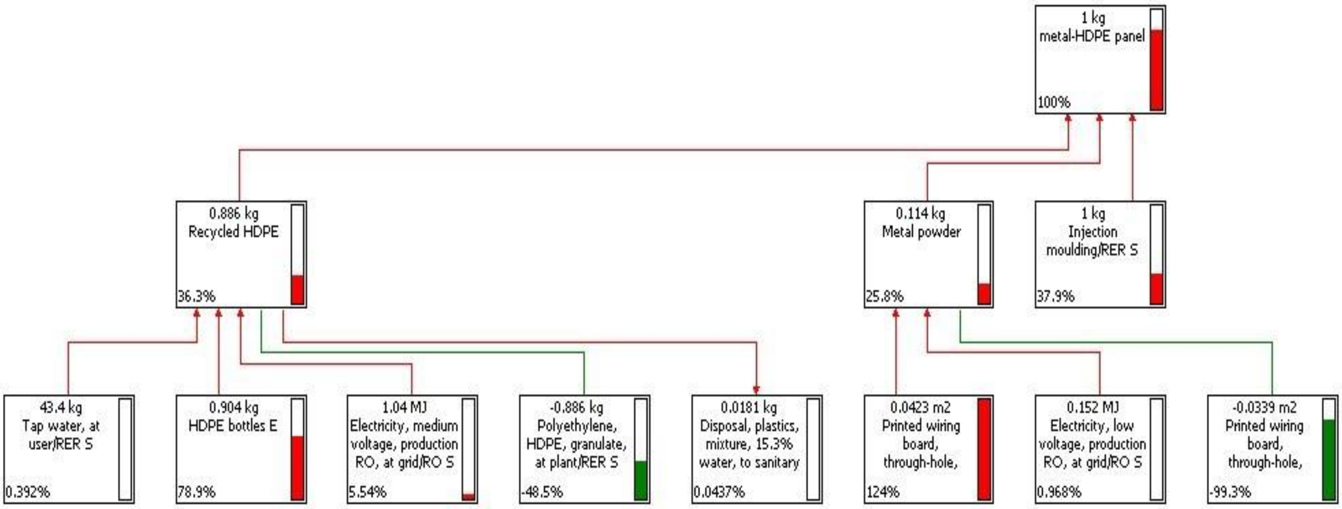

Figure 12

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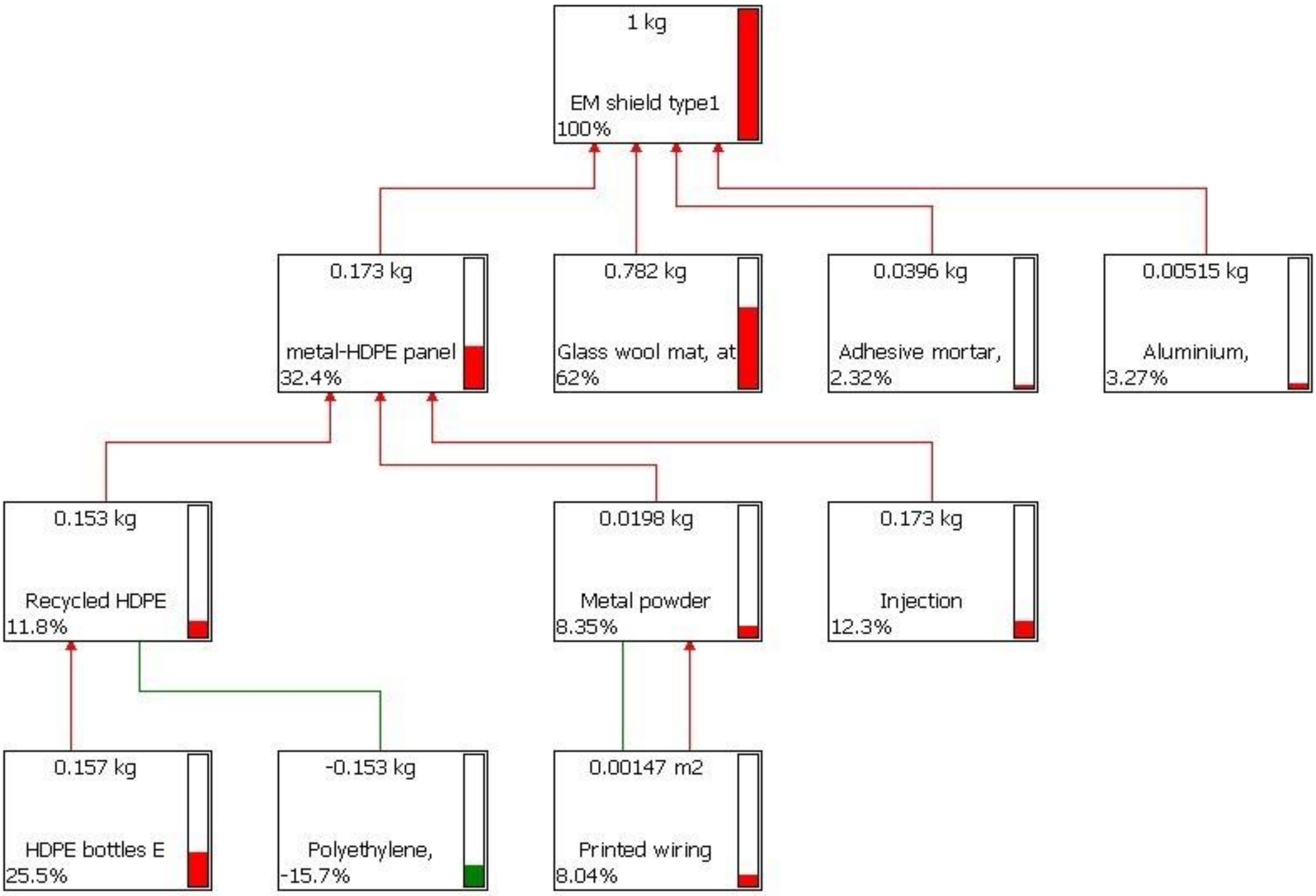


Figure 13

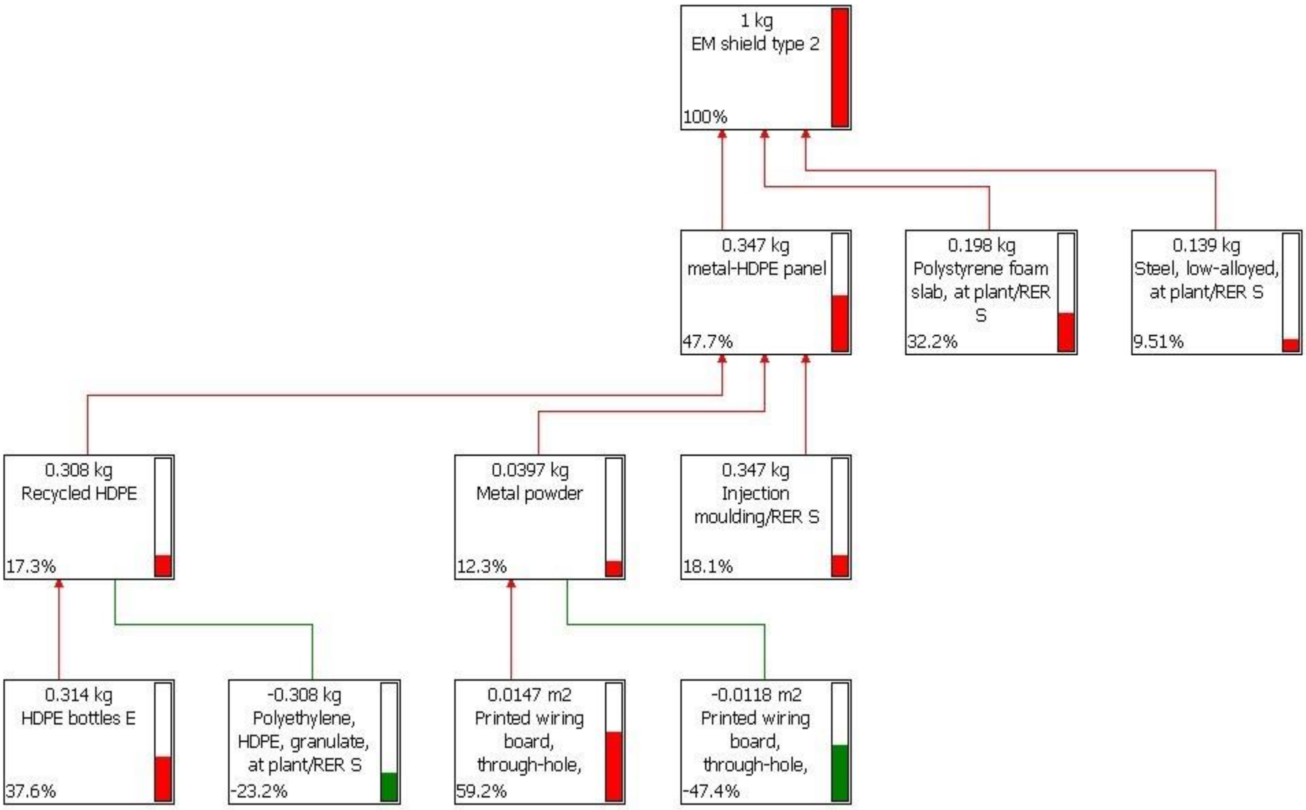
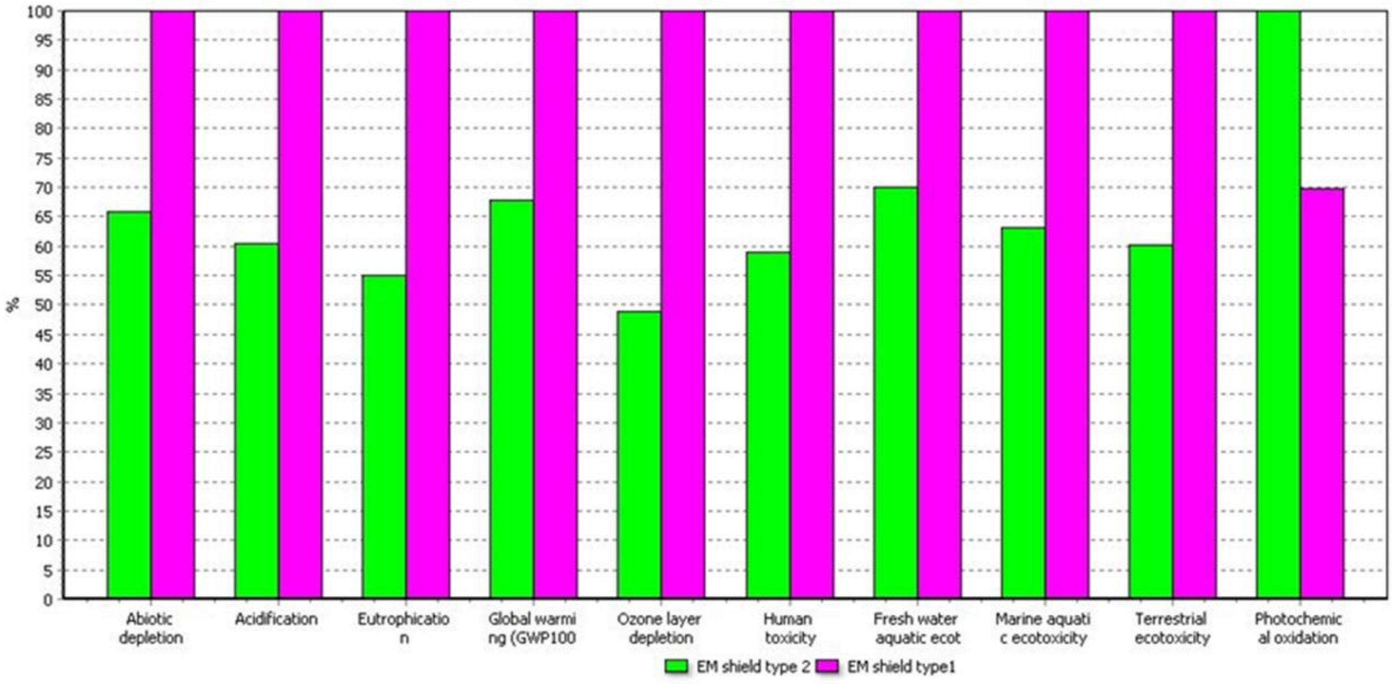


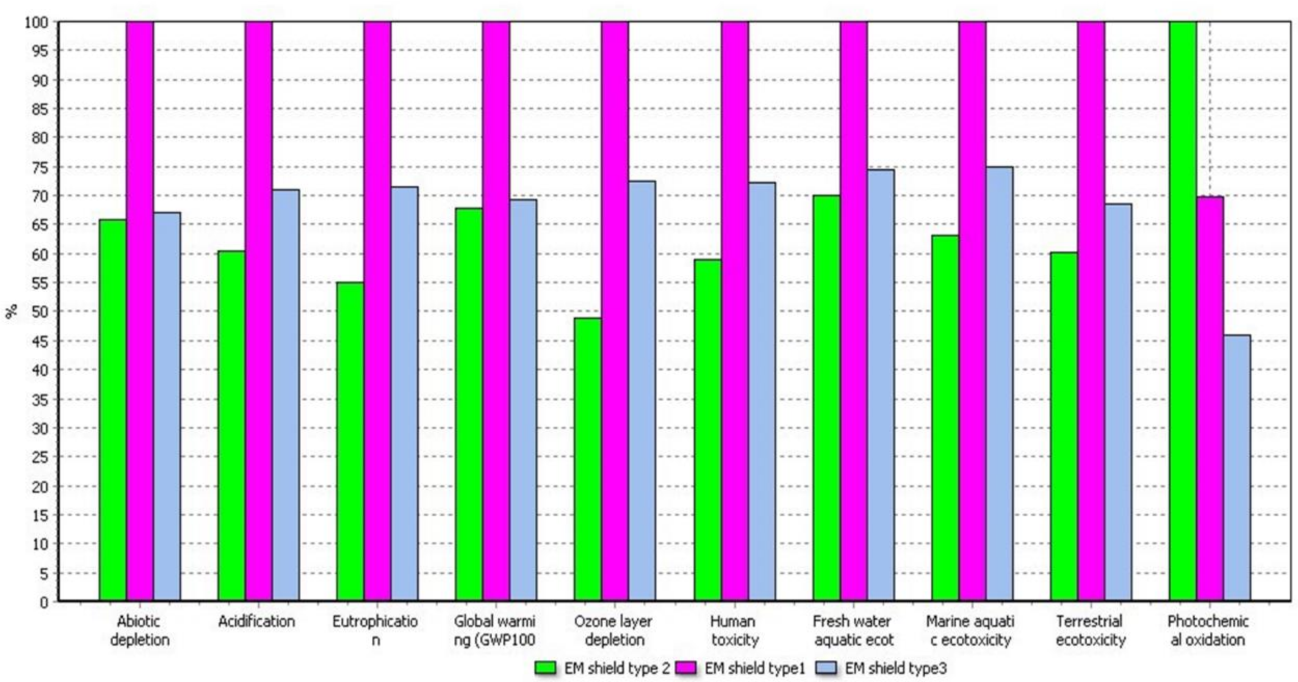
Figure 14



Comparing 2.52Kg EM shield type 2 with 5.05Kg EM shield type 1. CML2 Method. Characterization.

Figure 15

JCLEPRO-D-20-04955 accepted for publication in Journal of Cleaner Production
on 05 October 2020 with DOI: 10.1016/j.jclepro.2020.124593.



Comparing 2.52Kg EM-shield type2, 5.05Kg EM-shield type1 and 3.1Kg EM-shield type 1. CML2 Method. Characterization

Figure 16