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Influence of the Composition on the Environmental Impact of Soft Ferrites

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Abstract: The aim of this paper is to better understand the influence of the composition on the environmental impact of soft ferrite magnetic materials. Magnetically soft ferrites are ceramic homogeneous materials that have a cubic crystal structure. Soft ferrites have low coercitivity with a high resistivity, low losses and high permeability, and are commonly used in high frequency applications. A life cycle assessment (LCA) has been carried out analyzing EcoInvent average ferrite dataset and updating it with material compositions of manganese-zinc (MnZn) ferrites, one of the major categories of soft ferrites. MnZn ferrites use iron oxide as their main component adding manganese oxide (17%-24.5% in weight) and zinc oxide (6.5%-14% in weight). Depending on their composition, their magnetical properties change (such as permeability, losses, Curie temperature…). The influence of the material composition has been assessed, obtaining more knowledge of their environmental impact. The main environmental problem that generates the use of soft ferrites, under ReCiPe methodology, is in the metal depletion category. Ferrites use in their composition metals that are scarce, such as Manganese. Manganese is included in the 2017 EU strategic materials list due to its high economic importance in the EU industry, and also its supply risk. The software used to develop the LCA model was SimaPro 8.4, with EcoInvent v3.4 life cycle inventory database. Both are currently the most used tools to evaluate environmental impact in the LCA scientific community. By means of the performed LCA, environmental impact values under ReCiPe methodology will be obtained to assess the influence of the composition on the overall impact. This analysis shows the large influence of material composition on the environmental impact of ferrites, allowing engineers and material scientist to choose between different ones taking also into account its sustainability.

Keywords: Soft ferrites; magnetic materials; MnZn; material composition; environmental impact; critical raw materials.

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1. Introduction

Ferrites started to be used in the industry in the middle of the 20th century [1]. The main uses of ferrites in its origins were mainly in electronic devices: transformers, anti-electromagnetic filters or magnetic recording media [2-7]. Apart from previous applications, nowadays, the use of ferrites is increasing in other types of electronic devices such as televisions and radios, thanks to their low cost and their mechanical resistance [8]. Although the use of ferrites has mainly been focused on electronic components, they are also used in different applications, like in wastewater treatments [9-11], as a catalyst to increase the reaction rate of chemical reactions [12], or as an indicator in magnetic resonances [13] or in hyperthermia treatments [14].

Ferrites are mainly classified according to their chemical formula and they can be spinel, garnet, hexaferrites and orthoferrites. The most used are spinel type which have the next chemical formula

MFeO where M are metallic cations like the cobalt [15-17], manganese-zinc alloy [18] [19] or other metals like iron [20], and FeO are iron oxides.

The chemical formula and the structure give these compounds different properties that change depending on the cation used and the sites occupied by the both types of atoms due to the magnetic moments [21]. These properties can be high magnetic permeability, high resistivity and high Curie temperature [22].

Also, depending on the composition the environmental impact changes. Although iron oxides are usually in higher proportion than metallic cations, most of the impact of these compounds are caused by the cations, as many of these materials have high environmental impact and some are classified as critical. Critical materials are defined by different criteria such as ecological risk, supply risk or economy vulnerability [23-26].

Because of these reasons, it is important to obtain the environmental impact value taking into account the composition. One of the main methodologies to measure environmental impact is the Life Cycle Assessment (LCA). LCA evaluates the environmental impact of a product, material, service, process or the whole life cycle [27-29]. There are many examples of LCA applied to different products such as induction hobs [30] or luminaires [31].

LCA helps companies to evaluate how the environmental impact is generated, and modify the product to reduce the environmental impact in the design phase, instead of correcting it later. This process is called ecodesign [32-34].

LCA relies on large Life Cycle Inventory (LCI) databases, as EcoInvent, which help to assign each material, process or transport an environmental impact. The problem of these databases is that only have got a limited amount of compositions, therefore reducing the accuracy of the environmental impact results [35] [36].

The aim of this paper is to better understand the influence of the composition on the environmental impact of soft ferrite magnetic materials. A LCA has been carried out analyzing EcoInvent average ferrite dataset and updating it with material compositions of manganese-zinc (MnZn) ferrites, one of the major categories of soft ferrites. These soft ferrites (Figure 1) have low coercitivity with a high resistivity, low losses and high permeability, and are commonly used in high frequency applications.

Figure 1. MnZn soft ferrite.

2. Methods

This research is based on EcoInvent ferrite, but focusing on MnZn soft ferrites, which have a wide range of composition depending on the amount of Zinc and Manganese Oxides.

Table 1 shows the minimum and maximum molar percentages of MnZn [37]. These percentages have to be transformed to mass percentages (Table 2) in order to quantify the environmental impact of 1 Kg of soft ferrite material.

Table 1. Material molar composition percentage of soft ferrites.

Molar Percentage	Fe_2O_3	ZnO	MnO
Minimum (%)	50	10	30
Maximum (%)	60	30	40

Table 2. Material mass composition percentage of soft ferrites.

Mass Percentage	Fe_2O_3	ZnO	MnO
Minimum (%)	68,0	6,5	17,0
Maximum (%)	76,5	14,0	24,5

The percentages composition ranges shown in Table 2 establish all the possible composition combinations for soft ferrites, based on the molar composition shown in Table. Figure 2 shows the composition diagram for MnZn ferrites.

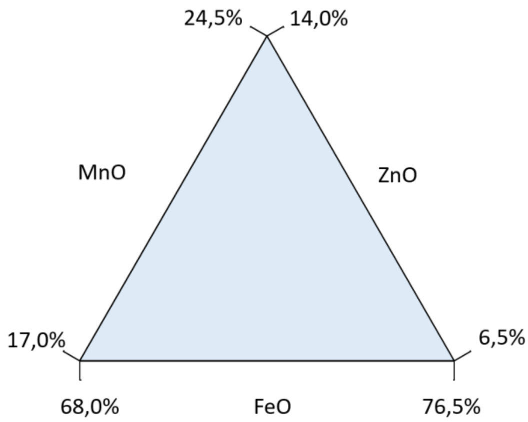

Figure 2. MnZn soft ferrite composition diagram.

The aim of this LCA is to analyze the influence of the composition on the environmental impact of MnZn soft ferrites. So, ISO 14040 and 14044 standards have been followed. EcoInvent dataset "Ferrite production {GLO}" has been used as a base, to make the same assumptions that EcoInvent, but it has been updated to include the composition of MnZn soft ferrites.

2.1. Functional Unit and System Boundaries

In order to carry out a proper LCA, the functional unit has to be defined. In this research, the functional unit is the production of 1 kg of MnZn soft ferrite.

The LCA has been carried out to assess the environmental impact of a wide range of ferrite compositions (Table 2) but also considering raw material acquisition, energy consumption (electricity, natural gas) and the infrastructure efforts. Following EcoInvent methodology, market datasets have been used to consider the transportation processes of raw materials from average providers to a ferrite manufacturing plant.

2.2. Inventory Data and Assumptions

The software used to develop the LCA model was SimaPro 8.4, with EcoInvent v3.4 LCI database. Both are currently the most used tools to evaluate environmental impact in the LCA scientific community. Table 3 shows the selected EcoInvent datasets for the main materials. In order to evaluate the environmental impact, ReCiPe endpoint methodology was used. ReCiPe is makes the results easy to analyze from an engineering point of view, making it easier to select between different materials [36].

Table 3. EcoInvent dataset selection.

Material	Dataset
Iron Oxide	market for portafer - GLO
Zinc Oxide	market for zinc oxide - GLO
Manganese Oxide	market for manganese - GLO

3. Results and Discussion

In this section, the results of the LCA study are shown. Using the composition ranges of Table 2, a MonteCarlo analysis is carried out to assess the environmental impact of samples that comply with the composition range. For this study, 68 different MnZn soft ferrites were calculated. The main results are shown in Table 4.

Table 4. Minimum, maximum and average environmental impact in ReCiPe methodology.

-	Fe_2O_3 (%)	ZnO (%)	MnO (%)	Environmental Impact (mPt/Kg)
Minimum	76,5	6,5	17,0	1571,6
Average	70	10	20	1833,3
Maximum	68	7,5	24,5	2223,9

Table 4 shows that, under ReCiPe methodology, a ferrite with 6.5% ZnO and 17% MnO has the lowest environmental impact, whereas the ferrite with 7.5% ZnO and 24.5% creates the highest environmental impact. These differences are created by the percentage of Manganese, as this material has a high environmental impact per Kg. In all cases, the environmental impact of soft ferrites, under ReCiPe methodology, is mainly cause in the metal depletion category due to the use of scarce metals such as Manganese. Manganese is also included in the 2017 EU strategic materials list due to its high economic importance in the EU industry, and its supply risk.

Figure 3 allows us to analyze these results in depth. The composition that creates the lower environmental impact is the one with a lowest Manganese and Zinc oxides composition percentages. This means that it has the highest Iron oxide percentage. Focusing on the environmental impact under ReCiPe methodology, the presence of Manganese oxide generates almost 95% of the overall environmental impact. Iron oxide creates 3.63% of the impact whereas production process only account to 1.1%. The presence of Zinc oxide is the one that produces the lower environmental impact percentage.

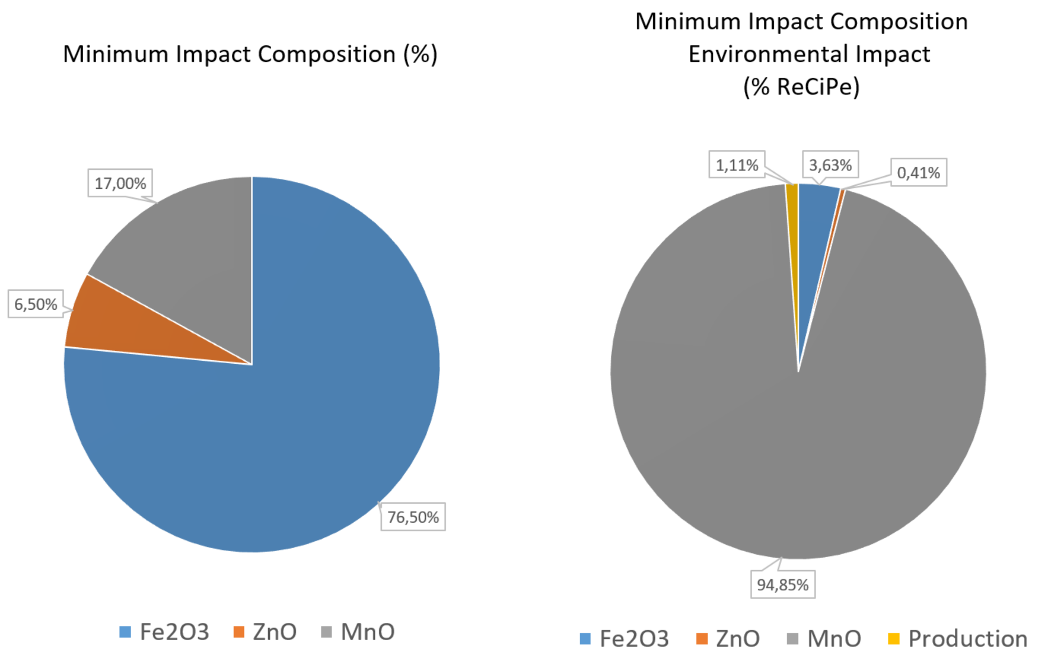

Figure 3. MnZn soft ferrite with minimum environmental impact.

Figure 4 shows the composition and environmental impact for the average soft ferrite. The composition has average values for all the used materials. Analyzing how the environmental impact is created under ReCiPe methodology allow us to obtain that the presence of Manganese oxide causes 95.7% of the impact. Iron oxide generates 2.8% of the impact while the production process of this ferrite are below 1%. In addition, the use of Zinc oxide is the one that produces the lower environmental impact percentage.

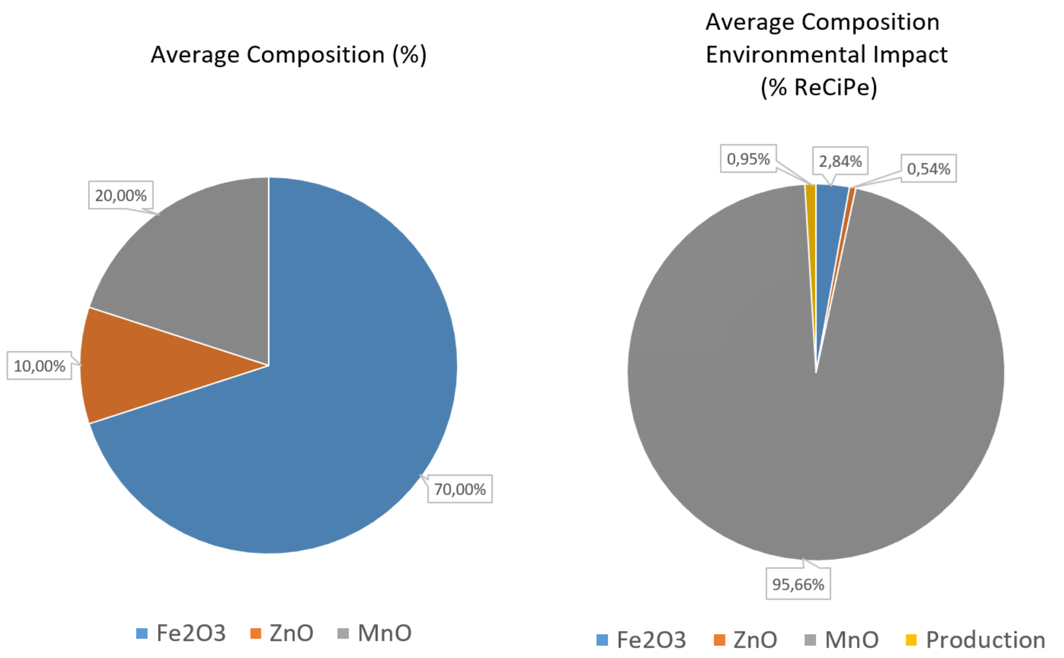

Figure 4. MnZn soft ferrite with average environmental impact.

On the other hand, Figure 5 represents the ferrite with the maximum environmental impact. The composition is the one with the highest Manganese oxide percentage, all almost the lowest percentages for Iron and Zinc Oxides. From an environmental impact point of view, the use of Manganese oxide produces 96.6% of the impact, while Iron oxide only creates 2.28% of the impact and production process only account to 0.78%. The presence of Zinc oxide also creates for this ferrite the lowest environmental impact percentage.

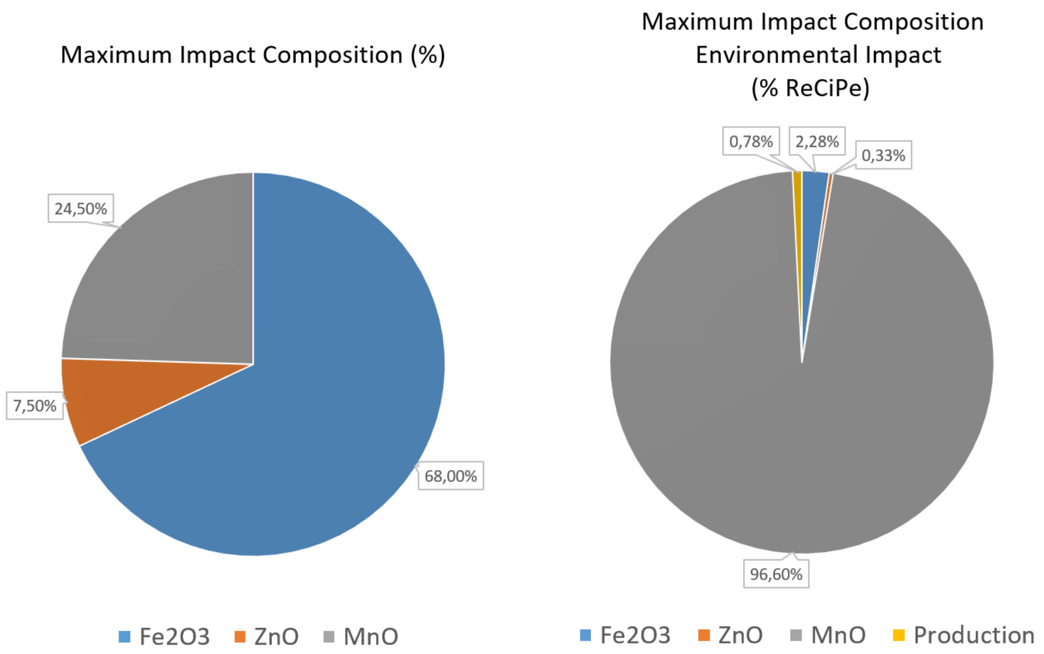

Figure 5. MnZn soft ferrite with maximum environmental impact.

Figure 6 represents all the analyzed ferrites composition. These values have been arranged from lower to higher environmental impact, showing that the presence of Manganese Oxide supposes the highest influence on the environmental impact.

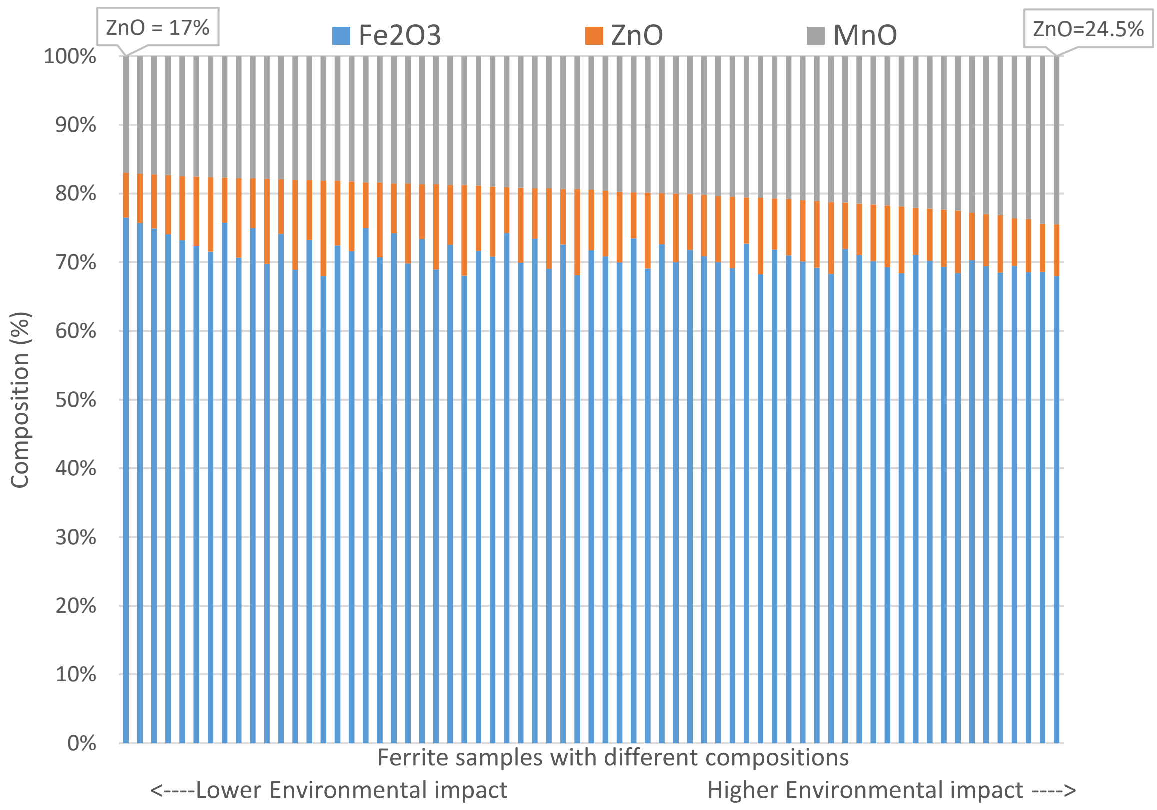

Figure 6. Range of the analyzed MnZn soft ferrite compositions.

Figure 7 shows all the calculated environmental impact for all the ferrites composition. These values have also been arranged from lower to higher environmental impact, showing that the distribution is homogeneous.

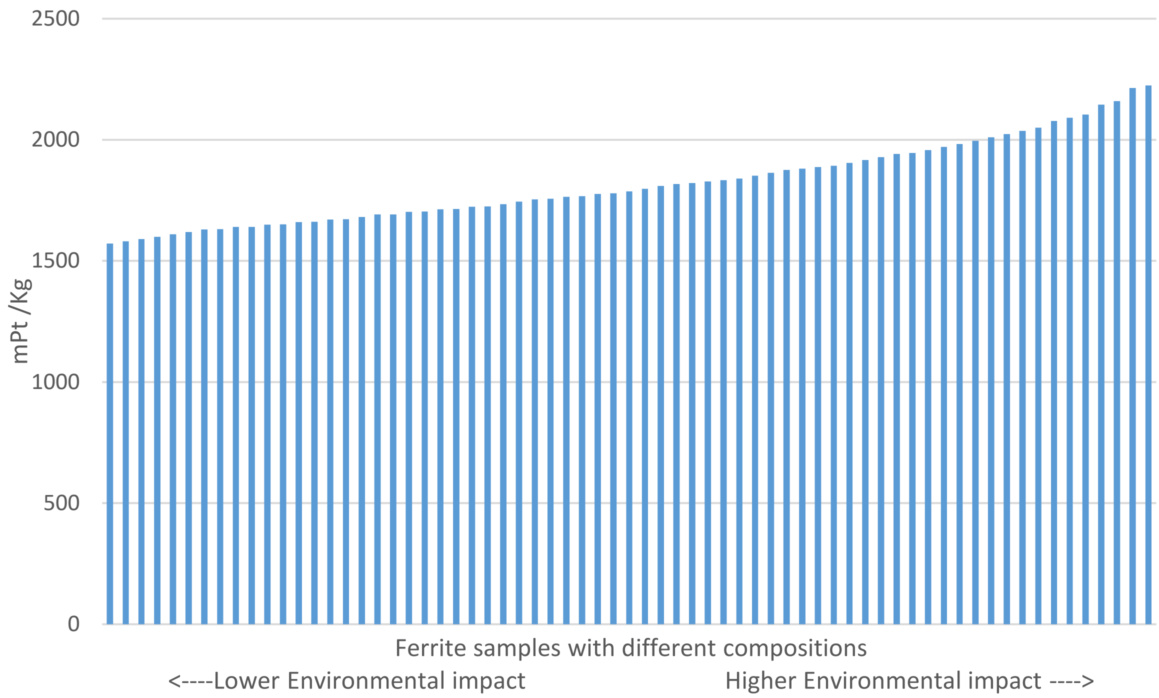

Figure 7. Range of environmental impact of 1Kg of MnZn soft ferrite depending on the composition.

When comparing all the results of Figure 7, almost a 42% difference can be found between the lowest and highest environmental impact. This difference is more important when comparing these results with EcoInvent´s "Ferrite production {GLO}", which is shown in Table 5.

Table 5. EcoInvent ferrite dataset environmental impact in ReCiPe methodology.

Fe_2O_3 (%)	ZnO (%)	MnO (%)	Environmental Impact (mPt/Kg)
55,0	15,0	30,0	2704,0

As we can see analyzing Table 5, EcoInvent ferrite composition has a higher Manganese content than the MnZn soft ferrites that are analyzed in this article. As previously explained, this manganese presence generates a high environmental impact, which can be up to 72% higher than the minimum environmental impact ferrite that has been calculated in this article with 6.5% ZnO and 17% MnO. Analyzing Figure 8, it shows us that as EcoInvent ferrite composition has a higher Manganese Oxide content, this presence also creates the highest environmental impact, almost 97.3%. The second contribution is caused by Iron Oxides, with 1.5%, which is a lower percentage of all the analyze ferrites. Production processes generate 0.64% while Zinc oxides produce 0.55%, the highest impact of all the studied ferrites.

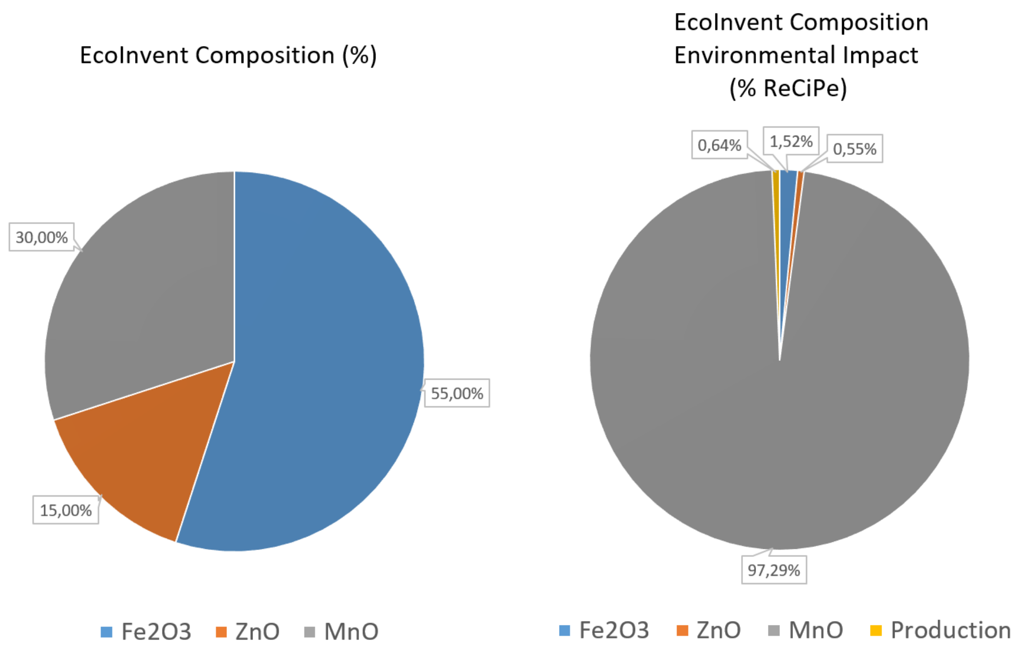

Figure 8. MnZn soft ferrite.

4. Conclusions

This article shows the importance of considering the material composition in order to accurately assess the environmental impact of MnZn soft ferrites. This will allow engineers to compare these ferrites based on cost, properties, but also environmental impact. To do that, EcoInvent "Ferrite production {GLO}" has been used as a reference, but customizing the composition ranges of MnZn soft ferrites.

The impact per Kg of the studied ferrites, using the ReCiPe endpoint methodology, varies from 1571,6 mPt to 2223,9 mPt, depending on the ferrite composition. These values are significantly different from the one from EcoInvent: 2704 mPt per Kg. This difference is mainly caused by the higher content of Manganese in EcoInvent's ferrite, as Manganese material has the highest environmental impact per Kg in a ferrite. This analysis shows the large influence of material composition, especially due to the presence of Manganese, allowing material scientist and engineers to be able to choose between different soft ferrites taking also into account its sustainability.

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Author Contributions: Patricia Gómez is responsible of customizing the analyzed datasets, processing the data and making the calculations using the environmental impact assessment software SimaPro; all mentioned in collaboration with Daniel Elduque. Carlos Javierre performed the first draft of the article, taking an active part in the entire manuscript and its conclusions. Carmelo Pina helped with the analysis of the results also to the final state of the article and its conclusions. All of the authors participated in the writing and correction of this article and they all agree to its final version.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

LCA: Life Cycle Assessment
LCI: Life Cycle Inventory

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