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IDENTIFICATION OF THE ENVIRONMENTAL IMPACT OF POLYURETHANE FOAMS USING ANSYS GRANTA SELECTOR

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Abstract: Before a new polymer material is placed on the market, it should be compulsory to assess its environmental impact at different stages of its life cycle. The main objective of the study was to identify the environmental impact of the production of polyurethane (PUR) foams. Ansys Granta Selector software was used to analyze this aspect. The environmental characteristic of material production included: embodied energy [MJ/kg], CO_2 footprint [kg/kg], and water usage [l/kg]. The Eco Audits of PUR foams, based on natural fillers, were investigated. The study showed that PURs generate significantly less CO_2 at the production stage compared to other foams. Furthermore, the modification of PUR foams can reduce the CO_2 footprint.

Keywords: polyurethane foams, eco audit, environmental characteristic, CO_2 footprint, ansys granta selector.

1. INTRODUCTION

Global warming has been a major environmental problem in recent decades due to the emission of huge amounts of carbon dioxide (CO_2) and other greenhouse gases [Rehman et al. 2021]. The observed climate changes are caused by global warming [Rehman et al. 2021; Mella 2022].

Global emissions of CO_2 from fuels and by industry have increased significantly since 2000 (Fig. 1) [Statista[a] 2021]. The maximum of CO_2 emissions was observed in 2019 and created 36.7 billion metric tons of CO_2. Emissions by selected countries show that China and the USA were the largest polluters in the world in 2020, emitting 10.6 and 4.7 billion metric tons of CO_2 [Statista[b] 2021]. In comparison, Poland's CO_2 emissions were almost 36 times lower than China and almost 16 times lower than the USA.

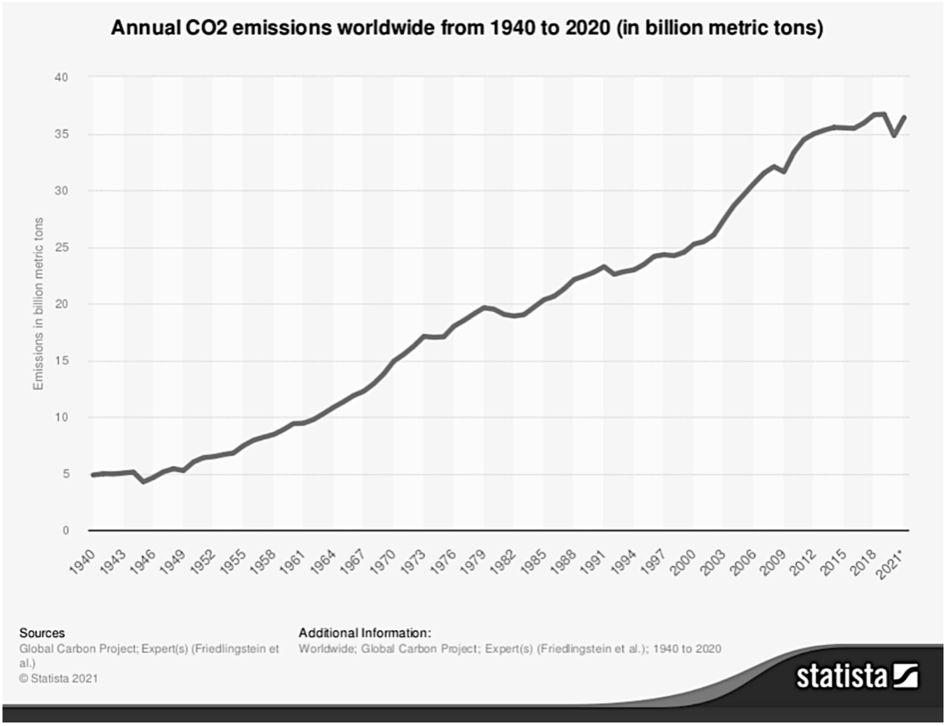

Fig. 4. Annual global emissions of CO_2 1940-2020

Source: Statista[a] 2021.

The development of the plastic industry also significantly influences the CO_2 emissions into the atmosphere. Furthermore, global plastic production is expected to increase from 370 million tons in 2020 to approximately 590 million tons in 2050 [Statista[c] 2021]. Therefore, the risk of CO_2 emissions will increase even more. More than half of the market for polymer foams in the United States is PUR foams [The Freedonia Group 2006; Sklenickova et al. 2022].

Before a new polymer material or other product is placed on the market, it should be mandatory to assess its environmental impact at all stages of its life cycle, mainly eco-aware product design and production [Ashby 2013; Ertekin, Nicoleta and Chiou 2014].

It has been shown that the Eco Audit tool, part of the Ansys Granta Selector software, is a fast and reliable tool for the environmental impact assessment of a product in comparison to the SimaPro results [Gradin and Astrom 2018].

Luna-Tintos et al. led a rethink of all the life cycles of production in the construction industry to reduce its environmental impact [Luna-Tintos et al. 2020]. The research showed a quantitative assessment of the embodied primary energy and

CO_2 production at each stage. The results of the work formed guidelines for the optimization of the production process.

The main objective of the work was to identify the environmental impact of PUR foams using the Eco Audit tool from the Ansys Granta Selector software.

2. MATERIALS AND METHODS

The source of tested materials was the MaterialUniverse database. This database is included in the Ansys Granta Selector software provided by Granta Design, Cambridge University [Ansys 2022]. The research was carried out under a research license. The database contains over 4000+ materials, including 135 various types of foam polymer materials. The environmental characteristic of the production of the selected synthetic foams and natural materials is presented in Table 1.

Table 1. Environmental characteristics of the material production of the selected synthetic foams and natural materials

No.	Material	Embodied energy [MJ/kg]	CO_2 footprint [kg/kg]	Water usage [l/kg]
1	Paper (cellulose based)	49.0-54.0	1.11-1.23	$1.62 \cdot 10^3$-$1.79 \cdot 10^3$
2	Cork (low density, closed cell)	3.8-4.2	0.19-0.21	665-735
3	Polycarbonate PC foam (structural)	113.0-125.0	7.70-8.49	495-547
4	Polyetherimide PEI foam (closed cell)	223.0-245.0	18.00-19.90	490-541
5	Polyethersulfone PES foam (rigid, closed cell)	220.0-243.0	17.90-19.70	299-896
6	Polyethylene PE foam (cross-linked, closed cell)	88.4-97.5	3.05-3.36	216-239
7	Polymethacrylimide PMI foam (rigid)	316.0-348.0	26.40-29.10	299-896
8	Polypropylene PP foam (structural)	75.2-83.0	2.91-3.21	112-124
9	Polyurethane PUR foam (open cell; elastomeric, open cell; flexible, open cell; microcellular, closed foam)	80.9-89.2	3.76-4.14	280-310

10	Polyurethane PUR foam (rigid, closed cell)	88.2-97.3	4.79-5.28	280-310
11	Polyvinylchloride PVC foam (cross-linked, rigid, closed cell)	76.5-84.3	4.90-5.40	436-482

Source: own study based on the Ansys Granta Selector browser.

There are 23 examples of PURs as a polyurethane plastic, thermosetting polyurethane elastomer or thermosetting rigid polyurethane. However, these PUR foam examples differ in the value of specific gravity, and, as it does not affect the value of the environmental parameters, only 4 types of materials were analyzed for this paper (no. 9 in Tab. 1). The types of tested PUR foams (PUR foam: open cell; elastomeric, open cell; flexible, open cell; microcellular, closed foam) have the same values of environmental parameters. The rigid PUR foam (no. 10 in Tab. 1) has poorer environmental production characteristics than other PUR foams.

As can be seen from the collected data (Tab. 1), there are huge differences in the amount of energy required and CO_2 footprint of material production between the various materials. For example, for cork (no. 2 in Tab. 1) the embodied energy and CO_2 footprint of its production are respectively 3.8–4.2 MJ/kg and 0.19–0.21 kg/kg, while for polymethacrylimide foam they are 316.0–348.0 MJ/kg and 26.40–29.10 kg/kg. It is also clear that both of these parameters are lower for natural materials than for synthetic ones. On the other hand, the amount of water necessary for the production of natural materials is much higher, amounting to $1.79 \cdot 10^3$ l/kg in the case of paper. It should be clear that the environmental impact of a given material should be taken into account for all the functional synergistic parameters. After all, it has been known for several years that organic cotton bags must be reused up to 20,000 times to have the same environmental impact as thin plastic bags [Ministry of Environment and Food of Denmark 2018].

The method used in this investigation was based on a software tool, Eco Audit. The tool allows us to determine the environmental impact of a product in six elements taken into account during the life cycle: material, production, transport, use, disposal, and end-of-life potential (EoL). The environmental impact of material production is defined by input energy [MJ/kg], CO_2 footprint [kg/kg] and water usage [l/kg]. Furthermore, the EoL potential means the amount of energy that can be recovered or lost during disposal (energy consumption [MJ/kg]). In addition, the EoL potential presents possibility to minimize the CO_2 footprint [kg/kg] of the material.
In the investigation, only four parts of their life cycle were analyzed: material, production, disposal, and end-of-life potential. The life of the product (years) was equal to one year.

3. ENVIRONMENTAL IMPACT

The environmental characteristics of the foams that are included in the database are shown in Figures 2–4.

Figure 2 shows the dependence of the CO_2 footprint during production on the kind of material [kg/kg], while Figure 3 presents the dependence of the CO_2 footprint of the material's production [kg/kg] on its embodied energy [MJ/kg]. For the sake of clarity in the diagrams, only the PUR foams and materials analyzed with extreme parameters were named.

One of the selected fillers, which is used in modified PUR foams – cork (low density), has a very low CO_2 footprint and embodied energy of its production. Moreover, both selected natural fillers (cork and paper) are the only ones among all the analyzed materials that are biodegradable. To sum up, it can be said that PUR foams are quite environmentally beneficial, while at the same time their composition still needs to be optimized in order to lower their environmental impact.

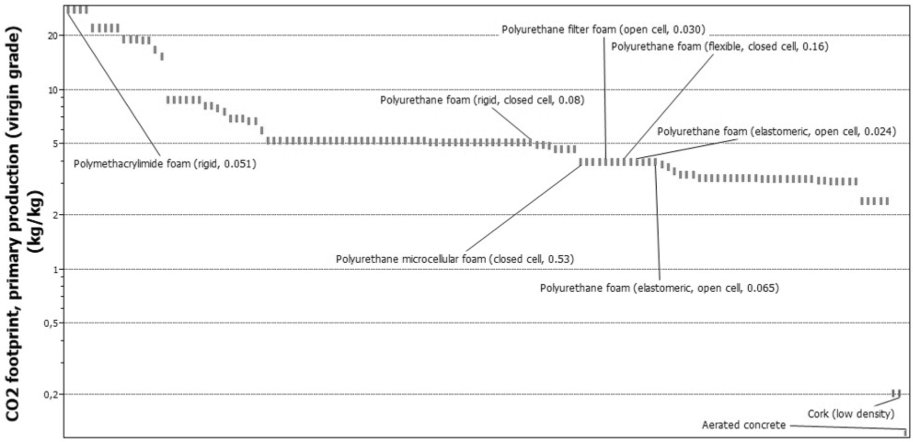

Fig. 2. Dependence of the CO_2 footprint of material production [kg/kg] on the types of material from which the foam was obtained

Source: own study based on the Ansys Granta Selector browser.

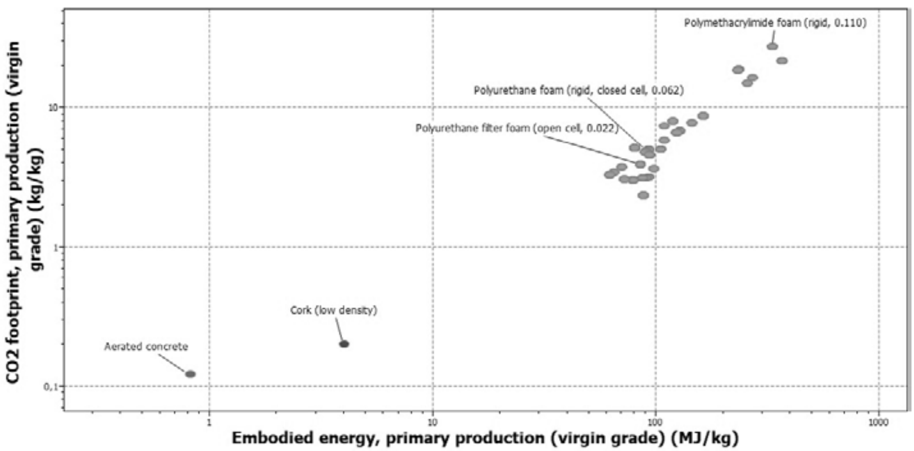

Fig. 3. Dependence of the CO_2 footprint of material production [kg/kg] on its embodied energy [MJ/kg]

Source: own study based on the Ansys Granta Selector browser.

In addition, Figure 4 presents the dependence of the CO_2 footprint of the material's production [kg/kg] and the water usage [l/kg] for their production.

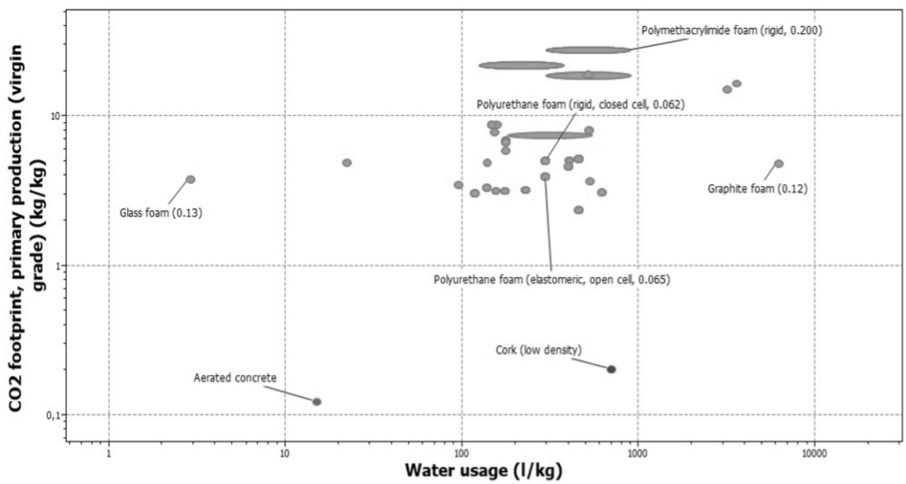

Fig. 4. Dependence of the CO_2 footprint of material production [kg/kg] on the water usage [l/kg] for its production

Source: own study based on the Ansys Granta Selector browser.

As mentioned before, when determining the environmental impact of a material (product), all kinds of environmental impacts need to be taken into account. The amount of water used in the production is also such a parameter. As can be seen in Figure 4, the production of glass foam generates a quite high CO_2 footprint during the material production; however, the amount of water used in this process is insignificant. The similar value of the CO_2 footprint was determined for graphite foam, the production of which, however, consumes a huge amount of water, which is related to the complicated and multistage production of this foam [Bonaccorsi et al. 2013]. The amount of water needed to obtain PUR foams is similar to that of polymethacrylimide; however, the CO_2 footprint generated from material production, as previously shown, is lower for PUR.

4. RESULT OF THE ENVIRONMENTAL IMPACT OF MODIFIED POLYURETHANE FOAMS

The tested PUR foams are not biodegradable materials, so only their modification by a natural filler might influence the development of their degradability after their use. The analysis was carried out on an example of PUR foam (no. 9 in Tab. 1) modified with natural fillers (paper (no. 1 in Tab. 1) or cork (no. 2 in Tab. 1)). In this analysis, the end-of-life was a landfill.

As shown in Figures 2–4, natural foams generally have a lower CO_2 footprint for the material production than PURs. Thus, one way to lower this parameter for PURs is blending with a natural filler. These modifications also affect the properties of the PUR, including its degradability [Alma et al. 2017; Brzeska et al. 2021], making these materials greener.

PUR foam (no. 9 in Tab. 1) was modified by two fillers: paper and cork, in the range of 0–40 wt% filler. Tables 2–3 present the quantitative composition of the tested foams with the paper filler (Tab. 2) or the cork filler (Tab. 3), and the values of their environmental material characteristics.

Table 2. Quantitative composition of the tested PUR foam with a paper filler and the values of its environmental characteristic during production

No.	Material	PUR mass [wt%]	Paper mass [wt%]	Embodied energy [MJ/kg]	CO_2 footprint [kg/kg]
1	PUR	100.0	0.0	85.1	3.95
2	PUR+paper1	99.5	0.5	84.9	3.94
3	PUR+paper2	98.5	1.5	84.5	3.91
4	PUR+paper3	97.5	2.5	84.2	3.88
5	PUR+paper4	97.0	3.0	84.0	3.87

cont. Table 2

6	PUR+paper5	95.0	5.0	83.4	3.81
7	PUR+paper6	92.5	7.5	82.5	3.74
8	PUR+paper7	90.0	10.0	81.7	3.67
9	PUR+paper8	80.0	20.0	78.3	3.39
10	PUR+paper9	75.0	25.0	76.7	3.26
11	PUR+paper10	70.0	30.0	75.0	3.12
12	PUR+paper11	65.0	35.0	73.3	2.98
13	PUR+paper12	60.0	40.0	71.6	2.84

Source: own study based on Eco Audit tool from Ansys Granta Selector software.

For comparison, the lowest footprint of CO_2, among all the synthetic foams, was polypropylene foam (2.91–3.21 kg/kg, average 3.06 kg/kg). The appropriate weight percent content of natural filler in the modified PUR foam allows the reduction of the CO_2 footprint to a value similar to that of polypropylene foam. Of course, the amount of added filler depends strictly on the desired properties of the end product. It is likely that the addition of as much as 40% of the paper would significantly deteriorate the mechanical properties of the PUR. Therefore, during the design, all expectations of this product should be analyzed.

Table 3. Quantitative composition of the tested PUR foam with a cork filler and the values of its environmental characteristic during production

No.	Material	PUR mass [wt%]	Cork mass [wt%]	Embodied energy [MJ/kg]	CO_2 footprint [kg/kg]
1	PUR	100.0	0.0	85.1	3.95
2	PUR+cork1	99.5	0.5	84.6	3.93
3	PUR+cork2	98.5	1.5	83.8	3.89
4	PUR+cork3	97.5	2.5	83.0	3.86
5	PUR+cork4	97.0	3.0	82.6	3.84
6	PUR+cork5	95.0	5.0	81.0	3.76

cont. Table 3

7	PUR+cork6	92.5	7.5	79.0	3.67
8	PUR+cork7	90.0	10.0	76.9	3.58
9	PUR+cork8	80.0	20.0	68.8	3.20
10	PUR+cork9	75.0	25.0	64.8	3.01
11	PUR+cork10	70.0	30.0	60.7	2.83
12	PUR+cork11	65.0	35.0	56.7	2.64
13	PUR+cork12	60.0	40.0	52.6	2.45

Source: own study based on Eco Audit tool from Ansys Granta Selector software.

Based on a linear regression of the dependences from Tables 2–3, calculations were made to determine the amount of filler needed to obtain the same value of the CO_2 footprint from the modified foams as from the polypropylene foam. The calculations confirmed that a foam consisting of 32 wt% paper or 24 wt% cork has the same CO_2 footprint as polypropylene foam. Considering the price of the filler, given in the Material Universe datasheet (about 1–1.5 EUR/kg paper and 2–11 EUR/kg cork), modification of the PUR by paper is economically more beneficial. Thus, as mentioned earlier, it should be taken into account in all the technical parameters (material properties), including the environmental and economic factors, when designing a new product.

5. RESULT OF THE ENVIRONMENTAL IMPACT OF POLYURETHANE FOAMS WITH DIFFERENT TYPES OF END-OF-LIFE

The type of end-of-life of the tested foams (PUR foam, no. 9 in Tab. 1) also influences the associated energy and carbon emissions. Analyses with three different disposal routes were carried out:

1) Landfill (collect and transport to landfill site),
2) Combust for heat recovery (collect, combust, recover heat),
3) Reuse [Ashby 2013].

The percentage of recovered material was equal to 50 or 100 percent.

The environmental characteristics of the production of PUR foam with different end-of-lives is presented in Table 4.

Table 4. The environmental characteristic of the production of PUR foams with different end-of-lives

No.	Material	End-of-life	Recovered material [%]	Eco Audit – end-of-life potential	
				Embodied energy [MJ/kg]	CO_2 footprint [kg/kg]
1	PUR	Landfill	100	0.00	0.00
2	PUR	Combust	100	-5.4	1.67
3	PUR	Reuse	100	-84.9	-3.95
4	PUR	Landfill	50	0.00	0.00
5	PUR	Combust	50	-2.7	0.84
6	PUR	Reuse	50	-42.5	-1.97

Source: own study based on Eco Audit tool from Ansys Granta Selector software.

The tested unmodified foam had 84.9 MJ/kg of energy embodied and a 3.95 kg/kg CO_2 footprint from material production. Combustion as a type of end-of-life enables recovery of some energy (negative value of the embodied energy in the EoL); however, it still has a CO_2 footprint from the material production, but smaller than the produced pristine material (from 3.95 kg/kg to 1.67 kg/kg or 0.84 kg/kg, depending on the percentage recovered material). Significantly minimalizing the CO_2 footprint and recovering more energy are possible throughout the reuse as a kind of end-of-life. At 100% recovered material, 16 times more energy recovery is achievable with reuse compared to combustion. This confirms the common belief that recycling polymer products is safer for the environment than burning them.

The search for energy recovery from the production of materials or the disposal of the material after its use could be one of the primary types of preventing global warming.

6. CONCLUSIONS

The foam materials industry is constantly evolving. Materials are energy intensive due to the high embodied energy and the associated CO_2 footprint. However, by choosing the right material (synthetic or natural), the amount of energy used and the CO_2 generated can be minimized at the design and production stage for the materials.

It should be remembered that the overall environmental impact of a product depends on many factors, only three of which (embodied energy, CO_2 footprint, and water usage of material production) are discussed in this paper. The data obtained from the Ansys Granta Selector program clearly show that the appropriate modification of the PUR synthetic foams with natural fillers reduces their environmental impact. Eco Audit is a fast and easy method for material manufacturers to make strategic decisions.

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