Polylactic Acid *vs.* Polyethylene Terephthalate: Which is Carrying a Heavier Ecological Rucksack?

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This paper deals with an input oriented method called Ecological Rucksack applied on two materials –corn starch polylactic acid (PLA) granules (bottle grade) and polyethylene terephthalate (PET) granules (bottle grade). We calculated the total mass of material inputs of PLA (from the cradle to the point of sale) and made comparative analysis with PET. Case study results indicate that Ecological Rucksack of PET granules (bottle grade) in terms of its abiotic material and biotic material requirement is about 44% lower than the Ecological Rucksack of corn starch PLA granules (bottle grade).However, PLA has significantly lower water requirement compared to PET. The study has highlighted some limitations of the Ecological Rucksack method arising from the limited data availability and uncertainties associated with its application.

Keywords: Ecological Rucksack, material intensity factors, corn starch PLA, PET

More than 20 years ago Schmidt-Bleek concluded that the core of sustainability challenge is to diminish resource use in absolute terms, rather than just reducing the harmful effects of specific substances [1]. Through production processes, sooner or later, material inputs become outputs [2]. Unfortunately, only very few of the outputs are usable or desired the products. Consequently, by measuring the input, we can make an estimation of the environmental impact potential. With that kind of measuring, we may not arrive at a qualitative impact assessment, but at a valuable quantitative indicator of resource use efficiency [2].

In the past two decades, a number of methodological approaches were developed which measure resource use and related environmental impacts caused by production and consumption[3].Their primary importance is reflected in the fact that they provide a basis for re-engineering of our production systems toward *better but less* instead of *more is better* [4].One of the methods from the group called *material flow accounting* methods (MFA) is the *Ecological Rucksack* method [5-7].

The metaphor *Ecological Rucksack*[1] was created in early 1990s to illustrate the fact that the industrial creation of every object requires much more natural material than it is contained in its final form. In a sense, this represents the *value lost* from an ecological point of view [2, 8]. An Ecological Rucksack is the total quantity (in kg) of materials moved from nature to create a product or service, minus the actual mass of the product. In this regard the Ecological Rucksack of a product measure the amount of materials not directly used in the product, but displaced because of the product.

The method takes a life cycle approach by calculating the amount of materials removed by human beings from their natural deposits [2,7] from the cradle to the point of sale of the analyzed product [7, 9, 10]and represents hidden material flow [5,11]. These materials are usually divided into 5 categories: abiotic materials, biotic materials, water, air and earth movement (detailed description of these categories is provided in appendix, table 1).

The objective of this paper is to demonstrate the applicability of the Ecological Rucksack method through a case study which aims to compare bottle grade granules made from biomass-based polylactic acid (PLA) and fossil-based polyethylene terephthalate (PET).

Table 1
FIVE CATEGORIES OF ER INPUTS [2,9,10]

Resource category	Description
Abiotic Raw Materials	Mineral raw materials (used extraction of raw materials, such as ores, sand, gravel, slate, granite),fossil energy carriers (e.g. coal, petroleum oil, petroleum gas), unused extraction (overburden, gangue etc.), soil excavation (e.g. excavation of earth or sediment), spoils (as overburden from mining activities or excavated materials for infrastructure).
Biotic Raw Materials	Plant biomass from cultivation, biomass from uncultivated areas, counted as fresh mass (meat is reduced to plant biomass inputs unless it is from wild animals. Domesticated animals are already part of the techno sphere, and are therefore referred back to biomass taken directly from nature, e.g. plant or animal fodder).
Water	Surface, ground and deep ground water (separated according to process and cooling water).
Air	Oxygen molecules (bonded in combustion air, chemical and physical transformation - aggregate state).
Earth Movements	Mechanically moved soil (while ploughing) or alternatively soil erosion in agriculture and silviculture.

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Experimental part

Methods and materials

The Ecological Rucksack method

In general, the Ecological Rucksack of a product can be calculated within each of the five material category *j* as the difference between the total mass (in kg) of material inputs (MI_j) for manufacturing of the product (i.e. from cradle to the point of sale [12]), and the mass (in kg) of the analyzed product (MsP).

$$ER = MI - MsP \quad (1)$$

Calculating the MI is extremely labor-intensive process given the large number of inputs in the production chain of the analyzed product. Therefore, practitioners usually base their first calculations on the material intensity factors (R_i) (also called the rucksack factors). Material intensity factors are pre calculated normalized values which indicate the total amount (in kg) of abiotic matter, biotic matter, water, air and soil movement that is directly or indirectly required in order to provide a specific input *i* (e.g. raw material, electricity, transport) [2, 13]. The main data source for R_i factors is given in the table on the Wuppertal Institute web site [14] which is updated and extended on annual basis.

If the material intensity factors are available than MI can be easily calculated by multiplying the amount of individual inputs (M_i) (e.g. raw material, electricity, transport) of the production process of the investigated product by their respective material intensity factor within each of the five material categories *j* ($R_{i,j}$).Thus, the material input within each of the five material input categories (MI_j) is calculated as follows (2):

$$MI_j = \sum_{i=1}^{n} M_i \times R_{i,j} \quad (2)$$

where M_i stands for the quantity of input *i* in the production process, whereas $R_{i,j}$ stands for the material intensity factor of the *i* input within the *j* material category.

Although, ER can be calculated for each of the five material categories (table 1), it is not allowed to sum up the results of different material categories [2]. It is permissible and often makes sense, however, to compile the abiotic materials, biotic materials and erosion categories [2]. The sum of these categories is called “Total Material Requirement (TMR)” [2]. Consequently, the ER is often calculated as the difference between TMR and MsP (3). This approach is followed in this study as well.

$$ER = TMR - MsP \quad (3)$$

Accordingly, the TMR is calculated by summing up the results within three material categories (abiotic material, biotic material and erosion) as follows (4):

$$TMR = \sum_{j=1}^{3} MI_j = \sum_{i=1}^{n}\sum_{j=1}^{3} M_i \times R_{i,j} \quad (4)$$

Material intensity factors of the bottle grade PET

Polyethylene terephthalate (PET) is the most common thermoplastic polymer resin of the polyester family and it is intensively used as a raw material for bottle production [15].As an important representative of plastic materials (fig. 1) PET was in the focus of Ecological Rucksack survey very often and its material intensity factors were recalculated several times [10, 14, 16].The newest material intensity factors ($R_{i,j}$) of bottle grade PET (2014), required for the calculation of its Ecological Rucksack, are available from the Wuppertal Institute website [14] and they are presented in table 2.

Inputs and material intensity factors of the bottle grade PLA

Based on their biodegradability and raw material (i.e. fossil or biomass) all bioplastics can be divided into three

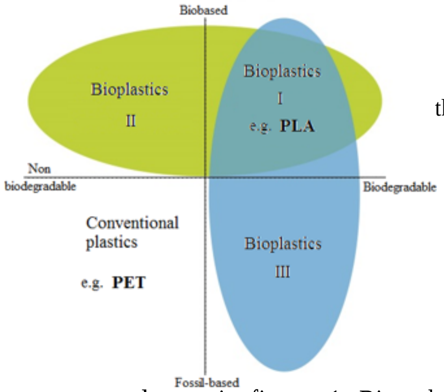

Fig. 1. PLA and PET position based on their biodegradability and primary raw material [18]

groups as shown in figure 1. Biopolymers are usually biodegradable and compostable, however non-biodegradable bioplastics exist as well [17].

PLA belongs to the group of biomass-based and biodegradable plastics. In 2013 around 185,000 metric tons of PLA was produced making around 11% of the total global production of bioplastics [18]. PLA is mainly produced from corn; however, there are other raw materials from which PLA can be obtained [19]. Figure 2 shows the process route of the pure corn starch PLA [20].

As the first step in calculating the Ecological Rucksack the individual inputs (M_i) of the PLA production process should be estimated. This is not an easy task since commercial PLA production is limited to only a few production sites and detailed material and energy flows are not available yet due to confidentiality issues. In this research a preliminary assessment of the main material and energy inputs in the production process of PLA is given based on the published eco-profiles of PLA granules produced at NatureWorks LLC from Nebraska, USA, the world’s largest PLA producer [21].

The inputs of PLA production can be divided into four categories: raw material (i.e. corn), heat, electricity, and transportation. According to [21] production of 1 kg of PLA granules requires 1.53 kg of corn (grain maize). The heat and electricity requirements of the production process are estimated indirectly based on data on energy content of the delivered fuel presented in Vink et al. [21]. The energy content of the delivered fuel used in the production chain

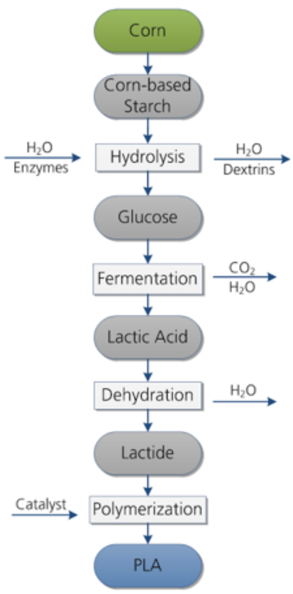

Fig. 2.Production chain of the corn-based PLA

of 1 kg PLA is 25 MJ[21]. This include the energy content of fuels (e.g. natural gas, coal, oil) used in the agricultural machines in the agricultural step and the heat and electricity requirements of the corn-to-PLA production process.

Under the assumption that the heat requirements of the process are fulfilled by natural gas, the heat requirements of the process are 18.1 MJ per kg of PLA granules. Based on the energy content of natural gas (41 MJ/kg [14]) the mass of natural gas input is 0.44 kg. The electricity consumption in the process is estimated as 6.1 MJ or 1.7 kWh assuming that oil is only used in the agricultural stage of the production chain and that natural gas is not used for electricity production. The later seems to be a realistic assumption since the electricity supplier of the PLA production plant in Nebraska (i.e. the Mid-Continent Area Power Pool – MAPP) has a negligible share (<1%) of natural gas and oil in its fuel mix [22]. In this research it is assumed that PLA granules are transported by diesel trucks to consumers located 200 km from the PLA production facility (or 0.2 tkm per 1 kg of PLA).

In the second step the specific material intensity factors ($R_{i,j}$) of inputs have to be identified. The specific intensity factors of individual inputs used in the production chain of PLA (e.g. grain maize, natural gas used as heat source, electricity and transportation with diesel truck) are available from the Wuppertal Institute's website [14] and they are summarized in table 2.

It is evident from table 1 that a comprehensive interpretation of the category *earth movement* is not possible at the moment due to very limited data on this category at the Wuppertal Institute's website. In fact data on earth movement is provided only for grain maize, though it is evident that this is a crucial aspect in a largely coal-based electricity production. Since there is no comprehensive data on this category we will not take soil erosion as a contributor to TMR in this study.

Results and discussions

A comparative analysis of material inputs of PLA and PET

We performed a comparative analysis of the material inputs associated with the production chain of 1 kg corn starch PLA granules (bottle grade) and 1 kg of PET granules (bottle grade) within the material categories investigated. The estimated results of Ecological Rucksack of PLA as well as the newest existing data for the PET are shown in table 3. Relative relation between material inputs of those two plastic materials within the 5 material categories is presented in figure 3.

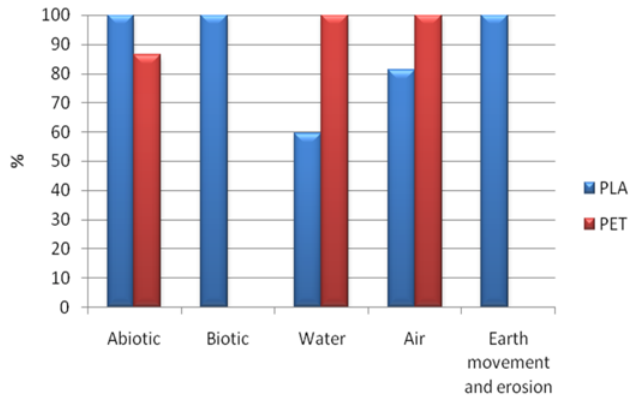

Fig. 3.Relative relation between the ecological rucksacks of bottle grade PLA and bottle grade PET within the five material categories

As indicated in table 3, total abiotic material input of PLA is 7.3 kg and for PET is 6.3 kg. This is quite surprising given the bio-based origin of PLA. High inputs of abiotic materials in the process chain of PLA are mainly due to high abiotic material intensity factor of the European electricity, which is largely produced from fossil fuels. In figure 3 we can notice that PET has about 13.7% lower total abiotic material input.

In terms of biotic inputs, total material input of PLA is 3.22 kg, whereas biotic material input of PET is negligible. Biotic resources have crucial importance for PLA because biomass (i.e. corn) is its primary raw material. In contrast, PET production doesn't contain biotic materials.

Total water material input is about 137 kg for PLA, and it is significantly higher for PET – amounts 230 kg. This amount includes processing and cooling water as well, since specific data are not available yet at the Wuppertal Institute's website. Large amounts of water for both production processes are not surprising - the consumption of water for creating industrial goods or food can easily surpass 100 or 1000 kg per kg of product [10]. As seen from table 3, the water consumption is mainly related to electricity generation, which requires large amounts of cooling and processing water. In figure 3 is noticeable that the participation of water is approximately 40% smaller in the PLA production process. Total air material input is 2.84 kg for PLA and 3.5 kg for PET, which means that this indicator is about 19% lower for PLA. Total earth movement material input cannot be determined because, as already mentioned above, the necessary data are not available. Therefore, it was not taken into account in the calculation of TMR.

Table 2
MATERIAL INTENSITY FACTORS ($R_{i,j}$) OF INDIVIDUAL INPUTS (M_i) USED IN THE PRODUCTION PROCESS OF PLA

Inputs (M_i)	Unit	Abiotic material ($R_{i,1}$)	Biotic material ($R_{i,2}$)	Earth movements: Erosion ($R_{i,3}$)	Earth movements: Mechanical earth movement ($R_{i,4}$)	Water ($R_{i,5}$)	Air ($R_{i,6}$)
Grain maize	kg/kg	0.89	2.06	0.9	625	25.01	0.21
Electricity	kg/kWh	3.15	0.04	/	/	57.64	0.514
Natural gas	kg/kg	1.22	/	/	/	0.50	3.64
Truck transport	kg/tkm	0.22	/	/	/	1.91	0.21

*Notes: * TMR includes only abiotic material and biotic material. Soil erosion is not taken into account due to the limitation as explained earlier in the text.*

Table 3
MATERIAL INPUTS (in kg) OF1 kg OF BOTTLE GRADE PLA OR PET GRANULES

	Inputs	Abiotic	Biotic	Water	Air	Erosion	Earth movement	TMR*
PLA	Corn (1.53 kg)	1.36	3.15	38.27	0.32	1.38	956.25	4.51
	Electricity (1.7 kWh)	5.36	0.07	97.99	0.87	n.a.	n.a.	5.42
	Natural gas (0.44 kg)	0.54	0.00	0.22	1.60	n.a.	n.a.	0.54
	Transport (0.2 tkm)	0.04	0.00	0.38	0.04	n.a.	n.a.	0.04
	Total	7.30	3.22	136.86	2.84	1.38	956.25	10.52
PET	Total	6.30	0.00	230.00	3.50	n.a.	n.a.	6.30

TMR in abiotic and biotic materials is 10.52 kg for PLA and 6.3 kg for PET. Consequently, amount of abiotic and biotic materials removed by human beings from their natural deposits during the PET production is approximately 40% less than in the case of PLA production (table 3).

Taking into account the selected service unit of 1 kg and according to equation (3), it is possible to calculate the Ecological Rucksacks of plastic materials that are included in this study.

$ER_{PLA} = 9.52$ kg $\qquad ER_{PET} = 5.3$ kg

It follows that the Ecological Rucksack of PET granules (bottle grade)is about 44% lower than the Ecological Rucksack of PLA granules (bottle grade).

Advantages and drawbacks of the ER method

Due to its simplicity, this method gives results in a very short period of time and provides a preliminary assessment and quick reaction. It is suitable for quick assessment of technical solutions and products from the point of their resource use efficiency. This method can help in the design of industrial products and planning of environmentally friendly processes, facilities and infrastructures [23]. Material and energy inputs are measured in the same units which makes easy to combine them within the same environmental assessment [23, 24].

However, the Ecological Rucksack method is often criticized since it only assesses material flow and not the quality of flow [9]. As already indicated, the method does not take into account the specific environmental toxicity of material flows [23]. However, this makes it suitable to be used as a screening step for LCA [23, 25]. Ecological Rucksack needs to be combined with other indicators as it does not allow the assessment of the qualitative aspect such as a large environmental impact caused by an extremely small quantity [9].

It should be noted that the Ecological Rucksack is a technique currently under development and the availability of R_i factors for potential inputs is insufficient [9]. The available rucksack factor for a specific input can vary significantly depending on their source which sometimes can cause problems in assessing their validity and usage [2]. The documents which provide R_i factors [14] generally do not contain detailed description of the calculation procedures, data sources and assumptions used for their calculation, which means that a very important piece of information is not available to the user. Also, it should be recalled that the creators of the method used Ecological Rucksack as a first approximation of an indicator that can technically describe the resource use intensity of a highly diverse set of goods and services [23]. Thus, the results obtained by this method cannot be considered completely accurate, but give a framework and orientation for further consideration of the observed problem.

Conclusions

PLA, as a bio based and biodegradable material, is often considered as a more sustainable and environment friendly alternative to fossil-based PET. Further increase in the global production of PLA is expected; therefore, it is very important to investigate the environmental impact of PLA from different aspects, including its Ecological Rucksack, as a comprehensive indicator of its resource use efficiency.

Surprisingly, this case study has showed, that the Ecological Rucksack and Total Material Requirement of PLA granules is less favorable compared to PET granules (on equal mass bases). This means that the production of PLA requires more abiotic and biotic resources than the production of PET granules. Results have also shown that PLA has lower water requirements than PET.

It is important to note, that the Ecological Rucksack method is still under development and high uncertainties are associated with its application. Therefore, the results presented in this study should be interpreted by taking into the account the limitations of the Ecological Rucksack method.

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