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COMPARATIVE LIFE CYCLE ASSESSMENT OF TORREFIED PELLET PRODUCTION FROM FIVE LIGNOCELLULOSIC BIOMASS TYPES

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ABSTRACT: To achieve the targets for reducing greenhouse gas emissions by 2020, many European countries intend to decrease fossil fuel consumption by promoting the use of biomass energy. Due to their renewable nature and to their density and physicochemical properties, which are similar to those of coal, torrefied biomass pellets seem to be a promising substitute for this fossil fuel. This study aims to evaluate, using cradle-to-plant gate life cycle assessment, the potential environmental benefit of the production of wood torrefied pellets compared to wood pellets. It also studies the possibility of using alternative sources of lignocellulosic biomass for pellet production. Four types of biomass (fescue, sorghum, maize and bamboo) were tested and their environmental results at production and transformation stages are compared with those of wood pellets. A comparison of the production of 1 GJ of energy from the four types of lignocellulosic torrefied biomass pellets reveals that torrefaction of wood provides the best environmental performance. This is mainly due to the production of biomass process: the growth of the wood used in this study does not require the use of mineral or organic fertilisers. These inputs greatly increase the environmental impact of agricultural biomass. Finally, increasing the lower calorific content of biomass by means of torrefaction may also be linked to a reduction in the environmental impact of biomass pellet production, depending on the type of biomass and the impact category. For all the biomass types studied, performance in the global warming impact category was improved by the torrefaction of the pellets.
Keywords: life cycle assessment, torrefaction, environmental impact, lignocellulosic source

1 INTRODUCTION

To achieve the targets for reducing greenhouse gas emissions by 2020, many European countries intend to decrease fossil fuel consumption by promoting the use of biomass energy. Agricultural and forest biomass is a promising alternative to fossil fuels for producing electricity, heat and liquid fuels because it can be exploited renewably. Moreover, biomass is a readily available local resource which will present local rural farmers who grow it with an opportunity to diversify their agricultural output and sources of income. From an environmental point of view, the use of biomass energy is expected to prevent climate change mainly due to its renewable and carbon-neutral nature [9] [24]. However, the use of biomass as an energy source also brings about economic competition between alternative methods of resource utilization. This is because resources and production areas are limited, both in Belgium and globally. It is therefore necessary to diversify resources, to adapt the associated economic processes and to innovate. This innovation will involve proposing new fuels, created using highly energy-efficient processes and techniques, and combining different processing chains with a view to overall energy optimisation.

Resulting in the production of a coal-like solid biofuel with higher energy density and better physical and combustion properties, torrefaction seems to be a promising technology [25]. Compared to pelletisation (84% energy conversion efficiency i.e. the ratio between the useful output of an energy conversion machine and the input, in energy terms) and pyrolysis (64%), which can also transform biomass into energetically dense fuels, torrefaction (94%) presents the prospect of greatest efficiency. When torrefaction and pelletization are combined, the product has an energy content of 22 to 25 GJ/tFM (fresh matter). This renewable fuel can be used in coal-fired power plants without major modification of the process.

The environmental assessment of a product must take all stages of its life cycle into account. The main objective of LCA is to provide a holistic assessment of emissions and of the resources needed for a production system. This evaluation tool makes comparisons possible between different biomass types used in the production of torrefied pellets, and provides valuable scientific information to the various stakeholders (producers, consumers, decision-makers). This is a comparative approach which makes it possible to evaluate the environmental impact of new uses for lignocellulosic biomass and 'low-carbon' processes. The potential for reducing greenhouse gas emissions from the various ways of generating energy from biomass can thus be evaluated with a view to meeting the drastic greenhouse gas reduction targets set for 2020. This method also makes it possible to identify the strengths and weaknesses of each stage and each process, and to draw conclusions which will aid in improving energy and environmental efficiency.

2 METHODOLOGIES

2.1 Environmental life cycle assessment

Life cycle assessment involves surveying and evaluating the inputs, outputs and potential environmental impacts of a system of production throughout its life cycle, from raw material acquisition or generation from natural resources to final disposal [6].

The LCA methodology can be used to assess the environmental burden created by renewable energy production systems at each stage in their life cycle.

There are four phases in an LCA study: goal and scope definition, life cycle inventory, impact assessment and interpretation [6].

SimaPro 8.2.3 and the database ecoinvent 3.1 (for background data) were used to perform this study.

2.2 Functional unit, goal and scope definition

The objectives of this cradle-to-gate study were to assess and compare the environmental impact of torrefied pellets from five lignocellulosic biomasses in order to identify new biomass types (i.e. other than wood) for production. The benefits of torrefied pellets relative to non-pre-treated pellets were also investigated. The use of the pellets (combustion) and the end of life of ashes are not included in this study

For these analyses, a functional unit of 1 GJ of potential energy from the pellets was used. The quantity of pellets needed to produce 1 GJ was calculated from the LHV (lower heating value) of each biomass type: fescue (F), sorghum (S), maize (M), bamboo (B) and wood (W). The LHVs of pellets and torrefied pellets are different, as is the LHV of each biomass type.

Data on the production of wood pellets and the torrefaction process came from an existing torrefaction plant in Wallonia.

This study included the harvesting and transportation of the biomass to the plant and the production of torrefied pellets (feeding, chipping, storage extraction, drying, torrefaction, pelletising, pellet feeding, pellet extraction and ventilation). The transportation to the point of sale, use and end of life of the pellets were not included. The system boundaries ended at the plant gate.

2.3 Life cycle inventory

The boundaries of the system studied are shown in Figure 1. The data used in this study are described below.

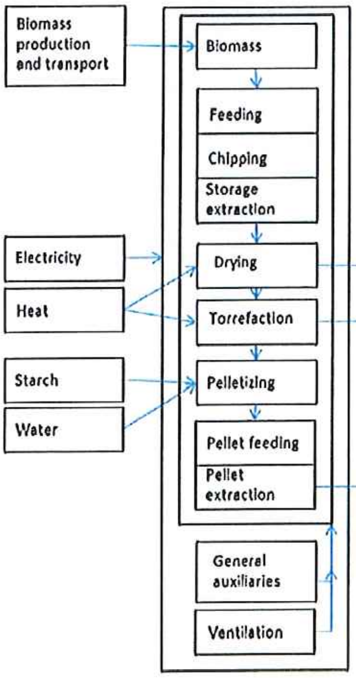

Figure 1: System boundaries

In order to describe the specific characteristics of the crops considered in the project, an inventory of the crop routes for the various biomass types was carried out. The crop routes of sorghum and tall fescue were established from the results of the Interreg IV A Enerbiom project [27]. The average yield of sorghum produced in Belgium is 49.94 t FM/ha at 28.5% DM (i.e. 14.24 t DM/ha), and the cultivation time is about 7 months. For heavy metal balances, sorghum's heavy metal content was based on the levels described for grain and straw in [19][2].

Based on tests, a yield figure of 17.3 t FM/ha at 80% DM (i.e. 13.8 kg DM/ha) was used for fescue. The crop's cultivation time is 12 months.

For bamboo, a crop route was determined on the basis of expert opinion (personal communication, Temmerman M.). The yields and the quantities of mineral fertilisers applied were based on the publication by [3]. The form of mineral fertiliser inputs was based on [7]. A yield of 12.6 t FM/ha/yr (i.e. 6.2 t DM/ha/yr) was estimated, taking the effect of fertiliser inputs into account. A cultivation time of 7 years was used. Mechanisation data were adapted from MECACOST and TtCR projects [15] [22].

For maize, the route described by [26] was used. The average yield is 51.2 t FM/ha at 33% DM (i.e. 16.91 t DM/ha), and the crop cultivation time is 5.5 months.

2.4 Torrefaction

In 2011, there was one torrefaction unit operating in Wallonia (Belgium). Data on the torrefaction of wood pellets were obtained from this plant. As the calorific value of the torrefied pellets produced is 23 GJ/t, 43.478 kg of pellets need to be produced to obtain fuel with a calorific capacity of 1 GJ.

For the other biomass types considered in this study, data from the plant inventory for the production of torrefied and non-torrefied pellets were adapted on the basis of the DM (dry matter) content of the different biomass types (wood, bamboo, maize, fescue, sorghum) and their LHV (lower heating value) (Table I).

Table I: LHVs for torrefied and non-torrefied pellets

Biomass	Biomass input %DM	LHV of non-torrefied pellets MJ/kg DM	LHV of torrefied pellets MJ/kg DM	Sources
Fescue	80%	19.1	20.8	[1]
Sorghum	29%	16.1	23.6	[8]
Maize	33%	16.5	20.8	[10][11]
Bamboo	50%	17.6	21.1	[21]
Wood	65%	16.25	23	Torrefaction plant (Belgium)

2.5 Life cycle impact assessment

2.5.1 Field emissions

Nitrogen losses (NH_3, NO_3^-, N_2O) were modeled using the models of the IPCC [5] and of the Swiss research station ART [16]. Heavy metal balances were based on those of ecoinvent, augmented with data from the analyses of the CONTASOL project [12] with regard to nutrient content and metal trace elements in mineral and organic fertilizers. Phosphorus losses (PO_4^{3-}) were also based on the SALCA-P models [14]. Concerning pesticide emissions, ecoinvent's position was followed. This postulates that all plant protection products end up in the soil (in agricultural contexts).

Agricultural work process emissions were based on emission factors from Swiss studies [18][28][4]. They were adapted on the basis of data such as the fuel consumption, working time, service life, nominal and average power and weight of the machines considered, derived from the MECACOST project [15].

2.5.2 Torrefaction emissions

NOx and CO emissions and the water balance were measured within the plant studied.

The heat reused in the process itself was disregarded. Only heat from external sources (a neighboring cogeneration unit) was modeled. All of the electricity consumed was considered to be emitted into the air as heat.

The environmental impacts of the five biomass types were expressed in terms of the functional unit, i.e. the quantity of torrefied pellets with a calorific capacity of 1 GJ.

2.5.3 Impact categories

The impact categories investigated were global warming (GWP), human toxicity (HTP), terrestrial acidification (TAP), eutrophication (EUP), ecotoxicity (AEP), soil occupation (ALO), cumulative energy demand (CED) and water consumption (WDP) (Table II). An uncertainty analysis based on Monte Carlo simulations of 1,000 runs was performed as an uncertainty analysis.

Table II: Categories and methods used

Impact category acronym	Impact category	Evaluative method
GWP	Global warming potential	IPCC 2013 GWP100a (*)
HTP	Human toxicity potential	USEtox recommended + factors derived from our own calculations for missing substances [17](°)
TAP	Terrestrial acidification potential	Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance [13]
EUP	Eutrophication potential	CML-IA baseline
AEP	Ecotoxicity potential	USEtox recommended + interim + factors derived from our own calculations for missing substances [17](°)
ALO	Agricultural land occupation	ReCiPe midpoint (H) (*)
CED	Cumulative Energy Demand	CED v1.8, except energy gross calorific value in biomass.
WDP	Water Depletion Potential	ReCiPe midpoint (H) (*)

3 RESULTS

3.1 Comparison of LCA for production of 1 GJ of torrefied pellets

The environmental profiles for the production of 1 GJ of torrefied pellets from fescue, sorghum, maize, bamboo and wood are presented in Figure 2.

These findings indicate that certain aspects of the pelletization (feeding, storage extraction, pellet feeding, pellet extraction, general auxiliaries, ventilation) have a negligible environmental impact (i.e. <2% of total impact) compared to the other processing stages.

In the production of torrefied pellets from biomass, the biomass production phase tends to be a stage with a high environmental impact (42±33%), with impacts of 39±33% for GWP, 51±38% for HTP, 33±30% for TAP, 38±34% for EUP, 40±48% for AEP, 57±39% for ALO, 44±31% for WDP and 30±22% for CED. For wood, however, the main production impact is in terms of ALO (88%), whereas for the other impact categories, the production phase of wood biomass has a much lower impact than biomass produced by agriculture.

The chipping stage has a low overall environmental impact, mostly in the GWP (2±1%), WDP (2±1%) and CED (7±3%) categories.

Drying is the most environmentally costly operation (8±7%) after biomass production. In terms of impact categories, it accounts for 7±3% of GWP, 6±3% of HTP, 3±1% of TAP, 4±2% of EUP, 3±1% of AEP, 17±7% of ALO, 8±3% of WDP and 17±7% of CED. Given their low DM rate at harvest, sorghum and maize need to undergo more drying, which affects the environmental profiles of these two biomass types, accounting for 12±8% and 12±9% of their total impact respectively. A potential reduction of the environmental cost of this operation would be to diminish the humidity rate at harvest.

The torrefaction process itself accounts for 5±6% of the total environmental profile of the process. It mainly affects the GWP (3±2%), TAP (11±6%), EUP (8±4%), WDP (4±3%) and CED (12±8%) categories. Bamboo, however, seems to differ from other biomass types at this stage, having a lower effect across the impact categories (1±1% vs 5±5% for fescue, 7±7% for sorghum, 8±8% for maize and 5±5% for wood).

Lastly, the pelletizing stage also has a low impact (3±3%) on the overall environmental profile of the torrefaction process, mainly in the GWP (3±2%), WDP (4±2%) and CED (10±4%) categories.

Table III: Uncertainty analysis of the LCAs of the production of 1GJ of torrefied pellets of fescue (F), sorghum (S), maize (M), bamboo (B) and wood (W) compared in pairs for different impact categories. Extremely significant: '***' $p \geq 0.999$; Highly significant: '**' $p \geq 0.99$; Significant: '*' $p \geq 0.95$; Not significant: 'p value', $p < 0.95$.

Biomass types		Impact categories							
		ALO	CED	AEP	EUP	GWP	HTP	TAP	WAP
F	S	***	0.35	0.32	***	***	0.32	***	0.48
F	M	***	0.38	**	**	***	0.45	***	0.45
F	B	***	***	***	***	***	0.25	***	0.44
F	W	0.47	***	***	***	***	**	***	0.44
S	M	0.15	0.07	***	***	***	**	***	0.46
S	B	***	***	***	***	***	0.35	***	0.49
S	W	*	***	0.37	***	***	0.42	***	0.44
M	B	***	***	0.21	***	***	0.36	***	0.46
M	W	*	***	***	***	***	0.24	***	0.45
B	W	0.44	**	***	***	***	0.12	***	0.43

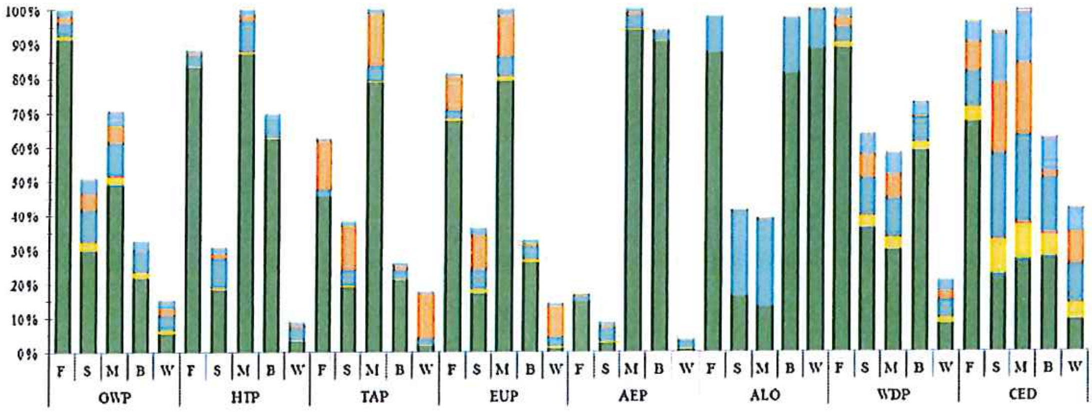

Figure 2: LCA comparison of the production of 1 GJ of torrefied pellets for fescue, sorghum, maize, bamboo and wood. Biomass ; Feeding ; Chipping ; Storage extraction ; Drying ; Torrefaction ; Pelletising ; Pellet feeding; Pellet extraction; General auxiliaries; Ventilation.

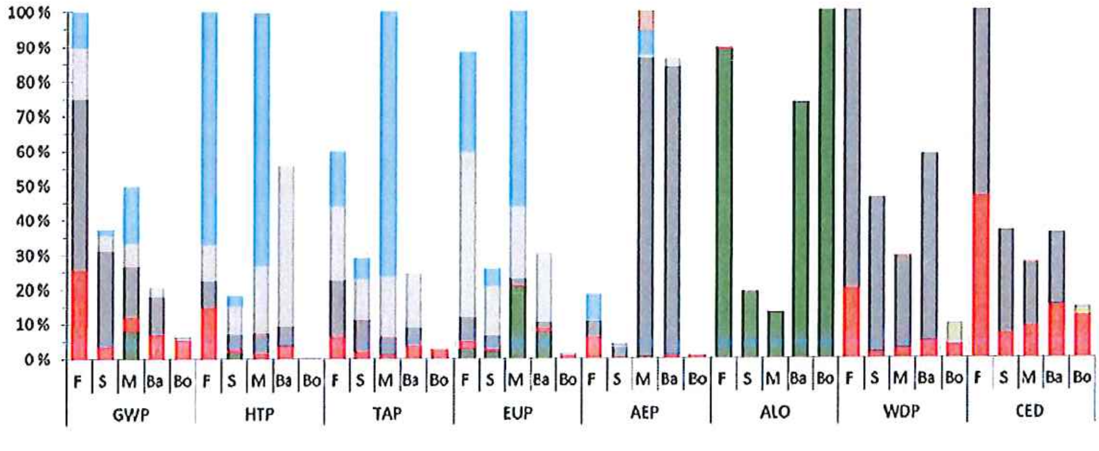

Figure 3: Life cycle assessment of the production of 1 kg DM of fescue, sorghum, silage maize, bamboo and wood. Cultivation effects ; Mechanisation ; Seeds ; Chemical fertiliser production ; Pesticide production ; Chemical fertiliser emissions ; Organic fertiliser emissions ; Pesticide emissions ; Gravel ; Transport.

The uncertainty analysis (Table III) allows us to identify any significant differences, per impact category, between the different biomass types in the production of 1GJ of torrefied pellets. The uncertainty analysis for GWP indicates that the environmental profiles of all five biomass types show extremely significant differences. Wood appears to have the lowest environmental impact, while fescue has the worst environmental score for this category.

The results of the uncertainty analysis are less varied for HTP. There are highly significant differences between fescue and bamboo and between maize and wood, to the disadvantage of fescue and maize respectively.

Again, some highly significant differences are found for the five biomass types. This time, maize has the worst environmental score, while wood remains a strong performer in the TAP and EUP categories.

For ALO, fescue and wood present the worst environmental performance, while there is no significant difference between maize and sorghum, which have the lowest environmental impacts for this category.

According to the uncertainty analysis, no significant difference is observed in terms of WDP. This result, however, must be strongly qualified, since it is due to a methodological bias. This is because the new version of the ecoinvent database (v3.1) has modified the calculation of water balances. In this new version, most of the processes have balanced water consumption. This amounts to saying that the quantity of water entering the system is equivalent to the quantity of water leaving it.

Incoming water quantities receive a positive characterization factor, while outgoing water flows are given a negative characterization factor. However, the simulations conducted during the uncertainty analysis seem unable to take account of the potential correlations between the incoming and outgoing water flows. In other words, depending on the standard deviation attached to the data, the uncertainty analysis may assume a high value for an incoming water flow and a low value for an outgoing water flow even though these two values are actually correlated for the water balance calculation (i.e. if more water enters the system, more water will leave). Despite the large number of processes involving the use of water in the early stages in our models (electricity production, fuel production, fertilizer production, etc.), the uncertainty analysis for water balances as modeled in ecoinvent v3.1 is no longer able to identify any significant difference.

Lastly, wood once again has the best environmental profile for CED, whereas there is no observable difference between the biomass types with the worst environmental performance in this category (maize, sorghum and fescue).

This first analysis of the environmental impacts of producing 1GJ of torrefied pellets for fescue, sorghum, maize, bamboo and wood suggests that the transformation of wood into pellets is the least costly from an environmental point of view. This superior performance is mainly due to wood's method of production: according to data from the enecobois project [23], the production of softwood requires no fertilizers (organic or mineral). By contrast, analysis of the environmental impact of producing 1 kg DM of the different biomass types (Figure 3) shows the significance of mineral fertilizer in the production phase and of the emissions linked to the use of both organic and mineral fertilizers. Using biomass derived from more agricultural production to produce torrefied pellets will generally have a greater environmental impact than forest biomass.

3.2 Environmental benefit of torrefaction

Another analysis was carried out in order to weigh the expected potential energy gain of torrefaction against its environmental impact. Thus, the production of 1GJ of torrefied pellets was compared with the production of 1GJ of non-torrefied pellets, and an uncertainty analysis was performed to identify any significant differences between them (Table IV).

It can be seen from this analysis that for fescue the effect of torrefaction is beneficial from an environmental point of view for the impact categories ALO (-6.2%), GWP (-4.4%) and probably WDP (see previous comments). On the other hand, torrefaction produces an extremely significant increase in the impact in the categories TAP (+22%) and EUP (+7%), and a significant increase in the impact in the category CED (+2.8%). For sorghum, torrefaction produces an extremely significant improvement in the environmental profiles for ALO (-31%), CED (-12.4%), EUP (-4.5%), GWP (-24.7%) and potentially WDP, whereas no difference is observed for AEP ($p=0.35$) or HTP ($p=0.39$). For maize, the impacts in the categories ALO, AEP, EUP, GWP and TAP are also reduced by torrefaction, by -17.9%, -17.7%, -7.4%, -12.4% and -12.8% respectively. No differences are observed for CED ($p=0.08$) or HTP ($p=0.33$).

With the exception of HTP (0.306), the torrefaction process reduces the environmental impact of bamboo for all impact categories (ALO -16.6%, CED -13.9%, AEP -16.5%, EUP -14.6%, GWP -15.9%, TAP -12.8%). Finally, for wood the torrefaction process has a positive influence in the categories CED (-40.8%) and GWP (-46.4%), but increases the environmental impact in EUP (+32.8%) and TAP (+80%).

These results therefore suggest that the increase in the calorific value of biomass may be accompanied by a reduction in the environmental impact of producing 1GJ of pellets, depending on the biomass type and the impact categories considered. The results also show that, for the biomass types studied, the torrefaction of the pellets produces better environmental performance in all cases in the GWP category.

As these initial indications are extrapolated from data obtained from the plant's process of transforming wood into torrefied pellets, their significance must be qualified. Different biomass types will probably react differently to the torrefaction process than wood.

Table IV: Comparative LCA results for the production of 1GJ of non-torrefied pellets versus 1GJ of torrefied pellets (T) for fescue (F), sorghum (S), silage maize (M), bamboo (B) and wood (W). In italics: the results of the uncertainty analyses of the LCAs. Extremely significant: '***' p≥0.999; Highly significant: '**' p≥0.99; Significant: '*' p≥0.95; Not significant: 'p value', p <0.95.

Biomass types	Impact categories							
	ALO	CED	AEP	EUP	GWP	HTP	TAP	WAP
F vs FT	-6.2	2.8	-4.5	7.0	-4.4	-5.7	22	-3.6
p value	***	*	*0.280*	***	***	*0.305*	***	*0.490*
S vs ST	-31.3	-12.4	-25.2	-4.5	-25	-29.1	3.96	-23.6
p value	***	***	*0.350*	***	***	*0.390*	***	*0.450*
M vs MT	-17.9	3.53	-17.7	-7.4	-12	-17.3	-3.6	-7.4
p value	***	*0.08*	*	***	***	*0.330*	***	*0.440*
B vs BT	-16.6	-13.9	-16.5	-15	-16	-16.5	-13	-16
p value	***	***	**	***	***	*0.306*	***	*0.438*
W vs WT	-54	-40.8	-49.1	32.8	-46.4	-51.5	80	-46.1
p value	*0.05*	*	*0.310*	***	***	*0.280*	***	*0.490*

4 CONCLUSIONS

The comparison of LCA for production of 1 GJ of torrefied pellets from different lignocellosic biomass types suggests that wood is the least impacting biomass from an environmental point of view. This superior performance is mainly due to wood's method of production which requires no fertilisers (organic or mineral).

The increase in the calorific value of biomass after torrefaction treatment may be accompanied by a relative reduction in the environmental impact of producing torrefied pellets, depending on the biomass type and the impact categories considered.

In all cases, the GWP category demonstrated better environmental performance when the pellets were torrefied.

However, further analysis is needed to support these initial observations. Indeed, the data used to model the production and the transformation stages were extrapolated from wood torrefaction process and came from sources representing different scales of data collection (field tests, laboratory tests, industrial data, literature, etc.). These differences create uncertainty about the results obtained and if these data enabled highlighting some trends, caution must be exercised to the interpretations and conclusions that can be drawn from them.

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