Full length article

Life cycle assessment of rubberized semi-dense asphalt pavements; A hybrid comparative approach

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ABSTRACT

This study employed the methodology of life cycle assessment (LCA) to assess the environmental impacts of rubberized semi-dense asphalt (SDA) pavement. Asphalt mixtures were prepared at the asphalt plant, followed by hybrid approach of mechanical and leaching tests in the laboratory to assess the possible service life and PAH leaching. The LCA was carried out considering two scenarios: (1) the reference scenario focuses on standard SDA produced of only virgin materials; (2) the test scenario refers to rubberized SDA using crumb rubber, a secondary material from waste tires. In the reference scenario, waste tires were assumed to be used as fuels for clinker production; while in the test scenario, waste tires were applied for SDA and primary fuels were used for clinker production (system expansion approach). In a sensitivity analysis, a scenario with waste tire treatment in municipal solid waste incinerators (MSWI) was also assessed. The impact assessment includes greenhouse gasses (GHG) emissions, nonrenewable cumulative energy demand (CED), human and ecotoxicity (USEtox), and the Swiss method of ecological scarcity. The results indicate that the investigated impacts were not improved by the test scenario. The USEtox results also reveal that the leaching impacts can be as serious as binder production and material transport if PAHs emit to groundwater. From an environmental point of view in Switzerland, it is not recommended to promote rubberized SDA by reducing the waste tires used for clinker production. However, if there are waste tires used for MSWI, the rubberized SDA is still an environmentally viable option.

1. Introduction

Semi-dense asphalt (SDA) is a widely used design for the low noise pavement (Mikhailenko et al., 2020). The concept "semi-dense" indicates the air voids content of asphalt mixture between that of dense-graded asphalt (ca. 4%) and porous asphalt (ca. 20%). Compared with the conventional asphalt mixture, the SDA requires high quality aggregates and polymer-modified binder, which not only increase the cost of pavement, but also bring heavy burdens to the environment. One possible solution to these challenges is the use of recycled materials to substitute the virgin materials of SDA (Piao et al., 2021). For example, several studies have demonstrated the use of base binder and crumb rubber from the waste tires as an alternative choice of polymer-modified binder (Loderer et al., 2018; Lyu et al., 2021; Rodríguez-Fernández et al., 2020; Shirini and Imaninasab, 2016). This design aims to mitigate the environmental burdens due to the production of virgin polymer and increase the recycling of waste tires as materials. In some countries, e.g. Switzerland, waste tires are already 100% used in terms of material or energy recovery (ETRMA, 2018). Hence, the implementation of rubberized SDA would change the supply of waste tires, as well as the resulting environmental impacts on related industries. Meanwhile, the preparation of crumb rubber and its use in asphalt may generate additional environmental burdens. Therefore, when the environmental impacts of the rubberized SDA are assessed, an effective holistic evaluation method is required to take various concerns into account.

According to ISO 14040 (2006) and ISO 14044 (2006), life cycle assessment (LCA) is a systematic method to quantitatively assess the environmental impacts of the product or service. For the current study, LCA is used to analyze the impact throughout the whole value chain of rubberized SDA, including the supply, usage and end-of-life. With the approach of system expansion, both the pavement and (co-)processing of waste tires (and the potential of substituting fuels) can be considered by LCA. Thus the shifting of environmental burdens among different processes and industries, and the shifting from one environmental impact to another, can be detected and assessed. LCA enables the identification of the most effective improvement strategies, making it a useful decision-support tool particularly for waste management (Hellweg and

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Abbreviations

General concept

CTU	Comparative toxic units
EAF	Electric arc furnace
FU	Functional unit
GHG	Greenhouse gasses
IPCC	Intergovernmental panel on climate change
ITS	Indirect tensile strengths
ITSR	Indirect tensile strength ratio
LCA	Life cycle assessment
MSWI	Municipal solid waste incineration
PAF	Potentially affected fraction of species
PmB	Polymer-modified binder
SDA	Semi-dense asphalt

Organic pollutant

ACN	Acenaphthene
ACY	Acenaphthylene
ANTC	Anthracene
BaA	Benz(a)anthracene
BaP	Benzo(a)pyrene
BbFLT	Benzo(b)fluoranthene
BghiPER	Benzo(g,h,i)perylene
BkFLT	Benzo(k)fluoranthene
CHR	Chrysene
DBahA	Dibenz(a,h)anthracene
FLT	Fluoranthene
FLN	Fluorene
IP	Indeno(1,2,3-cd)pyrene
NAPH	Naphthalene
PAH	Polycyclic aromatic hydrocarbons
PHEN	Phenanthrene
PYR	Pyrene

Milà i Canals, 2014).

Several authors have conducted an LCA for the rubberized asphalt pavement. Supporting Information (Table S1) summarizes their contributions in terms of the avoided disposal of waste tires, functional unit, investigated processes and impacts. In the study of Yu et al. (2014), waste tires and plastics were mixed with a ratio of 40: 1 as the modifier of the binder. The environmental impacts of the asphalt mixtures using the rubber/plastic-modified binder was compared to those using the polymer-modified binder. Their results showed that the rubber/plastic-modified mixtures consumed less energy and released less GHG than the reference. This was explained by the high environmental burdens due to the polymer production and the reduced consumption of virgin binder due to the use of crumb rubber and plastic. The study mainly focused on the production of raw materials and the mixing process of asphalt, while the impacts of further processes and the avoided disposal of tires were not discussed. Farina et al. (2017) investigated the environmental impacts of rubberized surface courses prepared by both the wet and dry processes. The same binder and various thicknesses were applied for the reference and rubberized surface courses. The service life was assumed to be longer for the rubberized surface course using the wet process than that using the dry process and the reference. The study also considered the benefits from the avoided landfill usage by waste tires and the recycling of byproducts (steel and textile) of tires. Their results indicated that the rubberized surface course using the wet process had significant environmental benefits (global warming, cumulative energy demand and impacts from the ReCiPe categories) compared to the reference pavement, while the rubberized surface course using the dry process had equivalent environmental burdens to the reference. Gulotta et al. (2019) investigated the rubberized porous asphalt pavement with recycled materials (mixed crumb rubber and waste plastic with a ratio of 1: 1) in both the friction and binder courses. Polymer-modified binder and base binder were used in the reference and rubberized asphalt mixtures, respectively. The thickness, service life and maintenance frequency were assumed to be the same for all the candidate pavements. The benefits of recycling the by-products of tires were not included in the assessment. Their results showed that the rubberized porous asphalt pavement was advantageous to mitigate the global warming, cumulative energy demand and impacts from the ReCiPe categories compared to the reference. Bressi et al. (2019) compared the base course of pavement with and without crumb rubber. The cradle-to-gate LCA included the material preparation, asphalt mixing and construction. The study reported that the rubberized base course showed higher scores in all the categories of ReCiPe than the conventional base course without crumb rubber addition. One of the

reasons is that both the reference and rubberized base courses used the same unmodified base binder, thus the potential benefits of replacing polymer-modified binder with crumb rubber were not considered in the LCA.

The studies above assumed that the waste tires would be landfilled if they were not used in the pavement. However, for the countries where waste tires are used for material or energy recovery, the environmental impacts of using crumb rubber in pavement need to be compared with conventional pavement and the current use of waste tires, in order to provide an appropriate decision recommendation. Moreover, the impacts during the use phase of pavement, such as leaching effects, were not included in the studies above. These research gaps will be closed in the present paper. System expansion was used as an allocation approach to include the environmental impacts of both the pavement and alternative treatment processes of waste tires (in this study it is clinker production). Base course, subgrade and embankments are same for all the candidate pavements, thus only the surface course with crumb rubber needed to be investigated for the comparison. This is because the use of crumb rubber aims to substitute the polymer-modified binder used for the surface course of standard SDA. Asphalt mixtures were prepared at the asphalt plant, followed by the mechanical testing in the laboratory to evaluate the possible service life of the surface course. Leaching tests were carried out to measure the release of polycyclic aromatic hydrocarbons (PAH) leached from the SDA. Data from the experiments, industrial partners in Switzerland and an existing database were used for the inventory analysis. The analysis was done for the case of Switzerland, representing countries where waste tires would otherwise be co-processed for material recovery.

2. Materials and experiments

2.1. Asphalt mixtures

The preparation of asphalt mixtures followed the Swiss standard SNR 640–436 (2015) for the SDA pavement. Supporting Information (Figure S1 and Table S2) shows the key parameters of the reference and test SDA. The reference SDA used the polymer-modified binder, while the test SDA used the crumb rubber and base binder (see Section 3.1.2, Fig. 1). The crumb rubber was obtained through the mechanical processing of the waste tires and was added by the dry process with the content of 1.0% (by mass of mixture). The binder content of the test SDA was 0.4% higher than that of the reference, in order to offset the binder absorption effect of the crumb rubber. All the SDA followed the same aggregate gradation, which is described in Supporting Information
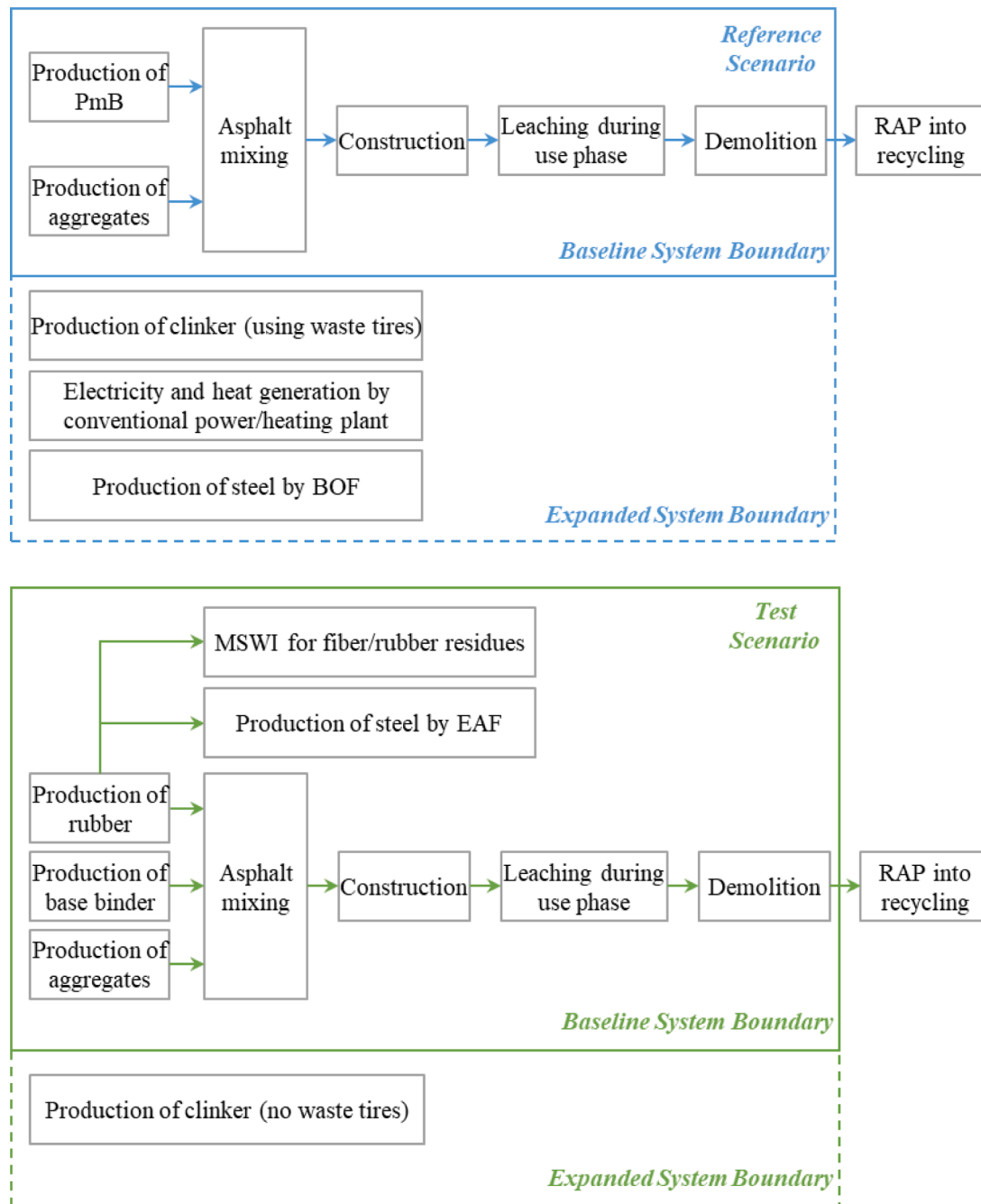
Fig. 1. System boundaries of the reference and test scenarios (BOF: basic oxygen furnace, EAF: electric arc furnace, MSWI: municipal solid waste incineration, PmB: polymer-modified binder, RAP: reclaimed asphalt pavement). System boundaries for the sensitivity analysis of tire treatment in MSWI are shown in Supporting Information (Figure S4 and S5).

(Figure S2).

2.2. Experiments

2.2.1. Mechanical test

Mechanical tests were performed to assure that the functional equivalence and service life of both pavement options were comparable. Service life is an important parameter relating to the consumption of pavement materials. The present paper estimates the service life by means of the water sensitivity test and wheel tracking test, which are based on the required performance criteria in Switzerland (SNR 640-436, 2015).

The water sensitivity test followed the European standard EN 12697-12 (2018) Method A. Six cylindrical specimens were prepared for each type of the SDA. Each specimen has a diameter of 100 mm and a height of 60 mm. Three specimens were kept dry in a climate chamber at 22 °C, the other three specimens were submerged in water at 40 °C. After conditioning for 68 to 72 h, the average indirect tensile strengths at 22 °C were tested for the wet and dry specimens. Then the ratios of indirect tensile strengths between the wet and dry specimens were calculated, deriving the indirect tensile strength ratio of the SDA. A value of 70% is required by the standard (SNR 640-436, 2015).

The wheel tracking test followed the European standard EN 12697-22 (2009). For each type of the SDA, two slab specimens were prepared and each had a length, width and thickness of 500, 180, 50 mm, respectively. Two wheels with treadles tires moved back and forth

on the two slabs. 15 points were defined on each slab to measure the rut depth. The average rut depth from all the measuring points was calculated. The present paper records the rut depth after 30, 100, 300, 1000, 3000, 10 000 and 30 000 load cycles. The test temperature was constant at 60 °C.

2.2.2. Leaching test

The toxicity characteristic leaching procedure (TCLP, Method 1311) according to US EPA (1992) is a representative method to investigate the leaching of asphalt with waste materials (Modarres et al., 2015; Sayadi and Hesami, 2017). It was designed to simulate the worst-case leaching scenario (Komilis et al., 2013). This study employed TCLP to quantify the concentrations of 16 PAHs leached from the reference and test SDA. All the specimens were prepared in triplicate. For each time, 100 g of SDA (particle size < 9.5 mm) were placed in the glass bottle and 2 L of acidic solution (PH = 4.93) was added. The bottle was rotated at 30 ± 2 rpm for 18 h at room temperature. Afterwards, the extract was separated from the solid using the borosilicate glass fiber filter (0.6 to 0.8 µm). Based on the U.S. EPA Method 525.1 (US EPA, 1991), the PAHs in the leachate was extracted by using the solid-phase extraction disk (ENVITM-18 DSK SPE disks, Supelco). GC-Ultra-HRMS (Orbitrap QExactive) was used to identify the PAHs.

Apart from the PAHs, the leaching of heavy metals from the surface course should also be taken in to account (Schwab et al., 2014). Since heavy metals were not measured during the leaching test in this study, an estimation is carried out based on the results of previous research. In the study of Vashisth et al. (1998), 3% crumb rubber (by mass of mixture) was added by the dry process. The reference and rubberized asphalt mixtures were compacted into slabs and pretreated under simulated sunlight and traffic. The slabs were then used for the leaching test simulating the rainfall with an intensity of 125 mm over 30 min. The pH of water was set as 4.3 and 7.0. Their results showed that at both pH values, the contents of six heavy metals (Cr, Ni, Cu, Pb, Cd, Zn) in the leachates were not worsened by the use of crumb rubber. Since the fraction of crumb rubber in the present paper (1%) is one third the fraction in Vashisth et al. (1998) and the dry process was also used, it is possible to assume that the leaching of heavy metals from the rubberized surface course would not result in more negative impacts than that from the reference.

3. Life cycle assessment

3.1. Goal and scope definition

3.1.1. Functional unit

The functional unit (FU) is defined as the SDA surface course with a length of 1 km and width of 7 m, with a service life of 10 years and T4 traffic load (300 – 1000 equivalent single axle load, ESALS per day) under Type B climate (average climate condition in Switzerland). The service life, traffic and climate conditions are based on the Swiss standards (SNR 640-430c, 2014; SNR 640-436, 2015). The reference SDA has a lifespan of 10 years, while the lifespan of the test SDA was estimated from the mechanical performance relative to the reference (see Section 5.1). Due to the system expansion, the FU also includes additional processes outside the field of road construction (as further defined below). The amounts of SDA were determined by their lifespans, dimensions and bulk densities. Table S3 in the Supporting Information summarizes the amounts of the two SDA and their corresponding raw materials per FU.

According to Feraldi et al. (2013), the fractions of rubber, steel scrap and fiber/rubber residues in the waste tires were determined as 80, 15 and 5% by mass, respectively. To provide 1 km of test surface course, 4.4 t of crumb rubber are needed. These 4.4 t can be retrieved from 5.5 t of waste tires, and the byproducts are 0.8 t of steel scrap and 0.3 t of fiber/rubber residues. The steel scrap is recovered by the electric arc furnace where 0.7 t of low-alloyed steel can be produced from it

(Ecoinvent, 2020). The fiber/rubber residues are disposed by municipal solid waste incineration (MSWI). With a net calorific value of 29 GJ/t and electrical and thermal efficiencies of 14 and 20% (average efficiencies of Swiss MSWI according to FOEN et al. (2019)), 304 kWh of electricity and 1620 MJ of heat are generated.

If the waste tires are used in the SDA instead of clinker production, the cement plant needs to find a substitute of waste tires. Specifically, the rubber and fiber in the waste tires are combustibles for heating the kiln system, while the steel scrap can save the consumption of iron ore in the clinker kiln. Since the cement industry in Switzerland is trying to obtain as many suitable waste materials (as fuels and raw materials) as possible (Cemsuisse, 2020), primary natural resources have to be used as substitution if waste tires are not available (due to their use in the pavement). In this study, hard coal and iron ore were selected to substitute the waste tires for clinker production. Based on the modeling of LCA4Waste – Cement Kiln (v3.3) (LCA4Waste, 2020), Supporting Information (Table S4) shows the components and amounts of fuels required per tonne of clinker and per FU. Specifically, 3200 MJ of heat is required by precalciner kiln system to produce 1 t of clinker. Referring to the experience of Swiss cement industry (Cemsuisse, 2020), we assumed that when waste tires are used, hard coal provides 40% of the heat, the rest is equally supported by four combustible waste materials (15% heat contribution by each; the mass values in Supporting Information Table S4 are calculated considering the net calorific values of each fuel). When waste tires cannot be obtained, hard coal would provide 55% heat, making up for the previous 15% heat contribution of the waste tires. The FU relates to 5.5 t of waste tires, which result in the production of 332 t of clinker with the fuel mix indicated in Supporting Information (Table S4).

Considering all the above, after system expansion the FU includes the production of 332 t of clinker, 304 kWh electricity, 1620 MJ heat and 0.7 t of low-alloyed steel, in addition to the original 1 km of SDA surface course.

3.1.2. System boundary

The investigated processes regarding SDA include the production of raw materials, asphalt mixing, construction, leaching during the use phase, demolition and transport. As demonstrated by various authors from several regions (Caltrans, 2005; Crockford et al., 1995; Wu et al., 2015), the reference and test SDA can undergo the same recycling process after use, and both can be further used in the new construction of road (e.g. base course and foundation). Since the end-of-life process are the same for both systems, they do not need to be considered in this comparison study. The system is cut off by the boundary after the transportation of demolished SDA to the mixing plant. Therefore, the further processing of demolished SDA for new construction is not included here, but would be considered in the life cycle assessment of new pavement. Considering the (co-)processing of waste tires, the present paper expands the system from pavement to other related industries, including the clinker production, MSWI, steel production and electricity/heat generation. This aims at making a fair and comprehensive comparison between the two scenarios and detecting the possible burden shift. Fig. 1 illustrates the systems of the two scenarios with details described as follows:

The reference scenario indicates the conventional processes. Polymer-modified binder is used in SDA and waste tires are used in clinker production. The steel included in the waste tires is a raw material for clinker production, thus it is not recovered by an electric arc furnace to produce low-alloyed steel. This amount of low-alloyed steel is compensated by conventional steel production using a basic oxygen furnace. The fiber/rubber residues in waste tires are the fuels for clinker production, thus they are not disposed for MSWI to generate electricity and heat. These amounts of electricity and heat are compensated by conventional power and heating plants. The type of electricity and heat are explained in Supporting Information (Table S6). In a complementary sensitivity analysis (Section 5.5), the treatment of waste tires in the

reference scenario was changed from clinker production to MSWI (see Supporting Information Figure S4 and S5 for system boundaries and results).

In the test scenario, crumb rubber (from the mechanical processing of waste tires) and base binder are used in SDA. The byproducts (steel scrap and fiber/rubber residues) from the processing of waste tires are recycled by an electric arc furnace and MSWI, respectively. The cement plant applies hard coal and iron ore to compensate the lack of waste tires.

In summary, Supporting Information (Table S5) compares all the processes of the two scenarios, both of which deliver the extended functional unit.

3.1.3. Modeling tools

The present paper employs three modeling tools for various processes in the system. Simapro (v9.1) was used to model the production of raw materials, asphalt mixing, construction, demolition and transport indicated in Fig. 1. It was also used to model the electricity and heat generated by conventional power and heating plants.

The modeling of clinker production was performed by LCA4Waste – Cement Kiln (v3.3), which is an environmental assessment tool for analyzing different scenarios of clinker production, especially the impacts caused by the (co-)processing of alternative fuels and secondary materials (Boesch et al., 2009; LCA4Waste, 2020). The program includes a mass-flow based model regarding the kiln system, material supply, waste treatment and impact assessments. Five kiln systems are available for modeling and 29 chemical elements that are released into clinker, air and dust can be identified (Boesch et al., 2009).

The MSWI was modeled by LCA4Waste – MSWI (v3.3) (Boesch et al., 2014; LCA4Waste, 2020), which includes the combustion of waste materials in a grate furnace incinerator, the production and use of ancillaries, the treatment of flue gas, the generation of electricity and heat, the material recovery from slag and fly ash, the landfill and transport.

3.2. Inventory analysis

3.2.1. Production of raw materials

This phase includes the preparation of aggregates, binder and crumb rubber. The aggregates were modeled as gravels and the inventory was provided by the ecoinvent database v3.6 cut-off (see Supporting Information Table S6). The emissions and resource consumptions for producing the base and polymer-modified binders are based on Eurobitume (2012). The information for processing waste tires was provided by a Swiss industrial partner, which indicates the electricity consumption of 308 kWh per tonne of crumb rubber. The inventory of electricity generation was obtained from the ecoinvent database (see Supporting Information Table S6).

3.2.2. Asphalt mixing

The mixing phase refers to the production of SDA. According to the data from Swiss mixing plants, 8.6 kWh of electricity and 216 MJ of heat are needed to produce 1 t of SDA (Birrer, 2019). The inventories of electricity and heat were obtained from the ecoinvent database (see Supporting Information Table S6). The mixing plants also confirmed that the energy demand is equal for producing the two SDA. The emissions during the mixing were not measured, but literatures show that the mixing of rubberized asphalt mixtures has similar emissions to that of the reference (Gunkel, 1994; Roschen, 2002). Thus we assumed the same emissions of mixing for the two scenarios.

3.2.3. Construction

The environmental burdens of construction are due to the fuel consumptions of different machines. According to a previous Swiss study of rubberized asphalt pavement (Birrer, 2019), the machines for construction include paver, material transfer vehicle, roller and generator, all of which are operated by diesel. Supporting Information (Table S7)

shows their unit fuel consumptions and performance. We assumed that the two SDA have the same workability, thus the fuel consumption of machine is determined by the mass of asphalt mixture. For 1 t of SDA, the paver directly consumes 5 MJ of diesel and in addition, three generators working for 3 h is needed; the roller consumes 13 MJ of diesel and three generators working for 7 h is required; the material transfer vehicle requires 4.5 MJ of diesel. The inventories of diesel for generators and machines were obtained from the ecoinvent database (see Supporting Information Table S6).

3.2.4. Leaching during the use phase of the pavement

For the use phase, the present paper investigates the leaching of PAHs from the reference and test SDA. The results are presented and analyzed in Section 5.3.

3.2.5. Demolition

This phase aims at removing the used SDA by milling machine, of which the performance is listed in Supporting Information (Table S7). The environmental impacts refer to the diesel consumed by the milling machine and generators. To demolish 1 t of SDA, the milling machine consumes 4.75 MJ of diesel and three generators are required to work for 4 h. The inventory of diesel for milling machine was obtained from the ecoinvent database (see Supporting Information Table S6).

3.2.6. Transport

This phase refers to the transportations that are not involved in the inventories of aforementioned processes. As Supporting Information (Table S8) indicates, the crumb rubber supplier, gravel supplier, steel plant, MSWI plant, asphalt mixing plant and construction site are located in Switzerland. The refineries producing base binder and polymer-modified binder are located abroad, as Switzerland has currently no refineries and imports asphalt binder. The present paper calculates the average distance from the refineries of three countries (Germany, France, Italy) to the mixing plant in Switzerland. The binder is transported by freight train, of which the inventory is separated as "foreign" (outside Switzerland) and "domestic" (within Switzerland). The inventories of foreign freight trains, domestic freight trains and lorry transport were obtained from the ecoinvent database (see Supporting Information Table S6). It shall be noted that the distance between the mixing plant and construction site was assumed as 50 km.

3.2.7. Clinker production, MSWI and steel production

The analysis of clinker production is based on the use of a precalciner kiln system that (co-)processes alternative fuels including waste tires. Same production technology was assumed for the two scenarios. For example, the compound operation rate was set as 90%; the electrostatic precipitator was used for dedusting; 50% of clinker kiln dust was extracted to cement mill and the rest was extracted back to silo/kiln; a bypass was not used to remove chlorine from the kiln. Therefore, the differences of environmental impacts between the two scenarios were only caused by the different fuel mix and raw materials. The fuel mix is discussed in Section 2.1. Supporting Information Table S9 shows the amounts of raw materials (limestone, clay and iron ore) for producing 1 t of clinker. The consumption of iron ore in the reference scenario is lower than the test scenario because the steel scrap in waste tires can substitute a certain fraction of iron ore. MSWI refers to the disposal of fiber/rubber residues (275 kg per FU), which was modeled by LCA4Waste – MSWI (v3.3) (LCA4Waste, 2020). The incinerator is a grate furnace with emission abatement, including dedusting (using electrostatic precipitator) and flue gas treatment (using wet cleaning). For the heat generated from MSWI, 14% was used for electricity supply and 20% was used for district heating, the rest was attributed to heat loss (FOEN et al., 2019). The inventories of steel production by basic oxygen furnace and electric arc furnace were provided by the ecoinvent database (see Supporting Information Table S6).

4. Impact assessment

The impact assessment converts the inventory in Section 3.2 into the indicators of environmental impacts. The present paper focuses on the following indicators:

(1) Climate change impacts were modeled with the global warming potential for 100 years, in kg CO_2-eq (IPCC, 2013);

(2) Nonrenewable cumulative energy demand, in MJ-eq (Boustead and Hancock, 1979);

(3) USEtox: human cancer and non-cancer toxicity, freshwater aquatic ecotoxicity, in CTU (comparative toxic units) (Rosenbaum et al., 2008);

(4) Ecological scarcity, in eco-points (UBP) (Frischknecht and Knöpfel, 2013).

The first and second indicators are related to the greenhouse gas (GHG) emissions and cumulative energy demand (CED), which are environmental indicators that correlate with a range of other environmental indicators when assessing the impacts of materials (Huijbregts et al., 2010, 2006; Steinmann et al., 2016). USEtox was employed to assess the impacts of PAH leaching during the use of SDA. The mobility of PAHs in the soil depends on various factors such as temperature, residential time and soil properties (Enell et al., 2005; Weigand et al., 2002; Zhang et al., 2008). On one hand, the mobility of PAHs in the soil can be limited due to their low water solubility and strong affinity to the humic substances (Maliszewska-Kordybach et al., 2010; Ping et al., 2007); on the other hand, it is also possible for PAHs to transport from soil to the groundwater with the existence of dissolved organic matters and colloids (Villholth, 1999; Zhang et al., 2008). The PAHs with high molecular weight (more than three rings) are inactive to move in the soil, while the mobility of PAHs with low molecular weight (two and three rings) is higher (Cai et al., 2019; Revitt et al., 2014). Currently, there are still insufficient quantitative analyses regarding the long term mobility of PAHs in the soil, implying large uncertainties to assess the leaching impacts of PAHs. As a result, our study considered different conditions of PAH mobility from "ideal" to "conservative": in the ideal case, all the leached PAHs would be bound by the soil; in the base case, 10% of PAHs with high molecular weight (HMW) and 50% of PAHs with low molecular weight (LMW) would emit to the groundwater, considering different behaviors of HMW and LMW PAHs; in the conservative case, all the PAHs would transport from the soil to the groundwater. The characterization factors of 16 PAHs regarding the "emission to natural soil" and "emission to freshwater" were pre-calculated by the USEtox methodology and used in our study. The ecological scarcity method is an aggregating method assessing pollutant emissions and resource extraction. It was chosen to include an indicator assessing a wide range of different impact categories. Moreover, it is a widely used method in Switzerland, which is the case study region of this paper. The impact categories considered by this method are listed in Supporting Information (Table S10). The final result is expressed in eco-points (UBP), using a distance-to-(political)target approach to weigh the various impacts and interventions. Both climate impacts (GHG) and water pollution effect are included in the ecological scarcity method, in addition to a range of further impact categories.

5. Results and discussion

5.1. Mechanical test

This section refers to the results of mechanical tests, which are used to estimate the service life of SDA. As shown in Fig. 2, the reference and test SDA present similar indirect tensile strength ratios, both of which meet the specification of SNR 640-436 (2015) (70%, the red line), indicating comparable water sensitivity. The candidate samples also present similar resistance to permanent deformation, as revealed by the results of rutting ratios (the rut depth over the original thickness of slab) in Fig. 2. Based on these experimental results, we assumed that the test SDA is able to achieve the same service life as that of the reference. Similar assumption can also be found in the studies of Farina et al. (2017), Bressi et al. (2019) and Gulotta et al. (2019). In Switzerland, the expected service life of SDA vary from 6 to 10 years, primarily due to the noise reduction properties that diminish during this time (Angst et al., 2011). This paper assumes 10 years for both of the two SDA.

5.2. Greenhouse gas emissions and cumulative energy demand

This section presents the results of greenhouse gas (GHG) emissions and cumulative energy demand (CED) of the reference and test scenarios. As shown in Fig. 3, the total GHG emissions of the two scenarios appear to be similar. Looking at the results closely, the reference scenario has higher emissions in binder production than the test scenario. This is because the production of polymer modified binder generates more GHG than the production of base binder. The processing of tires includes the production of crumb rubber from waste tires, together with the disposal of byproducts of tires by MSWI and steel plant. Although the production of crumb rubber and the disposal by MSWI generate additional GHG in the test scenario, the steel recovery by electric arc furnace
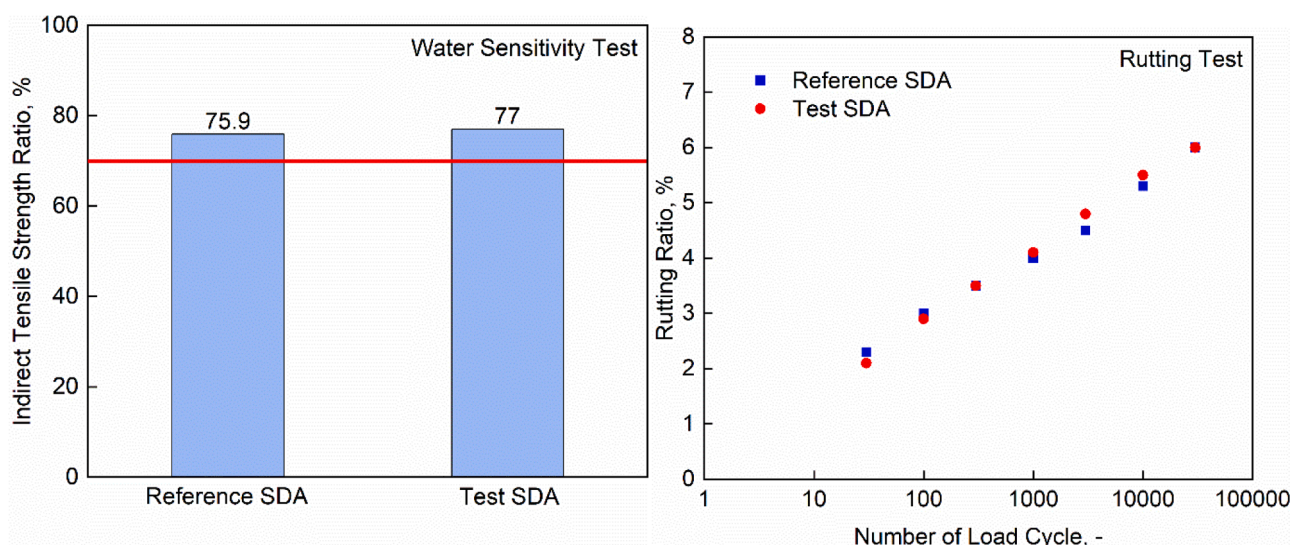

Fig. 2. Experimental results of (a) water sensitivity test and (b) wheel tracking test.
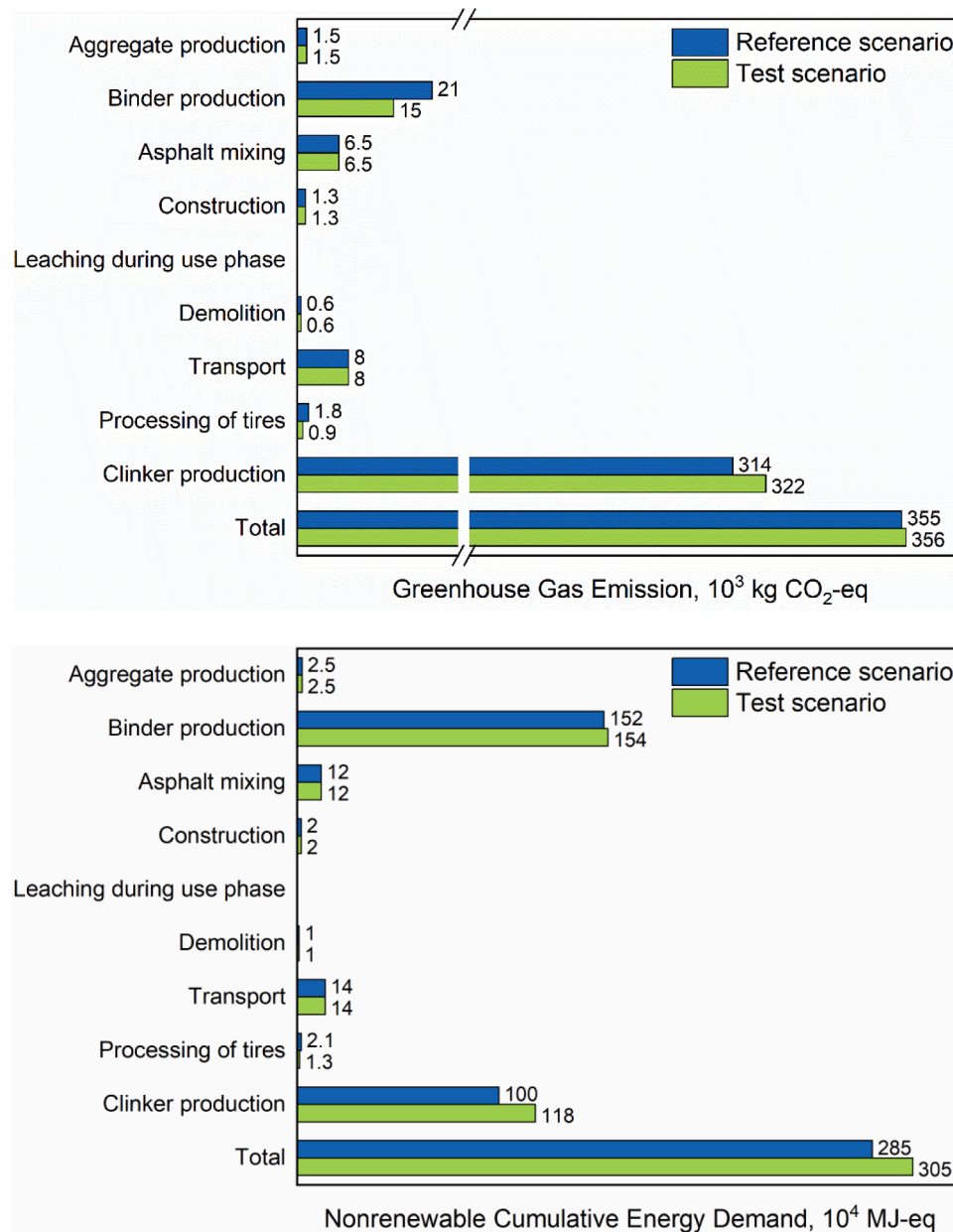
Fig. 3. GHG emissions and nonrenewable CED of the reference and test scenarios.

emits less GHG than the recovery by basic oxygen furnace. As a result, the reference scenario has still higher emissions in the processing of tires than the test scenario. For clinker production, however, the GHG emissions are lower in the reference scenario. This can be explained by the use of waste tires to save the demand of hard coal and iron ore for clinker production. Therefore, the two scenarios present advantages in the pavement related processes and clinker production separately, leading to similar total GHG emissions.

Fig. 3 also indicates that the total nonrenewable CED of the test scenario is slightly higher than that of the reference scenario. In contrast to the GHG emissions, the binder production of the test scenario shows no advantage of CED over the reference scenario, implying that the use of base binder to replace the polymer modified binder would not reduce CED. For the processing of tires, the treatment by MSWI and electric arc furnace have lower CED than the conventional power/heating plants and basic oxygen furnace. However, the main difference of total CED is caused by clinker production, which demands 16% more energy in the test scenario than in the reference. This can be explained by the higher

CED of hard coal than that of the waste tires. In short, the test scenario brings limited benefits of CED to pavement related processes, while it loses benefits of CED in clinker production.

5.3. USEtox results

5.3.1. Results of leaching test

Based on the test described in Section 2.2.2, Fig. 4 presents the concentrations of 16 PAHs leached from the reference and test SDA. It can be seen that the concentration of each PAH is either similar or lower for the test SDA compared to the reference. Moreover, the concentrations of leached PAHs are dominated by naphthalene (NAPH) and phenanthrene (PHEN). Nevertheless, the dominated PAH in crumb rubber is pyrene (PYR), while the fractions of NAPH and PHEN in crumb rubber are quite limited (see Supporting Information Figure S3). That means the PAHs leached from SDA are basically determined by asphalt instead of crumb rubber.
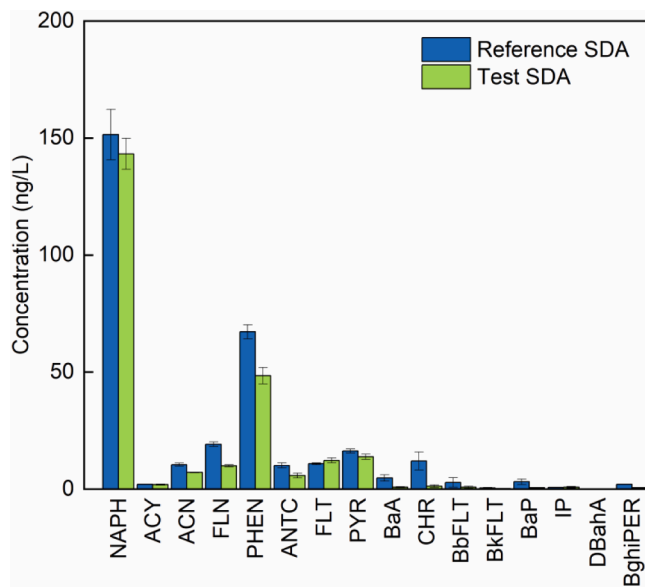
Fig. 4. Concentrations of 16 PAHs leached from the reference and test SDA.

5.3.2. Human toxicity and aquatic ecotoxicity

The results of USEtox are listed in terms of human carcinogenic/non-carcinogenic toxicity and aquatic ecotoxicity in Table 1. For the leaching of PAHs, different assumptions lead to large ranges in the results. The impacts of the conservative case are higher by two orders of magnitude than that of the ideal case, indicating that once the PAHs emit to groundwater, their toxicities can be as serious as the toxic effects of binder production and material transport. Instead, if all the PAHs can be bound by soil, their impacts can be neglected. Therefore, an accurate fate analysis of PAHs is of great importance to evaluate the leaching impacts in this LCA. In addition, since smaller amounts of PAHs were leached from the test SDA compared to the reference (see Fig. 4), the test SDA presents lower leaching impacts, which are especially noticeable under the base and conservative assumptions.

As to other processes, however, the toxicities due to clinker production are higher by several orders of magnitude compared to the pavement related processes. Thus, the toxicities of the expanded system and also the difference between the scenarios are dominated by clinker production, regardless of the assumptions for PAHs. It can be seen that the toxicities are slightly increased when waste tires are replaced by hard coal for clinker production, indicating no improvement by adopting the test scenario.

5.4. Ecological scarcity eco-points

Fig. 5 shows the results of ecological scarcity method, of which the total eco-points are similar for the two scenarios. In detail, the test scenario has slight benefits in binder production and processing of tires, while these benefits are offset in clinker production. This is similar to the case of GHG emissions in Section 5.2, where impact savings in the pavement processes are shifted to clinker production. The eco-points of the use phase are based on the leaching of PAHs under the conservative assumption (assuming all the leached PAHs emit to water). It can be seen that even in the worst case, the impacts of PAHs are negligible from the perspective of eco-points. However, since both the differentiations of 16 PAHs and impacts of PAHs in the soil are not considered in the ecological scarcity method (Frischknecht and Knöpfel, 2013), the leaching impacts may be underestimated by this method.

5.5. Discussion and sensitivity analysis

Based on the results from Section 5.2 to 5.4, the test SDA seems not to be beneficial in the investigated environmental impacts compared to the reference. Nevertheless, since we assumed that the waste tires for the test scenario are originally used in clinker production, the results are determined by both the pavement related processes and clinker production. If the waste tires are previously used by other industries, such as MSWI, the conclusion would be different (see results in Supporting Information Figure S5). In this case the test SDA would reduce the waste tires used for MSWI, thus the conventional power/heating plants are applied to supplement the loss of electricity and heat from the incineration of waste tires. The expanded system includes the pavement related
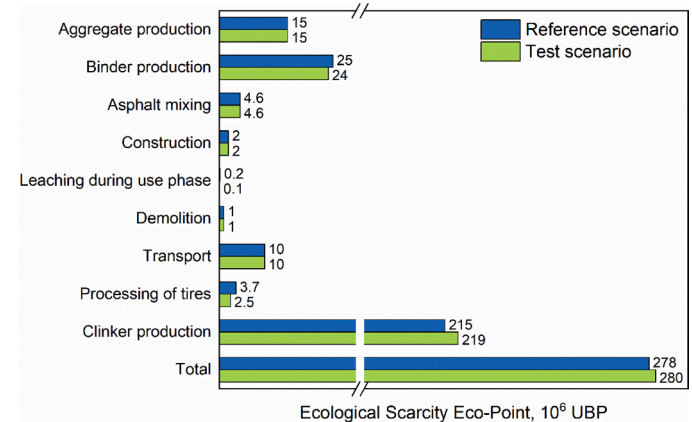

Fig. 5. Ecological scarcity eco-points of the reference and test scenarios.

Table 1
Human and ecotoxicity of the reference and test scenarios.

| Process | Human toxicity, cancer, 10^{-8} CTU$_h$ | | Human toxicity, non-cancer, 10^{-8} CTU$_h$ | | Aquatic ecotoxicity, CTU$_e$ | |
	Reference	Test	Reference	Test	Reference	Test
Aggregate production	13	13	9	9	5	5
Binder production	74	41	16	14	141	148
Mixing	26	26	2.8	2.8	1.4	1.4
Construction	1.3	1.3	0.9	0.9	2	2
Leaching (ideal)	0.3	0.1	0.002	0.002	1.1	0.9
Leaching (base)	6.2	2.6	0.02	0.02	40	30
Leaching (conservative)	41	13	0.1	0.1	235	194
Demolition	0.7	0.7	0.4	0.4	1	1
Transport of materials	44	44	257	260	16	16
Processing of tires	26	197	8.5	1.3×10^4	4.3	393
Clinker production	2.7×10^5	3.0×10^5	2.1×10^6	2.1×10^6	1.5×10^5	1.6×10^5
Total (ideal)	2.7×10^5	3.0×10^5	2.1×10^6	2.1×10^6	1.5×10^5	1.6×10^5
Total (base)	2.7×10^5	3.0×10^5	2.1×10^6	2.1×10^6	1.5×10^5	1.6×10^5
Total (conservative)	2.7×10^5	3.0×10^5	2.1×10^6	2.1×10^6	1.5×10^5	1.6×10^5

processes, processing of waste tires and electricity/heat generation (by MSWI or conventional power/heating plants). The results show that the GHG emissions of the test scenario are lower than the reference scenario by 23%. That means the assumption of what otherwise happens to waste tires, if not used in pavements, plays a decisive role in the environmental performance of the test scenario (and can even reverse the results). For example, if the cement plant is able to coprocess all waste tires in Switzerland, there is no environmental motivation to promote the rubberized SDA pavements. However, if there is a surplus of waste tires that needs to be treated in MSWI, the rubberized SDA would be a better option for these waste tires, compared with MSWI.

In addition to the use of waste tires, there are other factors influencing the uncertainties of the results. For example, the aggregates of SDA have a higher quality than the dense asphalt mixtures, thus the processing may lead to higher environmental impacts on the machinery. The machines for processing waste tires require regular maintenance, of which the impacts are not included in this paper. The roughness of the reference and test SDA might differ during the service life, thus the fuel consumptions of vehicles can be different for the two scenarios. The quantifications of these factors need extra modelings, experiment designs and database, which are challenging topics with huge work in future research.

6. Conclusions

The present paper employs LCA to assess the environmental impacts of polymer modified (reference scenario) and rubberized (test scenario) SDA. The conclusions are listed as follows:

(1) The mechanical tests indicated that it is possible to assume the same service life (10 years) for the reference and rubberized SDA. The leaching test shows that the leaching of PAHs was slightly improved by using crumb rubber in SDA;

(2) For the system expanded with clinker production, the use of crumb rubber in SDA cannot improve the GHG emissions, CED, toxicities and ecological scarcity eco-points compared to the reference scenario with waste tires co-processing in clinker kilns;

(3) From the view of human toxicity and aquatic ecotoxicity, if PAHs are able to reach groundwater, the impacts of leaching can be as serious as binder production and material transport. However, the toxic impacts from the clinker kiln system expansion dominate the impacts scores;

(4) For Switzerland, we recommend not to promote the rubberized SDA by reducing the waste tires for clinker production. However, if there are waste tires used for MSWI, the rubberized SDA is still a viable option from an environmental point of view.

In future research, the transport of PAHs between soil and groundwater should be quantified with high accuracy. More factors during the use phase of pavement, such as the noise-mitigating performance of SDA, should be included in LCA. Further, the conclusions of this article are based solely on the environmental impacts, while decision-makers will also take economic concerns into account.

Author contributions

Conceptualization: L.D.P. started the main concept of studying of crumb rubber modification of bituminous materials. S.H. and L.P. conceptualized the use LCA for waste materials. Z.P and S.H conceptualized use of CR in LCA. *Supervision*: L.D.P, S.H. and M.B supervised the study and provided critical feedback. *Methodology, validation, formal analysis, investigation, and visualization*: M.B. fabricated and characterized the materials, M.B. and L.D.P. designed and conducted the experiments, M.B. analyzed the data. Z.P. and S.H. designed the LCA experiment and Z.P conducted the LCA experiments and produced the figures. *Writing, original draft*: Z.P. wrote the initial draft of the paper S. H., L.D.P. and M.B. gave feedback and contributed to the revisions of the paper. All authors have read and approved the final version of the paper. *Funding acquisition*: L.D.P. and S.H. acquired financial support for the

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105950.

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