Carbon Footprint of Waste-Derived Composites

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Abstract
The modern world is facing unprecedented population growth and increasing demand for consumer goods which, in turn, causes a demand for an increasing supply of materials. At the same time, technological advancement has enabled the development of novel materials suitable for a wide range of applications. Composites are a great example of such materials because they can be produced from feedstock which is not suitable for other applications, such as waste. A substantial body of research has been conducted exploring various industrial and municipal waste streams. Composite matrices can be made of low-quality recycled plastic originating from construction and demolition activities while fillers can be made from a variety of waste streams, such as primary sludge, wood waste, sawdust, agricultural residues, mineral wool, and plasterboard, among others. Generally, the cumulative share of the matrix and filler is above 90% of the composites, thus significantly contributing to a potential reduction in environmental impacts, including climate change. The climate change impacts of waste-derived composites (WDC) can be best assessed using the carbon footprint (CF) methodology. The CF is a specific node of life cycle assessment (LCA) focusing on climate change impacts. The method accounts for the emissions and removal of greenhouse gases during all life-cycle stages of composites or parts thereof.

Keywords
carbon footprint,
carbon handprint,
circular economy,
climate change,
construction waste,
demolition waste,
greenhouse gas emissions,
greenhouse gases,
life cycle assessment,
waste plastic composites,
waste-derived composites,
wood-plastic composites,
wood-polymer composites

Glossary (optional)
Greenhouse gas – a gaseous constituent of the atmosphere, both natural and anthropogenic, that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds

Carbon footprint (CF) (or a carbon footprint of a product) – the sum of greenhouse gas emissions and greenhouse gas removals in a product system expressed as carbon dioxide equivalents (CO_{2eq}) and based on a life cycle assessment using a single impact category of climate change

Elementary flow – material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation

End-of-life (EoL) – a life cycle stage of a product indicating that the product under study is ready for disposal, recycling, reuse for different purposes, or energy recovery

Life cycle assessment (LCA) – compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle

Waste-derived composites (WDC)– composite materials which are manufactured fully or to a very large extent from waste feedstock

1 Introduction

During an age of rapid population growth (mostly in developing countries) and increasing living standards (mostly in developed countries), environmental conservation has become a cornerstone of the long-term survival of humankind. Deforestation, eutrophication, acidification, toxic impacts, drought, wildfires, accelerated extinction of species, and climate change are all threatening the fragile stability of natural ecosystems, as well as the well-being of modern humans.

Increasing mobility, mechanization, automation, and industrialization have all made us dependant on fossil fuels, which have been used as a primary source of energy around the globe. Long before we were alerted to climate change, fossil fuels were incinerated in large amounts, releasing substantial amounts of fossil-based carbon dioxide. The production of many materials, such as different types of synthetic polymers, requires fossil fuel consumption, either as a feedstock for the materials or as an energy carrier.

One effective pathway towards the reduction of human environmental impacts is the use of already manufactured materials and products to satisfy the existing needs of society. This implementation represents one of the pillars of the circular economy, focusing on the reuse, recycling, and recovery of materials within technical and biological cycles. Here, waste of various origins is seen as a feedstock for numerous production processes.

The highest recycling efficiency can be reached either through closed-loop recycling, whereby materials are circulated within the same manufacturing process, or open-loop recycling, whereby no changes occur in their inherent properties. However, closed-loop recycling often requires a separate collection system of waste, such as those of aluminum cans or PET bottles implemented via take-back systems, and is thus hard to set up. Instead, open-loop recycling can be proposed to ensure the utilization of materials in other production processes which could use waste streams with higher levels of impurities and less sensitivity to the homogeneity of feedstock.

Composites are a unique materials niche which allows for the utilization of various feedstock. Furthermore, polymer composites are renowned for their suitability for utilizing a wide range of waste, including recycled plastic and wood waste, among other waste fractions. Specific properties of WDC are then tailored using coupling agents, processing aids, stabilizers, flame-retardants, antioxidants, ultra-violet stabilizers, and antimicrobial aids. Finally, WDC are oftentimes used in technical applications, thus allowing for the possible presence of impurities therein.

The production of WDC has the potential to reduce environmental impacts, including mitigation of climate change. This could be achieved through the avoidance of feedstock production, which usually has a higher impact than the impacts associated with the collection of waste and its possible pre-treatment, such as sorting, drying, or size reduction. Furthermore, WDC can be recycled back into composites, thus extending the lifetime of the materials embedded in them. Finally, when WDC are manufactured, they could replace certain products on the market, such as those made of primary plastic, wood, or even metals.

However, the CFs of composites differ greatly. The major contributing factors are the manufacturing processes used, the amount of additives needed, the carbon intensity of the grid, their recyclability, and the EoL method. In some cases, the CF of WDC can exceed that of the baseline solution without their production.

This chapter of the Encyclopaedia offers insights into the assessment of the CF of composites produced from waste. It will introduce the core principles of LCA and its specific derivative, the CF. The concept of carbon handprint will also be spotlighted. The chapter will provide the principles of GHG emissions and removals accounting. Finally, it will elaborate on various possibilities of climate change impact from WDC.

2 LCA methodology

LCA methodology is governed by Standards ISO 14040 on the principles and framework of LCA (SFS-EN ISO 14040, 2006), as well as ISO 14044 on requirements and guidelines (SFS-EN ISO 14044, 2006) which was amended in 2018, mostly as concerns the critical review and footprint studies. The ISO standards, however, leave LCA practitioners with a range of methodological choices. Therefore, additional literature also exists to guide them, such as the International Reference Life Cycle Data System (ILCD) handbook (Joint Research Centre - Institute for Environment and Sustainability, 2010b, 2010a) and the Product Environmental Footprint (PEF) (Zampori and Pant, 2019), among others. Also, industry- or activity-specific LCA guidelines exist, such as those by the World Steel Association (2011) or International Energy Agency (2011).

Each of the LCA studies essentially follows the following phases: a) goal and scope definition, b) inventory analysis, c) impact assessment, and d) interpretation. Despite having a specific order, these phases are not consecutively arranged in LCA, owing to its iterative nature; thus, choices made during the goal definition could be adjusted based on the inventory or impact assessment stages. Each of the phases is important for the overall quality of the LCA studies and should not be omitted.

When LCA studies focus on specific areas of concern, they are termed footprint studies. Footprint studies can have their own methodology, such as those for water footprint calculations (SFS-EN ISO 14046, 2016) and CF calculations (SFS-EN ISO 14067, 2018). Footprint studies delve deeper into aspects of impact assessment in a specific area of environmental concern, such as climate change, which are otherwise not covered comprehensively in the overarching LCA standards ISO 14040/44. Figure 1 shows the key phases of LCA, as well as the connection of footprint standards with such overarching standards.

[Figure 1 close to here]

3 CF methodology

CF studies should follow Standard ISO/TS 14046 (2016) to ensure the correctness of calculations and be suitable for external communication. According to the Standard, a CF is the sum of "*GHG emissions and GHG removals in a product system expressed as CO_2 equivalents and based on a life cycle assessment using a single impact category of climate change.*" Therefore, to proceed with a CF study, each practitioner is expected to know LCA methodology.

An assessment of the climate change impacts of composite materials within the CF methodology is expected to be based on a declared unit as opposed to the functional unit, owing to the limitation of its life cycle in terms of the life-cycle stages included. When such studies include only cradle-to-gate impacts, they are called partial CFs (PCFs) of products. This is explained by the fact that the composites could be used later in various applications, thus having different impacts before their EoL is reached. The declared unit is oftentimes related to a specific amount of the studied product. In the case of composites, this would be a mass-based unit of, for example, 1 kg of composites or a volumetric unit of, for example, 1 m^3 of composites.

4 Carbon handprint approach

The carbon handprint approach was developed to quantify the positive climate impacts of products. In contrast to the CF, the carbon handprint presents the amount of reduced greenhouse gas emissions when a product is being used by a certain customer. The carbon handprint is always calculated against a fairly set baseline. A CF of a baseline solution and a CF of the alternative, often innovative, solution are quantified, and their difference equals to the carbon handprint. The carbon handprint approach can be utilized alongside the footprints to further communicate the positive impact of the products. Besides, the handprint approach may reveal product development needs, if the baseline solution already has a lower footprint (Pajula *et al.*, 2018; Grönman *et al.*, 2019).

In the carbon handprint assessment, it is important to recognize the *possible contributing mechanism*, which can allow footprint reduction (Pajula *et al.*, 2018; Grönman *et al.*, 2019). In the case of WDC, several benefiting factors may contribute to the carbon handprint:

- *Less GHG-intensive material use:* Depending on the intended application, WDC material or product may replace non-renewable materials, that might be of virgin origins and GHG-intensive material. When waste is utilized as raw material, material-use efficiency may be improved, given that processing does not require large additional material inputs.

- *Less GHG-intensive energy use*: Production of WDC can usually be assumed to be less energy-intensive than producing the material from primary origins, due to the lower energy required to melt smaller amounts of plastic.
- *Increased lifetime and performance:* When using WDC as raw material for a product, one must be certain that the properties of the composite material are comparable to, or better than, the properties of the material from which the product would otherwise be manufactured. The lifetime of the product should not be allowed to decrease even if WDC are utilized as a raw material. However, in this case, the lifetime of the (waste) material is prolonged when it reaches a second life as a composite material.
- *Reduced waste and losses*: Using waste as a raw material in the composite production naturally falls into the category of possible carbon handprint contributors. However, the producer of the WDC should acknowledge that the impurities in the waste feedstock, such as unintended waste fractions, may cause losses in WDC production.
- *Increased carbon capture and storage:* Utilizing waste as a raw material rather than primary sources may contribute to carbon sequestration if land use change can be avoided. Besides, the carbon already stored in the composite material remains unrealized for a longer period.

5 Inventory and interpretation of GHG emissions and removals

The CF method manifestly accounts separately for biogenic and fossil GHG emissions and removals occurring in the studied system, as well as those occurring as a result of direct land use, or as aircraft emissions. Additionally, climate change impacts from indirect land use change and land use can be included. The sequestration of carbon dioxide in biomass shall be characterized as -1 kg CO_{2eq} per 1 kg CO_2 when entering the product system and as +1 kg CO2eq per 1 kg CO_2 when being emitted back into the environment as carbon dioxide, thus resulting in zero net climate change impacts. The exception to the rule holds true when the carbon is not being oxidized to carbon dioxide but is converted to methane, non-methane volatile organic compounds, and other precursors, which is the case for organic matter used for landfill. To assess other GHGs and their characterization factors, the latest IPPC reports should be consulted.

6 Waste-derived feedstock and its climate change implications

From the CF study point of view, three major types of waste-derived feedstock can be distinguished: inorganic feedstock, bio-based organic feedstock, and fossil organic feedstock. The differences in feedstock can be accounted for in CF studies through their avoided environmental impacts if having a consequential approach to the study. Furthermore, the content of different feedstock will imply variations in the EoL impacts of WDC. The implications of the various feedstock for climate change impacts are illustrated in Figure 2.

[Figure 2 close to here]

Inorganic feedstock, such as mineral wool or plasterboard, is mostly used as a filler. Its inorganic nature implies potentially low impacts on climate change due to its conventional EoL, which could be landfill or re-use in the construction industry. Therefore, such material is not expected to contribute to a significant reduction of climate change impacts when used in composites and not disposed of conventionally. At the

EoL, inorganic materials do not generate emissions during incineration or contribute to the generation of landfill gases, if used as landfill.

Bio-based organic feedstock, such as agricultural residues, waste wood, and primary sludge, is also mostly used as a filler. Bio-based organic feedstock contains biogenic carbon, which is a part of the natural carbon cycle being sequestered during biomass growth. When bio-based organic feedstock is incinerated, the emissions are accounted for as climate-neutral. However, the same feedstock placed in landfill results in the formation of landfill gas containing methane, which contributes to climate change. It is worth mentioning that methane has a 28 times stronger radiative forcing than carbon dioxide over a time horizon of 100 years; that is, GWP_{100} of methane is 28 kg CO_2-eq (IPCC, 2014).

Fossil organic feedstock, such as various plastics, is used as a matrix material. Such feedstock contains carbon, which contributes to the global warming potential when released into the atmosphere. The incineration of fossil organic feedstock has the worst climate change impacts since all the carbon is converted into fossil-based carbon dioxide. Using such feedstock as landfill has a lower impact on climate change. However, this disposal method leads to increased abiotic resource depletion since more fossil resources would be required to replace that disposed of in landfill. An overview of the impacts from various feedstock is presented in the study by Sormunen *et al.* (2021).

7 Climate change impacts of WDC

7.1 Production process

The environmental impacts of WDC start with the collection of waste from its place of generation (Figure 3). The waste can originate from various activities, such as industrial production or construction, or can be commercial, demolition, or agricultural waste. When waste is collected for composite production, it first has to be pre-processed. Crushing and hammer milling are used to reduce the particle size, whereas magnetic separation might be used to remove undesired metal parts, such as nails (Liikanen *et al.*, 2019). Agglomeration is used to blend the pre-processed waste feedstock and additives into compounds. The primary composite production process is similar to the polymer production process, the most common processes being extrusion, injection molding, compression molding, or thermoforming (Gardner, Han and Wang, 2015).

[Figure 3 close to here]

In the extrusion process, continuous linear profiles are formed as melted thermoplastic is forced through a die (Migneault *et al.*, 2009). In injection molding, the heated mixture is fed into a highly pressurized mold cavity of the desired shape. In compression molding, a pre-shaped sheet is placed into a mold that is then forcefully enclosed under high pressure, whereas in thermoforming, the sheet is first heated and then formed into the desired shape with a mold.

7.2 Impact of production

The CF of composite production can be estimated based on the consumption of raw materials and energy in the production process. **Error! Reference source not found.** summarizes the CFs of the transportation process, electricity generation, and plastic and wood production. Relying on the data presented in Table 1 and the life-cycle inventory presented in the study by Liikanen et al. (2019), a PCF can be estimated for a declared unit of 1000 kg (or 1 metric ton) of WDC. The production recipe for WDC in the study by

Liikanen et al. (2019) comprises 54% wood waste, 40% plastic waste, and 6% additives. Since WDC production can utilize waste, its production efficiency is close to 100%; hence, to produce 1000 kg of WDC, the same amount of feedstock, such as fillers, matrix, and additives, would be needed.

[Table 1 close to here]

Transportation distances for waste collection can range significantly from one place to another. If the waste feedstock is collected from a distance of 100–200 km, the CF of the collection would be 8–16 kg CO_{2eq} per 940 kg. The additives might be transported from a more remote location using different transportation modes, such as ocean-going container ships. However, the impact is not expected to be high due to the relatively small amount of additives needed and the expected low impact of ocean-going transportation modes. Regarding the impact of additive production, manufacturing 30 kg of maleated polypropylene and 30 kg of a processing aid has a CF of around 100 kg CO_{2eq}. The impact of the additives might vary if other materials are used or the amounts are different. The electricity consumption for pneumatic moving, crushing, hammermilling, agglomerating, and extruding is around 1.6 MWh per 1000 kg of WDC. If injection molding is used, then the electricity consumption would increase to 2.3 MWh per 1000kg of WDC. Therefore, the CF of electricity provision to the WDC production process would range between 210 and 310 kg CO_{2eq} in the case of Finland and 870 and 1270 kg CO_{2eq} in China.

The waste used in the WDC production process is commonly not considered to have any environmental impacts from the previous life cycles of the materials under the so-called "zero-burden" approach (Ekvall *et al.*, 2007). However, the zero-burden approach is being questioned under the upcoming implementation of a circular economy in which all waste is supposed to be raw material in another production process (Djuric Ilic *et al.*, 2018). In such a case, allocation should be applied following the most recent LCA guidelines, for example those developed for paper products in Europe (Hohenthal *et al.*, 2019). Summing all the impacts from transportation, production of additives, and electricity generation, the cumulative impact from WDC production totals 310–420 kg CO_{2eq} in Finland and 970–1380 kg CO_{2eq} in China. The PCF of WDC production is lower than that of HDPE production, of 1800 kg CO_{2eq}. The PCF of wood, of 150 kg CO_{2eq} per 1000 kg of wood, is, however, considerably lower than that of WDC.

7.3 Impact of use

When WDC are used, they would usually be considered as a replacement for a specific product made of alternative materials. The replacement of plastics has a higher potential for the reduction of environmental impacts due to its higher CF (Table 1). However, in the case of wood, WDC production could also be beneficial owing to its specific properties, such as moisture and UV resistance, higher strength, lack of treatment needs, and production of complex geometrical forms. When considering the application of WDC in the production of wooden pallets, substantial benefits could be expected from the better durability of pallets made of WDC, assuming their performance is closer to that of plastic, rather than wooden, ones (Deviatkin and Horttanainen, 2020). However, use phase impacts are always case-specific, so making a PCF of WDC is beneficial to ensure the use of such data by LCA practitioners working on attributional or comparative LCAs of products made of WDC.

7.4 End-of-life impacts

WDC can have several EoL possibilities, of which recycling is the most circular. WDC are suitable for closed-loop recycling, for which only additives, such as a coupling agent, would be needed to ensure their technical properties meet specific requirements. In this case, the CF would be formed similarly as when producing WDC from waste, that is, transportation of WDC waste to the WDC production factory, followed by crushing, milling, agglomeration, and extrusion of molding. Here, the benefits of recycling would relate more to the extended lifetime of the material than the avoided impact from raw materials acquisition, which is the case for the recycling of paper, plastic, or metals, when materials produced from fossil resources are being replaced. In the case of WDC recycling, only zero-burden waste is replaced.

If closed-loop recycling cannot be implemented, which may well be the case since it usually requires the development of the take-back infrastructure enabling products made of WDC to be returned to the factory, their incineration with energy recovery can be practiced as a disposal option following recycling in the European waste hierarchy (European Parliament and the Council of the EU, 2008). In this case, the WDC are sent for thermal treatment, whereby electricity and thermal energy is generated. Energy outputs can, thus, replace the same amount of energy produced in a specific country. When considering electricity and heat substitution, a consequential approach is recommended (Ekvall and Weidema, 2004). In the consequential approach, additional electricity and thermal energy provision are assumed to be compared with the replacement of the electricity and thermal energy sources otherwise being phased out in the energy system of a specific country or a region. Such sources are usually coal, natural gas, and crude oil-based fuels.

Incineration of wood has almost no impact on climate change if carbon is oxidized completely and no other GHG emissions are being formed, such as methane or nitrous oxides, when providing electricity. Neither does the incineration of WDC containing inorganic materials, such as mineral wool, contribute to climate change, but their presence in the incineration process does not generate any electricity; on the contrary, it reduces the total energy efficiency due to energy consumption in the heating process. Finally, plastics have a high heating value and are highly calorific fuels. However, due to their fossil origin, plastic incineration has a tremendous impact on climate change. Plastics generally contain 80% carbon, so the incineration of 1 kg of plastics would result in emissions of 2.9 kg CO_{2eq}, stoichiometrically calculated from the mass of carbon oxidized to carbon dioxide.

Finally, WDC can also be used as landfill if legislation allows. In Finland, landfilling is no longer possible for wood and plastic waste due to the ban on organic waste landfill that has been in force since 2016. However, in many countries, landfilling is still widely practiced, posing the potential situation of plastics and composites outperforming wood. The reason for this is the stability of plastics and WDC to biological decay, whereas wood is subject to biological decay during landfill. Landfilling 1 kg of wood could emit 1.3 kg CO_{2eq}, of which some 95% is contributed by the methane formed. It should be noted that there is a large variation between existing landfill types so the actual CF from wood landfill could range significantly, depending on the implementation of the landfill gas collection system, its efficiency, the type and location of the landfill, and so on.

Conclusions

Composites represent a promising solution for the achievement of circular economy principles which are being widely developed. The circular economy can prosper from the utilization of waste in the production of composites, or the so-called WDC. WDC can be manufactured from a wide range of feedstock, such as bio-based organic materials such as wood waste and straw; mineral fillers such as mineral wool; and fossil-based organic materials, such as various plastics, which act as a matrix. The properties of WDC can be adjusted based on the application, using a wide range of additives, including coupling agents, lubricants, UV resisting agents, colorants, antimicrobial aid, and so on. WDC can be produced through several methods, such as extrusion to produce continuous linear profiles, and various types of molding and thermoforming allowing products of the desired shape to be manufactured. This wide variability in the possible feedstock, properties, and applications makes WDC a unique material.

However, the impacts of WDC on climate change are not always straightforward and positive since they always depend on the operating environment. If WDC are produced to potentially replace wood with a short service life, then the climate change impact of their production and consequent incineration at the EoL is expected to be higher than that of wood. However, if WDC are produced as a unique material serving purposes potentially not achievable with wood, due to their strength or geometrical shape, but which can still be achieved with plastic, then the WDC could outperform plastics due to their lower production and EoL impact. However, the production of WDC itself could also be important if it takes place in a country where the CF of electricity is high because an absolute majority of the CFs of WDC originate from electricity consumption.

Variability of the feedstock, products which may be made from WDC, and EoL options together make it practically impossible to draw any specific conclusion as to their superiority over alternative products or on their own. Each case must be assessed according to specific conditions and primary data on the production of the composites, which is still widely lacking as few studies have been conducted on this subject. The lack of verified primary inventory data on WDC production is pointed out and should be addressed in future research.

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Relevant websites

https://wimao.fi/company/ – a company manufacturing composites from waste on an industrial scale in Lappeenranta, Finland
https://www.carbonfootprint.com/ – a company providing a wide range of information related to CF, its calculations, and certain CF factors
https://lutpub.lut.fi/handle/10024/158938 – a link to the carbon handprint guide