Life cycle assessment of conventional concrete and green concrete with wood waste biochar

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Introduction

As the world's population continues to rise, pressure on agricultural systems intensifies, driving the expansion of farmland into previously forested areas. Each year, millions of hectares of forest are cleared to meet food production needs, leaving behind substantial amounts of unused plant material. This biomass waste is often left on fields, where it gradually decomposes and as a result greenhouse gases are formed and released into the atmosphere. In addition to agricultural sources, large volumes of organic waste originate from municipal wastewater treatment, sawmills, and the pulp and paper industry, all of which collectively generate hundreds of millions of tonnes of biomass waste annually. A significant portion of this material is still disposed of through open burning, a practice that contributes to air pollution and the release of climate-warming emissions (Gupta et al., 2022; Perea-Moreno et al., 2019).

Thermochemical conversion technologies offer a more sustainable pathway for managing these biomass streams. Among them, pyrolysis has gained particular attention because it transforms organic waste into three valuable products: syngas, bio-oil, and biochar. Depending on the feedstock and processing temperature, biochar typically accounts for 30–40% of the total mass yield. In recent years, biochar has emerged as a promising additive in the construction sector, especially as a partial substitute for cement in concrete mixtures (Tripathi et al., 2016; Zhang et al., 2010).

This interest is closely linked to the environmental footprint of cement production. Manufacturing one tonne of cement releases roughly 0.8 tonnes of CO_2, and with global concrete production surpassing 30 billion tonnes annually, the construction industry represents one of the largest industrial contributors to greenhouse gas emissions. Incorporating even a small proportion of biochar such as 5–10 vol.% as cement replacement could therefore significantly reduce emissions while simultaneously providing a productive use for biomass waste that would otherwise be burned or left to decay (Legan et al., 2022). To better understand the environmental implications of such material innovations, researchers increasingly rely on life cycle assessment (LCA). Therefore, a comparative LCA was conducted to evaluate the differences between conventional concrete and green concrete with wood waste biochar as partial cement replacement.

Materials and Methods

Conventional and biochar-containing concrete mixtures were designed in accordance with several relevant standards. The final concrete composition used a water-to-cement ratio of 0.45, which satisfies all exposure classes defined in the EN 206:2013 standard for structural concrete. For the biochar-containing concrete, a 5 vol.% replacement of cement with biochar was assumed.

In assessing the environmental performance of each concrete type, the production of every individual component was considered separately. This included raw material extraction, processing, and the transportation of each component to the concrete production facility. The same system boundaries (gate-to-gate) were applied to both concrete mixtures to ensure a consistent comparison.

To quantify the environmental impacts associated with producing biochar-containing concrete, a life cycle assessment (LCA) was performed using the ReCiPe 2016 impact assessment method. All modelling and calculations were carried out in the SimaPro software environment, which enabled a detailed evaluation of midpoint and endpoint environmental indicators.

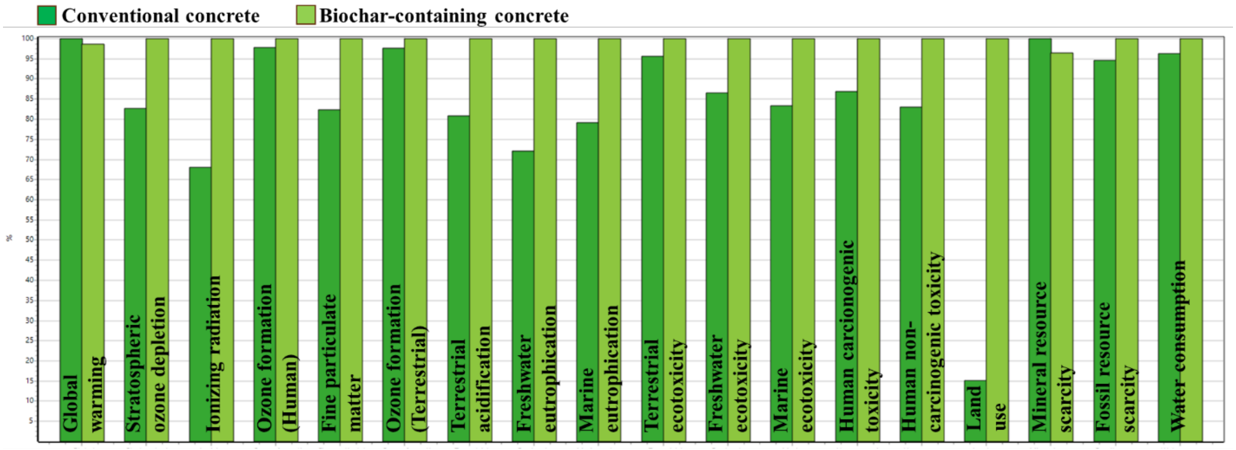
Results and Discussion

The LCA results in Figure 1 showed that replacing 5 vol.% of cement with biochar contributes to lower global warming potential and reduced mineral resource scarcity compared to conventional concrete. A more detailed analysis revealed that biomass waste preprocessing, particularly drying, significantly increases electricity consumption. This contributed to higher values in most impact categories. Based on these findings, future research should focus on improving the biochar production process by reducing the energy demand associated with biomass preprocessing.

The life cycle assessment (LCA) results clearly indicated that replacing 5 vol.% of cement with wood waste biochar can lead to notable environmental benefits when compared to conventional concrete. One of the most significant improvements was observed in the category of global warming potential, where the biochar-containing concrete demonstrated lower greenhouse gas emissions in terms of CO_2-eq. This reduction is primarily attributed to the partial displacement of cement, a material known for its high carbon footprint due to energy-intensive clinker production. Additionally, the use of biochar contributed to decreased mineral resource scarcity, since less cement and fewer raw materials were required for the final concrete mixture.

However, a more detailed breakdown of the LCA revealed important trade-offs. Among the individual stages, the preprocessing of biomass proved to be one of the most energy demanding steps. The drying process in particular required a substantial amount of electricity, which significantly elevated the environmental burdens in several impact categories, including terrestrial acidification, freshwater eutrophication, and fossil resource depletion. As a result, although the final concrete product shows environmental advantages, the upstream processes associated with biochar production partially offset these benefits.

Figure 1. Comparison of life cycle assessment results of conventional and biochar-containing concrete production.



Conclusions

The results of the LCA comparison highlighted the importance of optimizing the biochar production chain. Future research should therefore focus on reducing the energy demand of biomass waste preprocessing, for example by improving drying efficiency, utilizing waste heat, or exploring low-energy pretreatment alternatives. Enhancing the sustainability of biochar production would strengthen the overall environmental performance of biochar-containing concrete and support its broader adoption as a low-carbon construction material.

References

Gupta, N., Mahur, B. K., Izrayeel, A. M. D., Ahuja, A., & Rastogi, V. K. (2022). Biomass conversion of agricultural waste residues for different applications: a comprehensive review. *Environmental Science and Pollution Research*, *29*(49), 73622-73647.

Legan, M., Gotvajn, A. Ž., & Zupan, K. (2022). Potential of biochar use in building materials. *Journal of environmental management*, *309*, 114704.

Perea-Moreno, M. A., Samerón-Manzano, E., & Perea-Moreno, A. J. (2019). Biomass as renewable energy: Worldwide research trends. *Sustainability*, *11*(3), 863.

Tripathi, M., Sahu, J. N., & Ganesan, P. (2016). Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renewable and sustainable energy reviews*, *55*, 467-481.

Zhang, L., Xu, C. C., & Champagne, P. (2010). Overview of recent advances in thermo-chemical conversion of biomass. *Energy conversion and management*, *51*(5), 969-982.