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DEVELOPMENT OF GHG EMISSIONS CURVES FOR BIO-CONCRETES SPECIFICATION: CASE STUDY FOR BAMBOO, RICE HUSK, AND WOOD SHAVINGS CONSIDERING THE CONTEXT OF DIFFERENT COUNTRIES

L. R. Caldas[1,2]*, C. G. Bezerra[1], F. Pittau[3], Y. A. Araújo[1], M. Franco[1], N. Hasparyk[4], N. R. D. Toledo Filho[1]

[1] Programa de Engenharia Civil (PEC/COPPE), Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

[2] Programa de Pós-graduação em Arquitetura (PROARQ/FAU), Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

[3]Politecnico di Milano, Architecture, Built Environment and Construction Engineering (ABC) Department, Via Ponzio 31, 20133 Milano, Italy

[4] Furnas Centrais Elétricas

*Corresponding author; e-mail: lucas.caldas@fau.ufrj.br

Abstract

Bio-concretes are receiving special attention in recent research as an alternative for climate change mitigation due to their low carbon footprints. Different bio-based materials can be used, e.g., wood shavings, bamboo, rice husk, and coconut. However, various methodological parameters can influence the carbon footprint of bio-based materials, especially bio-concretes, like biogenic carbon, amount of carbon in dry matter, rotation period of bio-aggregates, and type of cementitious materials. It is important to have easier ways of estimating the carbon footprint of bio-concretes, using parameters and data easily available. This research aims to evaluate the (1) carbon footprint of different mixtures of three bio-concretes (wood bio-concrete - WBC, bamboo bio-concrete - BBC and rice husk bio-concrete - RBC), and the (2) development of GHG emissions curves for bio-concretes specification based on easily available data (such as density, biomass content, and compressive strength). Based on experimental data, the carbon footprint was performed using the Life Cycle Assessment (LCA) methodology. In order to extend the findings of this study, the context of the following four countries was evaluated: Brazil, South Africa, India, and China. In addition, the replacement of Portland cement for Supplementary Cementitious Materials (SCMs) are evaluated hypothetically. The results show that the increase of biomass content in bio-concretes and the replacement of Portland cement by SCMs leads to a radical decrease in life cycle GHG emissions. The percentage of carbon in biomass is a critical factor for reducing the carbon footprint. The WBC was the biomass that performed better for this parameter. The presented GHG emissions curves can be a useful way to estimate the carbon footprint of bio-concretes and can be adapted to other kinds of bio-concretes and countries.

Keywords:
Bio-concrete; LCA; Biogenic carbon; Brazil; India; South Africa; China.

1 INTRODUCTION

The need to address initiatives to mitigate the impacts of climate change is urgent. The construction sector is responsible for a great amount of greenhouse gas emissions (GHG). According to UNEP (2019), buildings account for around 40% of total CO_2 emissions (when the life cycle emissions is considered). Among the existing materials in the construction sector, concrete can be considered one of the most important due to its low cost, vast application, and durability. However, the production of concrete is responsible for a great amount of GHG emissions, principally due to the Portland cement production. During the last years, a substantial amount of strategies are developed, and are still in research, in order to decrease the negative environmental impacts of concrete products (Habert et al., 2020). One of these strategies is the development of bio-concretes. Bio-concretes can be defined as a mix of cementitious materials with bio-based aggregates, chemical additives, and water. They are light materials with good thermal performance and can reuse different kinds of bio-based waste, such as wood shavings, rice husk, and bamboo particles. They can be considered as circular building materials with the potential to stock CO_2 (Amziane and Sonebi, 2016; Caldas et al., 2020a, 2021). They can be produced in developing countries (especially African and Asian countries) where a great housing deficit exists and will continue to increase in the next years.

Recently, diverse studies with interest in the evaluation of the GHG emissions of bio-concretes have been conducted, using the Life Cycle Assessment (LCA) methodology, particularly the hempcrete (Arehart et al., 2020; Arrigoni et al., 2017; Florentin et al., 2017; Pittau et al., 2018) that is already used in commercial applications. Other researchers are interested in bio-concretes with wood-shavings (Caldas et al., 2020a, 2021) and bamboo (Caldas et al., 2020b). Most of these studies point out that the bio-concrete can be considered a low-carbon material when compared with conventional building materials such as ceramic, concrete, and steel. However, the LCA of bio-based materials' studies can have numerous uncertainties and inconsistencies, mainly concerning biogenic carbon. The biogenic carbon is the CO_2 that is sequestered and will be stocked in the biomass (Brandão et al., 2013; Hoxha et al., 2020).

Since bio-concretes are receiving more attention in different countries, it is important to have easier ways of estimating their carbon footprint, using parameters and data readily available. For example, physical properties such as density, biomass content, compressive strength, and other relations between them can be potential parameters. Therefore, it is important to have enough experimental data and different kinds of bio-concretes with biomasses with distinct characteristics such as carbon content and rotation periods. Da Gloria et al. (2020) evaluated 27 mixtures of wood bio-concretes (WBC), bamboo bio-concretes (BBC), and rice husk bio-concretes (RBC), and mechanical results are presented. Based on this kind of data is possible to evaluate the prospect of developing carbon footprint curves.

This research aims to (1) evaluate the carbon footprint of different mixtures of three bio-concretes (WBC, BBC, and RBC), and the (2) development of carbon footprint (GHG emissions) curves for bio-concretes specification based on easily available data (such as density, biomass content, compressive strength, and the relation between them), considering the context of different countries.

This is the first study that brings an overview and a general methodology for the development of low-carbon bio-concretes. Despite being focused on wood shavings, bamboo, and rice husk bio-concretes, our findings can be applied to study other kinds of similar bio-concretes. In order to extend the findings of this study, the context of four countries was evaluated: Brazil, South Africa, India, and China. These countries are located in continents, where the highest housing deficit increase is expected in the coming years (UNEP, 2019) and where different kind of biomasses, including rice husk, bamboo and wood shavings, are available for bio-concrete production. Therefore, this research brings a great contribution for the development of bio-concretes in the abovementioned regions and can have a global range.

2 METHODOLOGY

2.1 Characterization of bio-concrete mixtures

Twenty-seven mixtures of bio-concretes are evaluated: nine types of WBC, BBC, and RBC. The proportion of volumetric fraction of biomass in bio-concretes is the same for each one (52.5%, 50.0%, and 45.0%), as is the relation water/cement (0.40, 0.45, and 0.50), considering just the water used in the mixture. The composition and compressive strength results of each mixture are available in the study of Da Gloria et al. (2020).

2.2 Carbon footprint

The carbon footprint is based on LCA methodology and is performed based on EN 15804:2019 (CEN, 2013). It is divided into (1) Definition of the objective, scope, and functional unit; (2) Life cycle inventory; and (3) Biogenic Carbon and Life cycle impact assessment.

Definition of the objective, scope, and functional unit

The objective of this carbon footprint is to compare the balance of GHG emissions (in $kgCO_2$-eq) of three bio-concretes with a focus on different methodological aspects. This study can be considered as a cradle-to-gate scope and includes the following stages: raw materials' supply (A1), raw materials' transportation (A2), and bio-concretes manufacturing (A3). Firstly, the functional unit is defined as the volume of bio-concretes (in m^3). Secondly, a mechanical performance indicator (in m^3.MPa), considering compressive strength results, is employed. This indicator measures the amount of GHG emissions for each 1 m^3 and 1 MPa of compressive strength. The smaller this indicator, more efficient the material is.

Life cycle inventory (LCI)

For the Life Cycle Inventory (LCI), primary data is collected from the laboratory, while for secondary data, the Ecoinvent v. 3.6 and scientific literature are used. The electricity consumption of original Ecoinvent data is adapted to the Brazilian energy mix and market transports. The cut-off modeling is used for all datasets.

Biogenic Carbon and Life cycle Impact Assessment (LCIA)

For the biogenic carbon calculation, the first item is the definition of the carbon amount presented in dry matter. In the Life Cycle Impact Assessment (LCIA), we use the GWP_{bio} factor (using a 100-year time horizon) developed by Guest et al. (2012). In this method, different values are presented depending on the rotation period of the biomass and the number of years that the CO_2 sequestered by biomass will be stored in the anthroposphere. Since bio-concretes tend to mineralize the biomass due to cementitious materials (Pittau et al., 2018), we consider that this time is more than 100 years, as already used in other LCA of bio-concretes studies (Caldas et al., 2020a). For the rotation period, three different values are adopted for each biomass, as presented in Table 1.

Tab. 1: Parameters evaluated in the quantification of biogenic carbon.

Bio-based	% Carbon in dry matter			Rotation period			GWP_{bio} factor (%)		
	Best	Interm ediate	Worst	Best	Intermed iate	Worst	Best	Intermed iate	Worst
Wood shavings	53%	50%	47%	10	20	40	-96	-92	-84
Bamboo	47%	45%	42%	3	5	8	-98	-97	-96
Rice husk	41%	38%	35%	1	1-2	>2	-99	-99	-98

Sensitivity analysis

For the sensitivity analysis, part of the cement is replaced (in mass) by SCMs, metakaolin, and fly ash, based on a previous study of Caldas et al. (2020a) and Caldas et al. (2021), considering a proportion of 30:30:40 (cement: metakaolin: fly ash). In this analysis, it is important to see how the increase of biogenic carbon participation will affect the final results, since the use of SCMs for bio-concretes production significantly decreases the carbon footprint of bio-concretes. In order to improve the extension of this research to reach a global range, the LCI is adapted to the South African, Indian, and Chinese context, where these three bio-concretes can be developed. For the Portland cement, there is already available data in Ecoinvent v.3.6, for all these countries. For the other materials and activities, the electricity was adapted, changing the country-specific electricity mix for each process and sub-process.

2.3 Development of GHG emissions curves for the specification of bio-concretes

Two curves are developed, considering the context of Brazil, South Africa, India, and China, assuming the best (higher biogenic carbon and shorter transportation distances) and the worst scenario (smaller biogenic carbon and longer transportation distances):

- GHG intensity of bio-concretes (in $kgCO_2$-eq/m³.MPa) x efficiency indicator (compressive strength/density) – based on the study of Damineli et al. (2010). This curve allows estimating the GHG emissions balance of bio-concrete formulations and in the future can be used to define benchmarks.
- Carbon footprint (in in $kgCO_2$-eq/m³) x biomass content (biomass mass/bio-concrete materials total mass – in %). This curve allows estimating the carbon footprint of bio-concretes just using the quantity of materials used in the mixture.

For the hypothetical evaluation, using SCMs (metakaolin and fly ash), just the curve of "Carbon footprint x biomass content" has been evaluated since no compressive strength results are available.

3 RESULTS AND DISCUSSION

3.1 Evaluation of bio-concretes

For the evaluation of carbon footprint of bio-concretes, firstly (Fig. 1A), the original mixtures are developed experimentally, then the hypothetical mixtures (Fig. 1B) are evaluated considering the replacement of cement for the chosen SCMs (fly ash and metakaolin).

A B

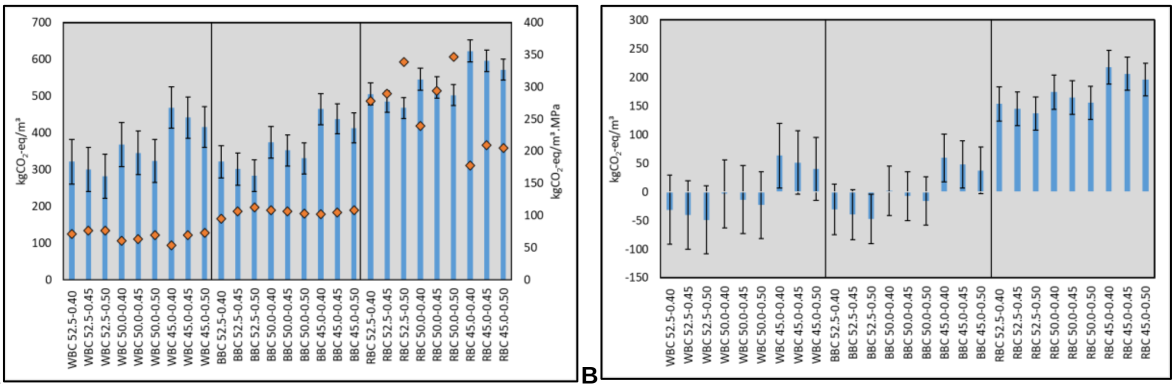

Fig. 1: Carbon footprint for Brazilian context. (A) Carbon footprint of the bio-concretes mixtures (blue bars). GHG intensity of bio-concretes (orange rhombus). (B) Carbon footprint of the bio-concretes hypothetical mixtures using SCMs. The error bars represent the variation in biogenic carbon and transportation distances.

The WBC and BBC presented a lower carbon footprint that is causally related to the higher content of biomass and the higher percentage of carbon in dry matter (as in the case of WBC). We can see that, for the development of low carbon bio-concretes, the use of SCM replacing Portland cement is required. In addition, the use of adequate SCMs can improve some properties, e.g., rheology and mechanical, as verified by Caldas et al. (2020a) and Andreola et al. (2019). It is important to say that a fair comparison among different bio-concretes must be done carefully, especially when they have diverse bio-based content and, consequently, properties. The type of application of the bio-concrete in a building will determine the most appropriate choice of the physical parameters that have to be used in the functional unit.

3.2 Development of GHG emissions curves for the specification of bio-concretes

For the evaluation of GHG emissions curves, the experimental and hypothetical data are used considering the LCA datasets for Brazil, India, South Africa, and China, and the original and hypothetical mixtures are evaluated. The first curve (Fig. 2) shows the GHG intensity x Efficiency indicator that requires compressive strength results. The other curves (Fig.3-4) show the carbon footprint x biomass content considering the mixtures with just Portland cement and the replacement by SCMs.

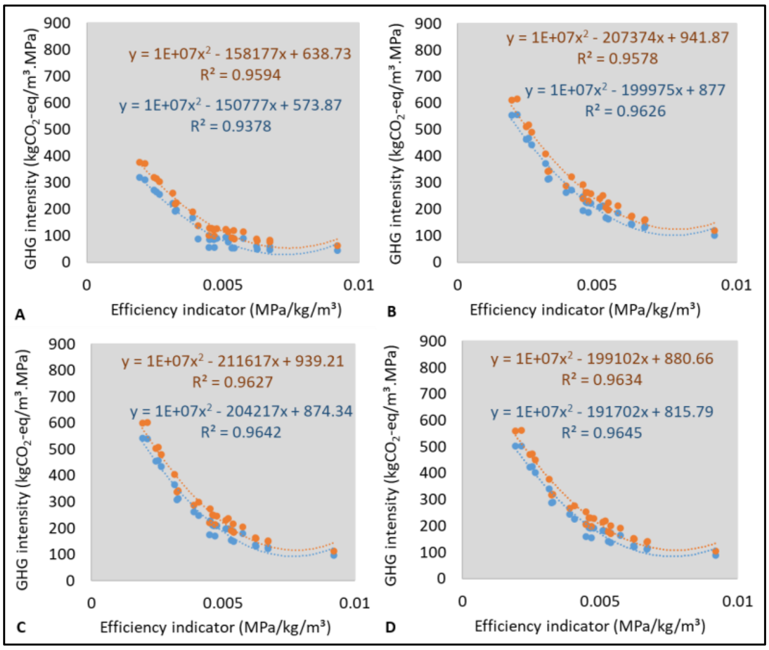

Fig. 2: GHG intensity of bio-concretes x efficiency indicator (compressive strength/density) curves. Bio-concretes with just Portland cement. (A) Brazil. (B) India. (C) South Africa. (D) China. The blue color refers to the best scenario (higher biogenic carbon and shorter transportation distances). The orange color represents the worst scenario (smaller biogenic carbon and longer transportation distances).

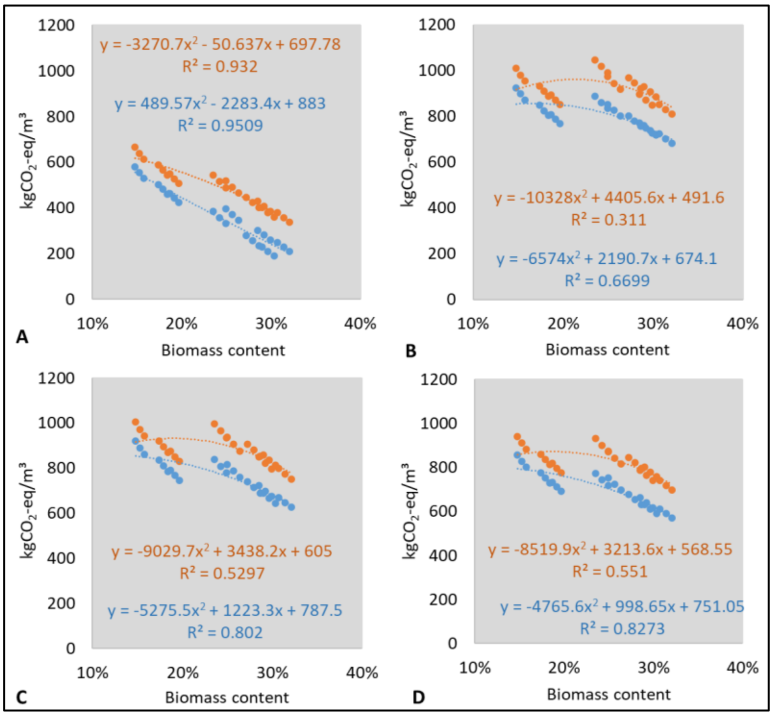

Fig. 3: Carbon footprint x biomass content curves. Bio-concretes with just Portland cement. (A) Brazil. (B) India. (C) South Africa. (D) China. The blue color refers to the best scenario (higher biogenic carbon and shorter transportation distances). The orange color represents the worst scenario (smaller biogenic carbon and longer transportation distances).

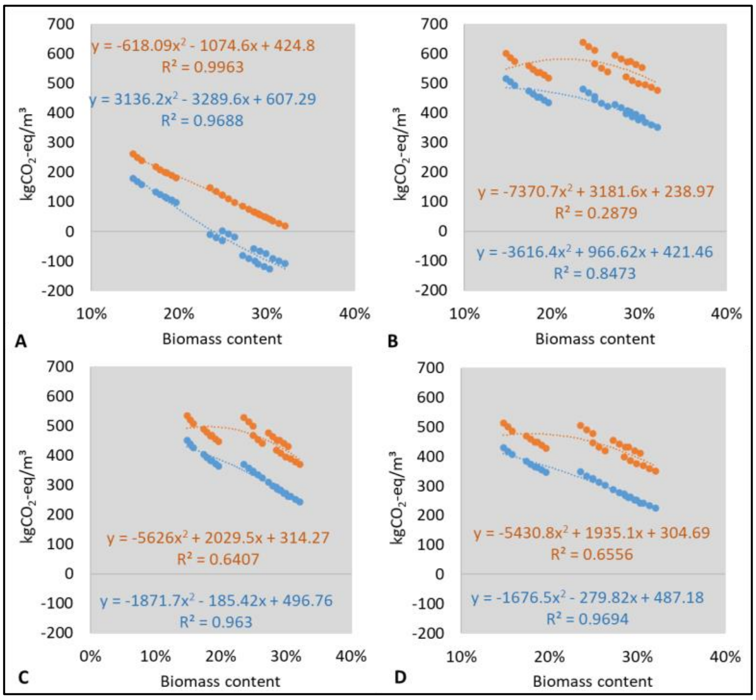

Fig. 4: Carbon footprint x biomass content curves. Bio-concretes with SCMs. (A) Brazil. (B) India. (C) South Africa. (D) China. The blue color refers to the best scenario (higher biogenic carbon and shorter transportation distances). The orange color represents the worst scenario (smaller biogenic carbon and longer transportation distances).

It is possible to see that, for the Brazilian case, the carbon footprint is lower, while for India, South Africa, and China, it is higher. This is a consequence mainly of each country's electricity mix used for biomass treatment. While Brazil has a matrix with a high share of renewable sources, the other three countries have a large share of fossil sources, mainly mineral coal. Therefore, we conclude that the country's electricity mix severely affects the bio-concretes carbon footprint and the curves' adjustment. The Brazilian curves present the highest correlation coefficient (R^2) since it has an electricity factor of 0.30 $kgCO_2$-eq/kWh. On the other hand, India presents the smallest R^2 with an electricity factor of 1.38 $kgCO_2$-eq/kWh, according to the Ecoinvent v. 3.6 data.

The curves can be used as a first approximation to define the carbon footprint of bio-concretes that use similar materials. When compressive strength is available, the curves have a better fit (Fig. 3). When is not available, the amount of biomass content is easily obtained and can be used by bio-concretes researchers and developers that are not specialists in LCA. The curves with SCMs and the best scenario (blue ones) present a better fit since the biogenic carbon exerts a greater influence on the carbon footprint. As the biomasses evaluated have a wide range of variation (in terms of carbon content and rotation periods), the curves can be used to estimate the carbon footprint of bio-concretes with other biomasses if they are within the range of the characteristics of the biomasses evaluated here. If thermal properties of the bio-concretes are available, e.g., thermal conductivity, a thermal efficiency indicator can be used. However, the bio-concretes must have the minimum mechanical requirements according with their application, as discussed by Caldas et al. (2020a).

4 CONCLUSIONS

In this research, the life cycle GHG emissions of twenty-seven mixtures of bio-concretes made of wood shavings (WBC), bamboo particles (BBC), and rice husk (RBC) are evaluated, considering different methodological parameters, assuming the production of these bio-concretes in Brazil, India, South Africa, and China. Based on our research and the premises adopted in the LCA modeling, it is important to highlight the main findings:

- The increase of biomass content and the replacement of the Portland cement for some SCMs in bio-concretes leads to a radical decrease in life cycle GHG emissions.
- The percentage of carbon in biomass is a critical factor for the reduction of the carbon footprint. The WBC is the biomass that performs better for this parameter.
- The electricity consumption for the biomass recycling and treatment process can have an important role in life cycle GHG emissions, especially in countries with a GHG intensive matrix, e.g., India, South Africa, and China.
- The relation between GHG intensity of bio-concretes x efficiency indicator shows to be particularly good in estimating the carbon footprint of different bio-concretes. However, compressive strength results are required.
- The relation between biomass and bio-concrete materials total mass shows to be good in estimating the carbon footprint of different bio-concretes, when mechanical results are not available.
- The presented GHG emissions curves can be a useful way to calculate/estimate the carbon footprint of bio-concretes and can be adapted to other kinds of bio-concretes and countries.

In addition, it is important to describe the main limitations of this research: firstly, some of the used databases are not adapted to the selected countries' context and can influence the final results; secondly, the type of modeling of biogenic carbon used here does not consider that some aspects, e.g., land use, were outside of the scope of the research; the allocation of waste materials are not considered and can also change the results; finally, the hypothetical mixtures with SCMs can have its development limited due to rheology or mechanical properties. These limitations should be explored in future studies. A thermal efficiency indicator can be proposed and evaluated.

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