IBRACON Structures and Materials Journal
Revista IBRACON de Estruturas e Materiais
ISSN 1983-4195 ismj.org

ORIGINAL ARTICLE

Circular economy in concrete production: Greenhouse Gas (GHG) emissions assessment of rice husk bio-concretes

Economia circular na produção de concretos: avaliação das emissões de Gases de Efeito Estufa (GEE) de bioconcretos com casca de arroz

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Received 02 February 2022
Accepted 17 September 2022

Abstract: Circular Economy (CE) is progressively attracting interest from construction sector stakeholders to support the development of products with higher amounts of recovered materials in order to decrease greenhouse gas (GHG) emissions. Concrete is one of the most used materials in the world and can be produced using waste as raw materials, including, bio-based sources, from both agricultural and forest activities. This research aims to assess the GHG emissions in the life cycle of innovative rice husk bio-concretes (RBC) in which rice husk (RH) and rice husk ash (RHA) are used as circular solutions. Four RBC, considering ordinary Portland cement replacement by 8% of RHA and, different contents of sand substitution by RH (0; 5 and 10%), were assessed. The Life Cycle Assessment (LCA) methodology was used, with a cradle-to-gate scope, using the GWPbio method, that contemplate the influence of biogenic carbon on the emissions reduction. Different transportation scenarios were evaluated considering the RBC production in different Brazilian regions. The service life of RBC in terms of carbon stock was also evaluated. Two carbon-performance indicators are also evaluated in terms of RBC compressive strength and thermal conductivity values. As the main conclusion, cement replacement by RHA alongside with sand replacement by RH are promising strategies to produce bio-concretes for specific applications, such as panels, partitions and façade elements, and to reduce its GHG emissions. However, this benefit varies according to RH availability, transport efficiency and RBC service life. The RBC can be considered a potential alternative for concrete industry, for specific applications, to reduce GHG emissions and can be developed where rice waste is an available source. This study contributes by presenting a new material and a methodology for the evaluation of life cycle GHG emissions of bio-concretes, which can help to promote a circular construction sector.

Keywords: concrete, circular economy, life cycle assessment, LCA, CO_2, biogenic carbon, rice waste.

Resumo: A Economia Circular (EC) está progressivamente atraindo o interesse dos *stakeholders* do setor de construção para apoiar o desenvolvimento de produtos com maior quantidade de materiais recuperados, a fim de diminuir as emissões de Gases de Efeito Estufa (GEE). O concreto é um dos materiais mais utilizados no mundo e pode ser produzido utilizando resíduos como matéria-prima, incluindo fontes de base biológica, tanto de atividades agrícolas quanto florestais. Esta pesquisa tem como objetivo avaliar as emissões de GEE no

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Financial support: R&D Project from ANEEL - National Electric Energy Agency, "Use of bio-concretes and Bio-MMFs with low environmental impact aiming the increasing of energetic efficiency of public buildings" – PD.0394-1719/2017.
Conflict of interest: Nothing to declare.
Data Availability: None.

ciclo de vida de Bioconcretos de Casca de Arroz (BCA) inovadores em que a Casca de Arroz (CA) e as Cinzas de Casca de Arroz (CCA) são empregadas como soluções circulares. Foram avaliados quatro BCA, considerando a substituição de cimento Portland comum por 8% de CCA e diferentes teores de substituição de areia por CA (0; 5 e 10%). Foi utilizada a metodologia da Avaliação do Ciclo de Vida (ACV), com escopo do berço ao portão, utilizando o método GWPbio, que contempla a influência do carbono biogênico na redução das emissões. Diferentes cenários de transporte foram avaliados considerando a produção do BCA em diferentes regiões brasileiras. Dois indicadores de desempenho de carbono dos BCA também são avaliados em termos de resistência à compressão e de valores de condutividade térmica. Como principal conclusão, a substituição do cimento por CCA e da areia por CA são estratégias promissoras para a produção de bioconcretos para aplicações específicas para reduzir suas emissões de GEE. No entanto, esse benefício varia de acordo com a disponibilidade de CA, eficiência de transporte e vida útil do BCA. O BCA pode ser considerado uma alternativa potencial para a indústria de concreto, para aplicações específicas, para reduzir as emissões de GEE e pode ser desenvolvido onde o resíduo de arroz é uma fonte disponível. Este estudo contribui ao apresentar um novo material e uma metodologia para a avaliação das emissões de GEE do ciclo de vida dos bioconcretos, que podem promover um setor de construção circular.

Palavras-chave: concreto, economia circular, avaliação do ciclo de vida, ACV, CO_2, carbono biogênico, resíduo de arroz.

How to cite: L. R. Caldas, A. F. Araujo, N. P. Hasparyk, F. Tiecher, G. Amantino, and R. D. Toledo Filho. "Circular Economy in Concrete Production: Greenhouse Gas (GHG) Emissions Assessment of Rice Husk Bio-Concretes," *Rev. IBRACON Estrut. Mater.*, vol. 15, no. 6, e15602, 2022, https://doi.org/10.1590/S1983-41952022000600002

1 INTRODUCTION

The construction and building sector is responsible for about 40% of global energy consumption, 40% of Greenhouse Gas (GHG) emissions, 25% of the water and 40% of the global resources consumptions [1], [2]. Cement and concrete are the most used industrial materials in the world. Cement industry alone is responsible for 5-8% of global CO_2 emissions [3]. Besides that, concrete is used in large quantities and considering its performance due to important properties (durability, fire safety, water resistance and others) and ease of usage, a great replacement of concrete by other materials does not seem to be feasible within the next years. Therefore, it is crucial to develop alternatives to reduce the environmental impacts of the concrete industry [3], [4]. To achieve this challenge, understanding and applying the concepts and principles of Circular Economy (CE) to construction materials are of vital importance.

CE can be understood as a new economic model that incentives the reduction of natural resources consumption, the minimization of waste generation by keeping them in a closed loop and the use of renewable and local resources. It is based on the 5R principles: Rethink, Reduce, Reuse, Repair and Recycle [5]–[8]. The concept of circularity involves essentially a decrease of the GHG emissions in the concrete industry and the whole construction sector [9], [10]. This could enable the sector to archive low carbon targets to meet the Paris Agreement goals of limiting global warming well below 2°C and even to reach a net-zero carbon pathway [11].

The Life Cycle Assessment (LCA) is one of the most used and scientifically accepted methodologies for evaluating the potential environmental impacts of products and processes, and it is especially important for the evaluation of the environmental performance of innovative materials. LCA is standardized by ISO series (ISO 14040 and ISO 14044) [12]–[14]. The Global Warming Potential (GWP), converted in life cycle GHG emissions, is one of the most evaluated impact category since climate change is perhaps the greatest contemporary challenge of humanity [15], [16].

The vast literature about LCA applied to concrete has demonstrated that the use of Supplementary Cementitious Materials (SCM), originated from other industrial processes (*e.g.*, waste and byproducts) for cement replacement is a very good strategy for reducing GHG emissions and, depending of the content, such replacements can also increase mechanical and durability performances [3], [17]–[21]. This has also been confirmed for bio-concretes [22]. However, the local availability of some SCM, such as fly ash or biomass ashes, can compromise its use due to the increase of GHG emissions related to other factors, like transportation, especially in continental countries, such as Brazil [15], [23]–[25]. Most of SCM used for concrete production are waste or byproducts from other industrial processes, such as fly ash, blast furnace slag, rice husk ash, municipal waste incineration ash, which can be considered examples of CE strategies [25].

Another strategy for the concrete industry aligned with the CE concept is the replacement of virgin mineral aggregates by recycled ones. Although most of the studies about LCA and GHG emissions evaluation in the literature are concerned about conventional concrete with only mineral aggregates, it is possible to produce bio-concretes that can reuse different kinds of bio-based materials as aggregates and/or even as SCM. The main advantages of using plant aggregates for the production of bio-concretes involve the reduction of material density, thermal conductivity and carbon footprint. These aggregates can act as carbon stocks since the cementitious materials tend to store carbon by its mineralization in the matrix after hydration [26].

In the literature, the most studied bio-concrete is the hempcrete, that is a mixture between cement, lime and hemp shives. Hempcretes can have negative carbon footprint or, in other words, they can generate carbon credits [27]–[30]. However, the main issue of the hempcrete is attributed to its low mechanical strength (around 1-2 MPa) [23]. For this reason, it is regularly used as an insulation or filling material in buildings. On the other hand, different bio-concretes made with wood shavings and bamboo waste, have better mechanical performances, with compressive strengths values ranging from 5 MPa to 10 MPa [22], [26], [31] and can be used for other building applications, like walls (for internal partitions and façades), ceilings, shading elements, furniture, etc. In addition, there are other options and available sources of bio-based materials, such as rice husk, corn flakes, coconut, etc. However, there are few studies about the environmental performance of these bio-concretes, since most of the available research is concerned about its mechanical and thermal characterization [32].

Waste from rice production is substantial, especially in the south of Brazil. The global rice production reaches about 500 million tons/year and Brazil is responsible for around 11 million tons/year [33]. The waste husk generated by the rice processing is equivalent to 20% of the rice grains mass. In general, this rice husk (RH) is burned in an attempt to reduce its disposal problem. Furthermore, the potential benefits of the use of rice husk ash (RHA) in the concrete properties as well as in the durability are well known and depend on the burning conditions [34]–[37]. The RHA can be used in partial substitution to cement due to its chemical composition, with high contents of reactive silica. Nonetheless, not all the RH is burned and the remaining husk volume is available to be stocked, especially in cement matrices considering the use as bio-aggregates in substitution to mineral aggregates for producing bio-concretes.

Considering the above, this paper aims to assess GHG emissions in the life cycle of innovative RBC in which RH and RHA are used as circular solutions. Two carbon-performance indicators are also evaluated in terms of RBC compressive strength and thermal conductivity values. Finally, design guidelines for GHG emissions reduction during RBC production are proposed.

This study brings forward as its main contribution the presentation of a new bio-concrete, the RBC, with mixed types of aggregates (minerals and bio-based). In addition, the methodology used can be adapted for the evaluation of life cycle GHG emissions of other bio-concretes. Since the RBC makes use of two CE strategies, use of waste and renewable materials, it can promote a more sustainable and circular concrete production.

2 MATERIALS AND METHODS

Figure 1 presents the main stages followed in the Materials and Methods. The presented approach can be used for the evaluation of life cycle GHG emissions and choice of best mixture of other bio-concretes as well, even though a specific RBC is evaluated in this study.

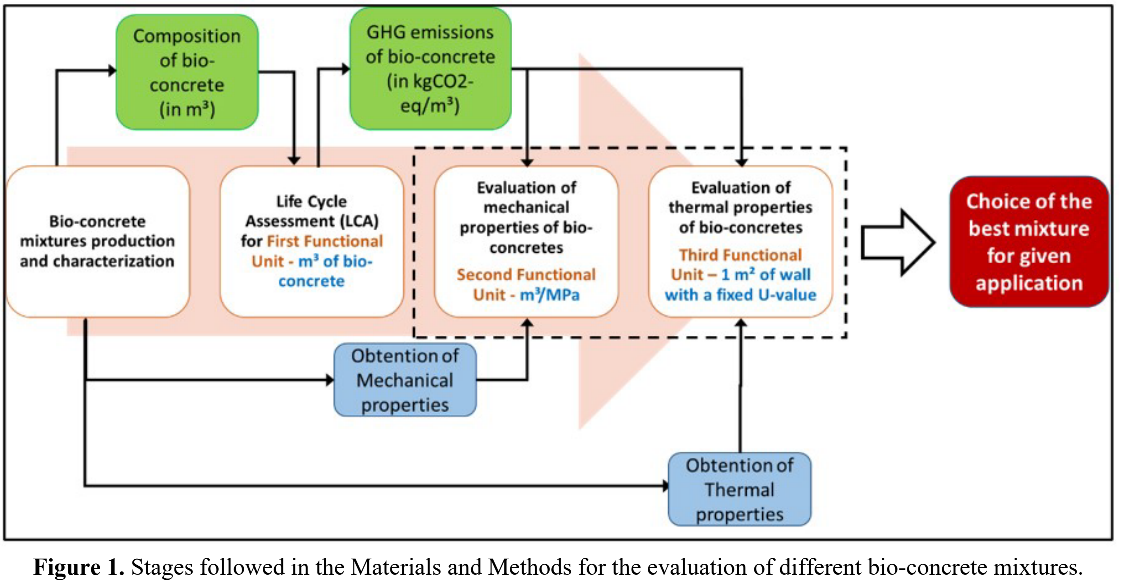

Figure 1. Stages followed in the Materials and Methods for the evaluation of different bio-concrete mixtures.

2.1 Bio-concrete Production and Characterization

RBC – Rice husk Bio-Concretes were cast with the following materials: Brazilian ordinary Portland cement (OPC): high early strength, CP V-ARI Type (equivalent to cement type III, ASTM-150); SCM: rice husk-ash (RHA) in partial substitution to cement at 8%, by weight; mineral aggregates: coarse and fine aggregates from granitic origin; bio-aggregate: rice husk used as a partial replacement of fine aggregate, by volume, in fractions of: 0%, 5%, 10%; chemical admixture: polyfunctional.

The concrete mix proportion was based on a conventional concrete to be applied in various construction elements. The mixture was obtained based on the fineness modulus method, considering the aggregates and a specific range of estimated strength. The four evaluated mixtures contained the same cementitious material content of 350 kg/m^3 (of which 8% was RHA for the RH00, RH05 and RH10 mixtures), and a water: binder ratio equal to 0.58. The difference between them was the content of RH, as follows: 0% (RH00), 5% (RH05) and 10% (RH10) in substitution to the fine aggregate (by volume). The amount of chemical admixture was within the recommended range by the manufacturer. Throughout preliminary tests, the chemical admixture content of 0.30% by cement weight was established in order to produce proper workability, through the slump test [38]. The RBC mixtures composition is presented in Table 1. The main properties determined for the RBC (density, compressive strength and thermal conductivity) are presented in Table 2 [39]. The properties of materials used in the RBC production are detailed in the study of Amantino [39].

Table 1. Rice husk bio-concrete mixtures composition (kg/m^3).

Mixtures	OPC	RHA	G	S	RH	CA	W
REF	350	0	1078	781	0	1.1	203
RH00	322	28	1078	781	0	1.0	203
RH05	322	28	1078	742	21	1.0	203
RH10	322	28	1078	704	42	1.0	203

REF – Reference mixture. OPC – Ordinary Portland Cement. RHA – Rice husk ash. G – Gravel. S – Sand. RH – Rice husk. CA – Chemical admixture. W – Water.

Table 2. Rice husk bio-concrete properties in 28 days.

BC-RH (in %)	REF	RH00	RH05	RH10
Density (kg/m^3)	2312,04	2218,9	2176,11	2009,13
Compressive Strength (MPa)	30.20	25.26	19.14	15.11
Thermal conductivity (W/m·K)	1.87	1.51	1.06	0.94

2.2 Life Cycle Assessment (LCA)

The LCA was performed according to ISO 14040 [40], ISO 14044 [41], EN 15978:2011 [42]. and EN 15804:2019 [43]. The two first standards refer to the LCA of any product, while the last two are applied to the construction sector. According to them the LCA is divided in the following stages: (1) Goal and scope definition; (2) Life Cycle Inventory (LCI); (3) Life Cycle Impact Assessment (LCIA) and (4) Interpretation. They are presented below.

2.2.1 Goal and Scope definition

The goal of this LCA study is to evaluate the GHG emissions (in kgCO_2-eq) on the life cycle of different mixtures of RBC. The scope, from cradle-to-gate, considers raw materials supply (A1), transport (A2) and RBC manufacture (A3), following the recommendations of EN 15804 [43], as presented in Figure 2.

Three Functional Units (FUs) were adopted: first, “the volume (in m^3) of the RBC”; second, a FU based on “the volume and compressive strength (in m^3.MPa) of the RBC”, which is a common indicator used for the evaluation of new materials, including concretes and bio-concretes [22]; finally, a FU based on the thermal conductivity (presented in Table 2) and U-value (thermal transmittance), considering “1 m^2 of wall with a fixed U-value of 2.5 W/m^2.K”, according with the criteria of NBR 15575-4 [44] for façades in Brazil. With this value fixed, it was possible to calculate the wall thickness for each RBC mixture, according with the procedure of NBR 15220-2 [45], as presented in Table 3. This approach is common in the literature for the evaluation, by LCA, of materials, especially bio-based ones used in buildings’ façades [46].

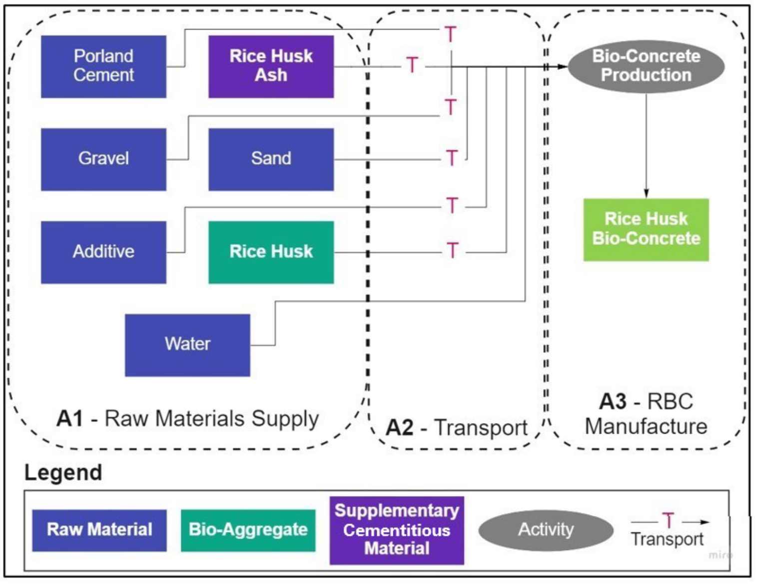

Figure 2. System boundaries for the production of Rice husk bio-concrete.

Table 3. Parameters for the calculation of wall thickness for the third FU.

BC-RH (in %)	REF	RH00	RH05	RH10
RBC thermal conductivity (W/m.K) [43]	1.87	1.51	1.06	0.94
Wall U-value (W/m^2.K)	2.5	2.5	2.5	2.5
Wall thickness (cm)	58	43	25	21

2.2.2 Life Cycle Inventory (LCI)

For the LCI primary data was collected in the laboratory during RBC production and development, while secondary data was collected from Ecoinvent v. 3.8 and literature. The electricity consumption of original Ecoinvent data was adapted to the Brazilian energy mix and market transports. The data used in the modeling is presented in Table 4, where it is possible to see that most of them are already developed for the Brazilian context. RH was considered with zero GHG burden since it is a recovered waste from rice production, while for RHA it was only considered the electricity for grinding, obtained from Silva [47].

Table 4. Raw materials, activities and datasets used in Rice husk bio-concrete (RBC) LCI.

Materials and Activities	Dataset
Portland cement	Cement, Portland {BR}| cement production,
Sand	Sand {BR}| sand quarry operation, extraction from riverbed
Gravel	Gravel, crushed {BR}| gravel production, crushed
Rice husk ash	Modeled by the authors Based on Silva [47], Electricity, medium voltage {BR}
Chemical admixture	Plasticizer, for concrete, based on sulfonated melamine formaldehyde {GLO}| production
Water	Tap water {BR}
Transportation	Transport, freight, lorry 16-32 metric ton, EURO3 {BR}
Electricity	Electricity, medium voltage {BR}| market group for electricity
Bio-concrete production	Concrete, 25MPa {BR}| concrete production

2.2.3 Life Cycle Impact Assessment (LCIA)

For the LCIA, the EN 15804 + A2 (v. 1.00) method [48] was used, considering the Climate Change impact (Climate Change – Fossil and; Land use and land use change). The Climate Change – Biogenic was modelled for the RH according with another method that is described below.

2.2.4 Biogenic Carbon

For the RH biogenic carbon quantification, the method developed by Guest et al. [49] that defines a GWPbio index was employed. It was considered that the biologic CO_2 is stored indefinitely (for more than 100 years) since the cementitious materials of bio-concretes tend to mineralize the biomass [25], [30]. Furthermore, based on the rotation period of 1 year of the rice production and the storage period in the anthroposphere, the GWPbio factor of -99% for rice husk based on Guest et al. [49] was adopted. As a sensitivity analysis, another service life was considered assuming that CO_2 would be stored for 50 years in the anthroposphere, resulting in a GWPbio factor of -40%. The Equations 1 and 2 were used with the parameters presented in Table 5.

$$Mco_2 = m_{dry}\ x\ GWP_{bio} \tag{1}$$

$$GWP_{bio} = C\ x\ Factor_{bio}\ x\ \frac{mm_{CO2}}{mm_C} \tag{2}$$

Where Mco_2 = CO_2 uptake and storage (kg) – biogenic carbon; m_{dry}= dry mass of rice husk (kg); C = percentage of carbon in dry matter (%); GWPbio Factor = considered according to Guest et al. [50]; mm_{CO2} = molecular mass of CO_2 (44); and mm_C = molecular mass of C (12).

Table 5. Parameters and data for the biogenic carbon modeling of rice husk.

Scenario	C (%)	Time in Anthroposphere (years)	GWPbio Factor (%)	MCO_2 ($kgCO_2/kg$)
Best – 1	41	100	-99	-1,49
Intermediate – 1	38	100	-99	-1,38
Worst – 1	35	100	-99	-1,27
Best – 2	41	50	-40	-0,60
Intermediate – 2	38	50	-40	-0,56
Worst – 2	35	50	-40	-0,52

2.2.5 Sensitivity analysis

For the sensitivity analysis two items were evaluated in this research:

- RHA and RH transportation considering that these materials are locally available, using the approach presented by Caldas et al. [25] and Lima et al. [15] which assumes different transportation efficiency scenarios in terms of truck capacity and way of return (empty or loaded). The following scenarios were considered: (1) Round trip 100% loaded (more efficient); (2) Going 50% loaded and empty return (less efficient). For that, Ecoinvent datasets were used (Transport, truck 10-20t, EURO3, 100%LF, default/GLO Mass; Transport, truck 10-20t, EURO3, 50%LF, empty return/GLO Mass).
- Storage of biogenic carbon (described in the Biogenic carbon section). The sensitivity analysis was performed for the reference RBC (REF) and RBC with higher content of RH (RH10).

3 RESULTS AND DISCUSSION

This section is divided in: (3.1) GHG Emissions in the Three Functional Units (FU); (3.2) GHG Emissions Profile; (3.3) Sensitivity Analysis, and; (3.4) Design Guidelines for Producing Low-Carbon Bio-Concretes.

3.1 GHG Emissions in the Three Functional Units (FU)

The GHG emissions results considering the three FU are presented in Figures 3-5. Two scenarios of biogenic carbon storage in anthroposphere were considered, as follows: (A) for more than 100 years and (B) for 50 years.

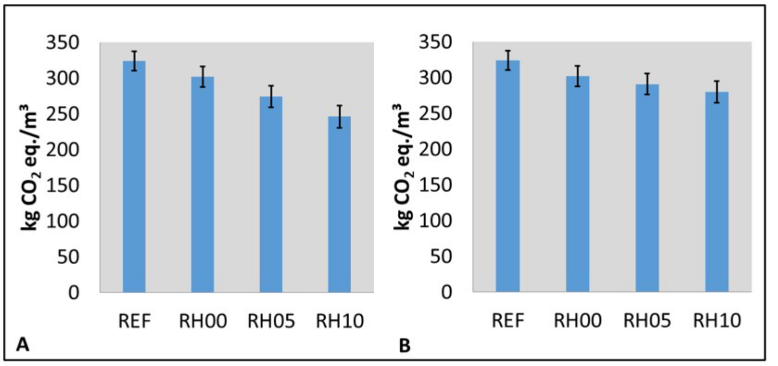

Figure 3. GHG emissions in the first Functional Unit (in m^3 of bio-concrete). (A) Biogenic carbon scenario 1. (B) Biogenic carbon scenario 2.

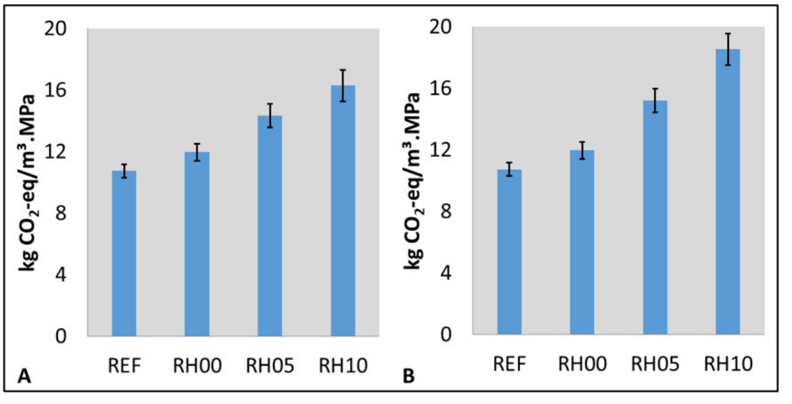

Figure 4. GHG emissions in the second Functional Unit (in m^3 of bio-concrete and 1 MPa). (A) Biogenic carbon scenario 1. (B) Biogenic carbon scenario 2.

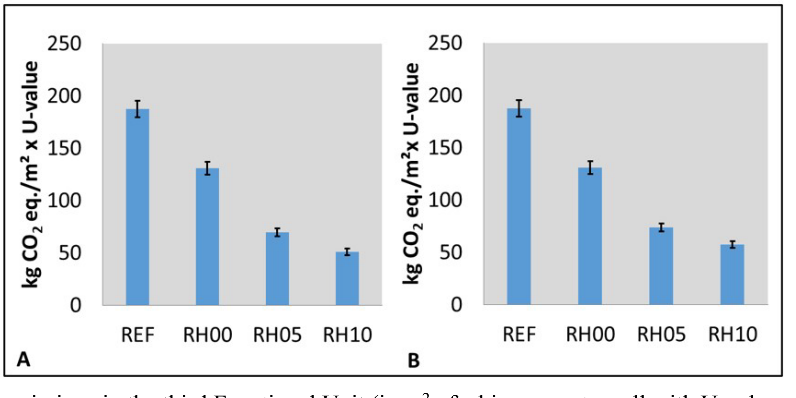

Figure 5. GHG emissions in the third Functional Unit (in m^2 of a bio-concrete wall with U-value of 2.5 W/m^2.K). (A) Biogenic carbon scenario 1. (B) Biogenic carbon scenario 2.

For the first FU, in "m^3 of bio-concrete", according to Figure 3, it can be noticed that the RBC with highest content of RH (RH10) presented the lowest GHG emission, while the RBC without any RH or RHA (REF) presented the highest value, for both scenarios of biogenic carbon, as expected. For the first scenario of biogenic carbon (considering biologic CO_2 is stored indefinitely, for more than 100 years), there is a difference of 24% between RH10 and REF. On the other hand, for the second scenario (assuming a storage period of 50 years) the difference between them was of 14%.

The evaluation of these two scenarios showed the influence that methodological choices for biogenic carbon storage accounting have in total GHG emissions estimation of the RBC, which meets with previous literature findings that have already highlighted the importance of the period of carbon storage in the building material to decrease the global warming potential impact [25], [46], [50], [51]. Therefore, these results underline the importance of considering different carbon storage periods in LCA modeling of bio-based materials, even bio-concretes, due to the uncertainty of service life of building materials, especially innovative ones, like the RBC. Additionally, it highlights the importance of designing for durability, which results in lower GHG emissions.

When the second FU is analyzed, "m^3 of bio-concrete for each 1 MPa", in Figure 4, the results point to a different direction. The RBC RH10 presented the worst value, while the REF presented the best in terms of strength, reaching a difference of 42%. This is a direct consequence of the compressive strength that had suffered a pronounced decrease (around 50%) when more biomass was added, and sand was replaced. The biogenic carbon did not show an expressive influence in the results due to the low level of biomass used in the studied mixtures. In other words, this FU shows that 1 MPa of RH10 emits more GHG emissions than the REF RBC. However, the interpretation of this FU should be done with care since bio-concretes are not designed to be applied in buildings as structural elements, such as beams and columns. They are normally designed to be used as materials for the building envelope, especially façades and roofs, due to the better thermal performance [22], [52] of those materials. The bio-concretes should have a proper mechanical performance, that also influences durability aspects, allowing their use for this kind of application.

Based on this explanation, the third FU, "in m^2 of a bio-concrete wall with U-value of 2.5 $W/m^2.K$", can be justified and understood in a better way. This FU allows a better realistic quantification of the material consumption that would be used in a building; advances in the scale analysis, from a material to a building element and is more related with one of the main bio-concretes' advantages, the thermal performance. When this FU is used, according to Figure 5, differences of around 72% between RH10 and REF for the biogenic scenario 1 and of 69% for biogenic scenario 2 are observed.

The three presented FU, especially the last two, provide subside for choosing the most appropriate RBC mixture in function of its application, and in this case, for a wall in a building façade. Pretot et al. [52], Pittau et al. [30] and Carcasi et al. [46] used the U-value as a reference for FU definition of buildings' walls made of bio-based materials, mainly hempcretes. However, the studied properties (mechanical and thermal) are just two among a bigger universe of buildings performance (acoustic, waterproof, fire resistance, etc.).

If the target of the design is a concrete wall with a lower GHG emissions and a better thermal performance, thus, the RH10 tends to be the best option. Additional materials can be used as coverings of the bio-concrete wall such as paintings and plastering's, and this choice can also be assisted by the LCA. For example, clay plasters reinforced with bio-based fibers tend to be a good low carbon option and compatible with bio-concretes [15], [53].

3.2 GHG Emissions Profile

The GHG emissions profile (considering the biogenic carbon scenario 1) is presented in Figure 6 in terms of the contribution for each material.

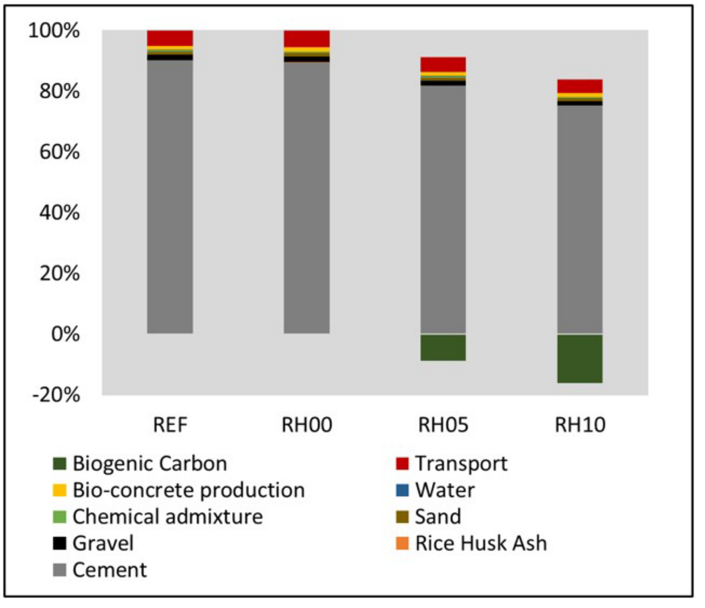

Figure 6. GHG emissions profile.

Cement production is the main GHG emitter, reaching average values of 80%. This occurs especially due to the calcination process of clinker that occurs during the production of cement and the use of fossil fuels, such petrol coke, for the case of most Brazilian cement factories. This finding agrees with the literature that already showed that OPC is the main impactful material for concrete [19], [54], [55] and bio-concrete production [22], [25]. Transport contributed with around 10%, while sand and gravel presented a very small contribution in emissions, below 5% (both materials, together), since these materials are not energy intensive and, in this case, just the extraction process from nature is considered. The biogenic carbon present in the RH helps to the decrease of the final values, but since it is used in small fractions its influence is not so significant.

Based on these findings the use of different pozzolanic materials from other industrial waste or byproducts such as fly ash, should be evaluated as cement replacement, as an alternative for lowering life cycle GHG emissions. A greater amount of sand replacement by RH would also contribute for this reduction, however, resulting in a trade-off of deteriorating the mechanical properties.

About the allocation process of coproducts, such as fly ash and other commercial residues, it is important to mention that it is often a very controversial subject in LCA studies [25], [56]. In the present study, the allocation process was not considered, and, in the literature, it was verified that most studies that evaluate SCMs do not consider the allocation for concrete production. In the case of market practices, the tendency is to consider the economic allocation, which takes only a small amount of impact into the byproducts given its economic value in comparison to the primary product, in some cases, bellow 1% and, therefore, not influencing in the final results [22], [56]–[58].

3.3 Sensitivity Analysis

For the sensitivity analysis, the results considered the efficiency in transportation and the biogenic carbon scenarios, as presented in Figure 7.

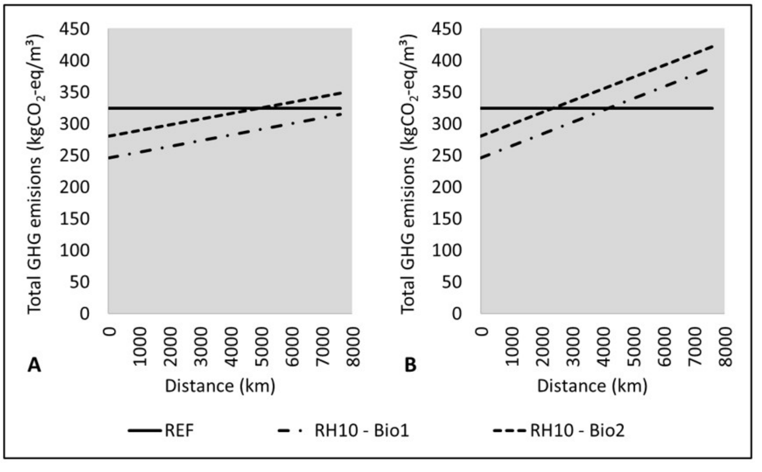

Figure 7. Analysis of RH and RHA transport distances influence in total GHG emissions. (A) More efficient transport (100% default). (B) Less efficient transport (50% empty). Bio 1 – Biogenic scenario 1. Bio 2 – Biogenic scenario 2.

It is clear that the transport distances of RHA and RH have a small influence in the total GHG emissions due to low biomass content in the mixtures. For a more efficient transport scenario these materials should be transported for more than 4.000 km, while for a less efficient scenario for more than 2.000 km (which is also an expressive value, considering the geographical conditions of the Brazilian territory), and RH10 would still have lower impact than REF RBC. Considering this comparison and the condition that RHA and RH mostly comes from the South region of Brazil, these materials could be transported to Southeast and West-Center regions for the worst scenario. For the more efficient scenario it could also reach Northeast and North regions. Based on these findings, the use of RBC could also be encouraged in terms of GHG emissions in regions where rice production is not available. However, this can completely change in terms of costs or other logistics aspects.

These results are different from the literature, e.g [25], where transport showed to have a big influence and the amount of bio-aggregate and residual SCM, namely fly ash, in bio-concrete composition was higher. On the other hand, in the present research RHA and RH in RBC composition reached 1% and 2% in dry mass, respectively. For RBC, mineral coarse and fine aggregates are the materials that most influence in GHG emissions of transportation stage, since their participation in dry mass are around 50% and 30%, respectively, and normally, they are available materials in most of Brazilian regions.

3.4 Design Guidelines for Producing Low-Carbon Bio-Concretes

Based on the findings of this research and the analyzed literature, design guidelines are proposed for producing low-carbon bio-concretes. Table 6 summarizes these strategies, their priority level, and associated trade-offs that can influence technical/performance aspects of the bio-concretes.

Table 6. Design guidelines for producing low-carbon bio-concretes.

Strategy	Description	Priority	Technical trade-off	
			Positive	Negative
Decrease cement consumption	Use the least possible cement amount	High	Decrease density and increase thermal performance	Decrease mechanical performance and durability
Replace cement by waste based SCM	Replace cement by SCM (that have good pozzolanic reactivity) that are waste or by-products from industrial activities, such as fly ash and rice husk ash	High	It varies. The increase or decrease of mechanical performance and durability will depend on the content of replacement for each SCM	
Increase bio-aggregates amount	Use as much bio-aggregates as possible	High	Decrease density and increase thermal performance	Decrease mechanical performance and durability
Design for durability	Increase the service life of bio-concretes and the time that CO_2 remains stocked (e.g., treat bio-aggregates for extractives removal).	High	Tend to increase building service life	Can increase costs
Prioritize bio-aggregates with higher carbon content	Biomaterials with higher carbon content stock more CO_2 (e.g., timber and bamboo)	Medium	Can increase or decrease thermal, mechanical performance and durability depending on the compatibility with other materials in the mixture	
Prioritize bio-aggregates with shorter rotation periods	Biomaterials with shorter rotation periods have more climate benefits (e.g., rice, timber from planted forests, bamboo, etc.)	Medium	Can increase or decrease thermal, mechanical performance and durability depending on the compatibility with other materials in the mixture	
Use of chemical additives	Two kinds of chemical additives: (1) superplasticizer, that favor rheological properties and decrease water and cement consumption; (2) cement set accelerators, as extractives from bio-aggregates can affect setting process	Medium	Increase mechanical performance and rheological properties	Decrease thermal performance and can increase costs
Use of local materials	Use raw materials located near the factory where the bio-concrete will be produced	Medium	-	-

These strategies can be used as a first approach for the development of future bio-concrete mixtures that seek low carbon footprints and adequate performance. It can observe that the high priority should be given for the cement consumption reduction, cement replacement by SCM, and the bio-aggregate amount increase, since these materials are those with the greatest influence in the GHG emissions results. Besides, high priority should be also given for designing for durability strategy.

The trade-off between thermal and mechanical/durability performances must be evaluated with care for bio-concretes development. This is one of the most attractive characteristics of this type of material, an inorganic/mineral (concrete) and a bio (timber, bamboo, etc.) in-between material, making possible to take advantage of the positive properties of each one.

4 CONCLUSIONS

Based on the results obtained in the present study the main established findings were:

- The RH10 (rice husk - RH used as a partial replacement of fine aggregate, by volume, in a fraction of 10%) presented lower life cycle GHG emissions, with differences ranging from 14% to 72% when compared to the reference (REF) mixture, depending on the type of functional unit (FU) and biogenic carbon scenario.
- The biogenic carbon storage had an important influence in overall results. The results showed the importance of increasing the service life of building elements to improve the storage period of the biogenic carbon and, consequently, reduce the life cycle GHG emissions.
- The cement production was the main impactful source of GHG emissions in RBC production, reaching average values of 80%. Therefore, its use should be reduced, however, without compromising the mechanical performance and durability.
- The use of three types of FU helped in the understanding of which are the best applications of the evaluated bio-concretes (e.g., wall for façades) and provided a fairer comparison between the evaluated bio-concrete mixtures.
- The FU in "m^2 of a bio-concrete wall with U-value of 2.5 $W/m^2.K$" tends to provide the most appropriate analysis, considering the application of RBC for buildings' façades.
- Different transport distances of rice husk and rice husk ash were assessed. It was observed that the transportation distances of these materials have a small influence in total GHG emissions, even for a less efficient transportation scenario.
- Finally, the presented design guidelines for producing low-carbon bio-concretes can help bio-concrete researchers, developers and users.

Finally, this study verifies that RBC production has the potential to become a circular solution for the built environment. As RH gradually replaces sand content, mechanical performance tends to decrease, on the other hand, thermal performance is improved, and GHG emissions are lowered. Therefore, the material application must be carefully considered.

For future studies it is recommended the evaluation of RBC with higher contents of cement replacement by other pozzolanic materials and mineral aggregates replacement by rice husk and other types of biomasses. Other environmental impacts and life cycle stages of RBC should also be assessed.

ACKNOWLEDGEMENTS

This research was based upon a R&D Project from ANEEL - National Electric Energy Agency, "Use of bio-concretes and Bio-MMFs with low environmental impact aiming the increasing of energetic efficiency of public buildings" – PD.0394-1719/2017, supported by Eletrobras Furnas with NUMATS/POLI/COPPE/UFRJ and IMED cooperation.

REFERENCES

[1] United Nations Environment Programme, *2020 Global Status Report for Buildings and Construction: towards a zero-emission, efficient and Resilient Buildings and Construction Sector*. Nairobi, Kenya: UNEP, 2020.

[2] United Nations Environment Programme. *Sustainable buildings and climate initiative*. Paris, France: UNEP, 2009.

[3] K. L. Scrivener, V. M. John, and E. M. Gartner, "Eco-efficient cements: potential economically viable solutions for a low-CO2 cement-based materials industry," *Cement Concr. Res.*, vol. 114, pp. 2–26, 2018, http://dx.doi.org/10.1016/j.cemconres.2018.03.015.

[4] G. Habert et al., "Environmental impacts and decarbonization strategies in the cement and concrete industries," *Nat. Rev. Earth Environ.*, vol. 1, no. 11, pp. 559–573, 2020, http://dx.doi.org/10.1038/s43017-020-0093-3.

[5] Ellen MacArthur Foundation. "Towards the circular economy: economic and business rationale for an accelerated transition." www.ellenmacarthurfoundation.org/business/reports (accessed Feb. 2, 2012).

[6] Ellen MacArthur Foundation. "Towards the circular economy - opportunities for the consumer goods sector." www.ellenmacarthurfoundation.org/business/reports (accessed Feb. 2, 2013).

[7] G. Foster, "Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts," *Resour. Conserv. Recycling*, vol. 152, pp. 104507, 2020, http://dx.doi.org/10.1016/j.resconrec.2019.104507.

[8] H. Ping Tserng, C. M. Chou, and Y. T. Chang, "The key strategies to implement circular economy in building projects-a case study of Taiwan," *Sustain.*, vol. 13, no. 2, pp. 1–17, 2021, http://dx.doi.org/10.3390/su13020754.

[9] J. Cantzler, F. Creutzig, E. Ayargarnchanakul, A. Javaid, L. Wong, and W. Haas, "Saving resources and the climate? A systematic review of the circular economy and its mitigation potential," *Environ. Res. Lett.*, vol. 15, no. 12, pp. 123001, Nov 2020, http://dx.doi.org/10.1088/1748-9326/abbeb7.

[10] A. Gallego-Schmid, H. M. Chen, M. Sharmina, and J. M. F. Mendoza, "Links between circular economy and climate change mitigation in the built environment," *J. Clean. Prod.*, vol. 260, pp. 121115, 2020, http://dx.doi.org/10.1016/j.jclepro.2020.121115.

[11] World Business Council for Sustainable Development, *Decarbonizing construction: guidance for investors and developers to reduce embodied carbon*. Geneva, Switzerland: WBCSD, 2021.

[12] M. R. M. Saade, G. Guest, and B. Amor, "Comparative whole building LCAs: how far are our expectations from the documented evidence," *Build. Environ.*, vol. 167, pp. 106449, 2020, http://dx.doi.org/10.1016/j.buildenv.2019.106449.

[13] L. F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, and A. Castell, "Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review," *Renew. Sustain. Energy Rev.*, vol. 29, pp. 394–416, 2014, http://dx.doi.org/10.1016/j.rser.2013.08.037.

[14] C. K. Anand and B. Amor, "Recent developments, future challenges and new research directions in LCA of buildings: a critical review," *Renew. Sustain. Energy Rev.*, vol. 67, pp. 408–416, 2017, http://dx.doi.org/10.1016/j.rser.2016.09.058.

[15] R. Lima et al., "Potentiality of earth-based mortar containing bamboo particles for GHG emissions reduction," *Constr. Build. Mater.*, vol. 317, pp. 125971, 2022, http://dx.doi.org/10.1016/j.conbuildmat.2021.125971.

[16] M. Röck et al., "Embodied GHG emissions of buildings: the hidden challenge for effective climate change mitigation," *Appl. Energy*, vol. 258, pp. 114107, 2020., http://dx.doi.org/10.1016/j.apenergy.2019.114107.

[17] A. P. Gursel, H. Maryman, and C. Ostertag, "A life-cycle approach to environmental, mechanical, and durability properties of 'green' concrete mixes with rice husk ash," *J. Clean. Prod.*, vol. 112, pp. 823–836, 2016, http://dx.doi.org/10.1016/j.jclepro.2015.06.029.

[18] K. Celik, C. Meral, A. P. Gursel, P. K. Mehta, A. Horvath, and P. J. M. Monteiro, "Cement & Concrete Composites Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended portland cements containing fly ash and limestone powder," *Cement Concr. Compos.*, vol. 56, pp. 59–72, 2015, http://dx.doi.org/10.1016/j.cemconcomp.2014.11.003.

[19] E. R. Teixeira, R. Mateus, A. F. Camõesa, L. Bragança, and F. G. Branco, "Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material," *J. Clean. Prod.*, vol. 112, pp. 2221–2230, 2016., http://dx.doi.org/10.1016/j.jclepro.2015.09.124.

[20] A. Petek Gursel, E. Masanet, A. Horvath, and A. Stadel, "Life-cycle inventory analysis of concrete production: a critical review," *Cement Concr. Compos.*, vol. 51, pp. 38–48, 2014, http://dx.doi.org/10.1016/j.cemconcomp.2014.03.005.

[21] J. Li, W. Zhang, C. Li, and P. J. M. Monteiro, "Green concrete containing diatomaceous earth and limestone: workability, mechanical properties, and life-cycle assessment," *J. Clean. Prod.*, vol. 223, pp. 662–679, 2019, http://dx.doi.org/10.1016/j.jclepro.2019.03.077.

[22] L. R. Caldas, M. Y. R. Gloria, F. Pittau, V. M. Andreola, G. Habert, and R. D. Toledo Fo., "Environmental impact assessment of wood bio-concretes: evaluation of the influence of different supplementary cementitious materials," *Constr. Build. Mater.*, vol. 268, pp. 121146, 2020, http://dx.doi.org/10.1016/j.conbuildmat.2020.121146.

[23] Painel Brasileiro de Mudanças Climáticas, *Role of bio-based building materials in climate change mitigation: special report of the Brazilian panel on climate change*. Rio de Janeiro, Brasil: PBMC, 2018.

[24] V. Göswein, A. B. Gonçalves, J. Dinis, F. Freire, G. Habert, and R. Kurda, "Transportation matters – Does it? GIS-based comparative environmental assessment of concrete mixes with cement, fly ash, natural and recycled aggregates," *Resour. Conserv. Recycling*, vol. 137, pp. 1–10, 2018, http://dx.doi.org/10.1016/j.resconrec.2018.05.021.

[25] L. R. Caldas, A. B. Saraiva, A. F. P. Lucena, M. Y. Da Gloria, A. S. Santos, and R. D. Toledo Fo., "Building materials in a circular economy: The case of wood waste as CO2-sink in bio concrete," *Resour. Conserv. Recycling*, vol. 166, pp. 2020, 2021., http://dx.doi.org/10.1016/j.resconrec.2020.105346.

[26] L. R. Caldas, A. B. Saraiva, V. M. Andreola, and R. D. Toledo Fo., "Bamboo bio-concrete as an alternative for buildings' climate change mitigation and adaptation," *Constr. Build. Mater.*, vol. 263, pp. 120652, 2020.

[27] M. Sinka, A. Korjakins, D. Bajare, Z. Zimele, and G. Sahmenko, "Bio-based construction panels for low carbon development," *Energy Procedia*, vol. 147, pp. 220–226, 2018, http://dx.doi.org/10.1016/j.egypro.2018.07.063.

[28] A. Arrigoni, R. Pelosato, P. Melià, G. Ruggieri, S. Sabbadini, and G. Dotelli, "Life cycle assessment of natural building materials: the role of carbonation, mixture components and transport in the environmental impacts of hempcrete blocks," *J. Clean. Prod.*, vol. 149, pp. 1051–1061, 2017, http://dx.doi.org/10.1016/j.jclepro.2017.02.161.

[29] T. Lecompte, A. Levasseur, and D. Maxime, "Lime and hemp concrete LCA: a dynamic approach of GHG emissions and capture," in *ICBBM Ecografi 2017*, Clermont-Ferrand, France, 2017.

[30] F. Pittau, F. Krause, G. Lumia, and G. Habert, "Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls," *Build. Environ.*, vol. 129, pp. 117–129, 2018, http://dx.doi.org/10.1016/j.buildenv.2017.12.006.

[31] M. Y. R. da Gloria, V. M. Andreola, D. O. J. dos Santos, M. Pepe, and R. D. Toledo Filho, "A comprehensive approach for designing workable bio-based cementitious composites," *J. Build. Eng.*, vol. 34, pp. 101696, 2021, http://dx.doi.org/10.1016/j.jobe.2020.101696.

[32] S. Amziane and M. Sonebi, "Overview on biobased building material made with plant aggregate", in *Fourth International Conference on Sustainable Construction Materials and Technologies*. Las Vegas, Nevada, USA, 2016, pp. 1-12. http://dx.doi.org/10.18552/2016/SCMT4S257.

[33] EMBRAPA, "Estatistica de produção." https://www.embrapa.br/estatistica-de-producao (accessed Feb. 2, 2021).

[34] B. S. Thomas, "Green concrete partially comprised of rice husk ash as a supplementary cementitious material: a comprehensive review," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 3913–3923, 2018, http://dx.doi.org/10.1016/j.rser.2017.10.081.

[35] G. A. Akeke, M. E. Ephraim, and J. O. Ukpata, "Structural properties of rice husk ash concrete," *Int. J. Eng.*, vol. 3, no. 3, pp. 8269, 2013.

[36] R. Kishore, V. Bhikshma, and P. J. Prakash, "Study on strength characteristics of high strength rice husk ash concrete," *Procedia Eng.*, vol. 14, pp. 2666–2672, 2011, http://dx.doi.org/10.1016/j.proeng.2011.07.335.

[37] N. P. Hasparyk, "Investigação dos mecanismos da reação álcali – agregado: efeito da cinza de casca de arroz e sílica ativa," M.S. thesis, Universidade Federal de Goiás, Goiânia, Brasil, 1999.

[38] Associação Brasileira de Normas Técnicas, *Concreto – Determinação da consistência pelo abatimento do tronco de cone* NBR NM 67, 1998.

[39] G. M. Amantino, "Bioconcretos com resíduos a partir do arroz: análise de desempenho ao longo do tempo," M.S. thesis, IMED, Passo Fundo. 2021.

[40] British Standards Institution, *Environmental management — Life cycle assessment — Principles and framework*, ISO 14040, 2006.

[41] British Standards Institution, *Environmental management — Life cycle assessment — Requirements and guidelines,* ISO 14044, 2006.

[42] British Standards Institution, *Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method,* EN 15978, 2012.

[43] British Standards Institution, *Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products,* EN 15804:2012 + A2:2019, 2012.

[44] Associação Brasileira de Normas Técnicas, *Edificações Habitacionais – Desempenho*, NBR 15575, 2013.

[45] Associação Brasileira de Normas Técnicas, *Thermal performance in buildings Part 2: Calculation methods of thermal transmittance, thermal capacity, thermal delay and solar heat factor of elementes and components of buildings*, NBR 15220-2, 2005.

[46] O. B. Carcassi, P. Minotti, G. Habert, I. Paoletti, S. Claude, and F. Pittau, "Carbon footprint assessment of a novel bio-based composite for building insulation," *Sustainability*, vol. 14, no. 3, pp. 1384, 2022, http://dx.doi.org/10.3390/su14031384.

[47] L. Silva, "Avaliação de ciclo de vida de concretos com substituição parcial de cimento por cinzas do bagaço de cana-de-açúcar e da casca de arroz," M.S. thesis, UFRJ, Rio de Janeiro, Brasil, 2015.

[48] V. Durão, J. D. Silvestre, R. Mateus, and J. de Brito, "Assessment and communication of the environmental performance of construction products in Europe: Comparison between PEF and EN 15804 compliant EPD schemes," *Resour. Conserv. Recycling*, vol. 156, pp. 104703, 2020, http://dx.doi.org/10.1016/j.resconrec.2020.104703.

[49] G. Guest, F. Cherubini, and A. H. Strømman, "Global warming potential carbon dioxide emissions biomass stored anthroposphere used bioenergy end life," *J. Ind. Ecol.*, vol. 17, no. 1, pp. 20–30, 2012, http://dx.doi.org/10.1111/j.1530-9290.2012.00507.x.

[50] G. Guest, F. Cherubini, and A. H. Strømman, "Global warming potential of carbon dioxide emissions from biomass stored in the anthroposphere and used for bioenergy at end of life," *J. Ind. Ecol.*, vol. 17, no. 1, pp. 20–30, 2013, http://dx.doi.org/10.1111/j.1530-9290.2012.00507.x.

[51] E. Hoxha et al., "Biogenic carbon in buildings: a critical overview of LCA methods," *Build. Cities*, vol. 1, no. 1, pp. 504–524, 2020, http://dx.doi.org/10.5334/bc.46.

[52] S. Pretot, F. Collet, and C. Garnier, "Life cycle assessment of a hemp concrete wall: impact of thickness and coating," *Build. Environ.*, vol. 72, pp. 223–231, 2014, http://dx.doi.org/10.1016/j.buildenv.2013.11.010.

[53] R. L. M. Paiva, L. R. Caldas, A. P. S. Martins, P. B. Sousa, G. F. Oliveira, and R. D. Toledo Fo., "Thermal-energy analysis and life cycle ghg emissions assessments of innovative earth-based bamboo plastering mortars," *Sustainability*, vol. 13, no. 18, pp. 10429, 2021, http://dx.doi.org/10.3390/su131810429.

[54] A. F. Araujo, C. F. Santos, G. L. Moraga, A. P. Kirchheim, and A. Passuelo, "Avaliação do ciclo de vida de concretos: impacto ambiental do uso de cimentos Portland," in: *59 Congresso Brasileiro do Concreto*, 2017.

[55] A. P. Gursel, H. Maryman, and C. Ostertag, "A life-cycle approach to environmental, mechanical, and durability properties of ' green ' concrete mixes with rice husk ash," *J. Clean. Prod.*, vol. 112, pp. 823–836, 2016, http://dx.doi.org/10.1016/j.jclepro.2015.06.029.

[56] M. U. Hossain, C. S. Poon, Y. H. Dong, and D. Xuan, "Evaluation of environmental impact distribution methods for supplementary cementitious materials," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 597–608, 2018, http://dx.doi.org/10.1016/j.rser.2017.09.048.

[57] C. Chen, G. Habert, Y. Bouzidi, A. Jullien, and A. Ventura, "LCA allocation procedure used as an incitative method for waste recycling: an application to mineral additions in concrete," *Resour. Conserv. Recycling*, vol. 54, no. 12, pp. 1231–1240, 2010., http://dx.doi.org/10.1016/j.resconrec.2010.04.001.

[58] E. R. Grist, K. A. Paine, A. Heath, J. Norman, and H. Pinder, "The environmental credentials of hydraulic lime-pozzolan concretes," *J. Clean. Prod.*, vol. 93, pp. 26–37, 2015, http://dx.doi.org/10.1016/j.jclepro.2015.01.047.

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Editors: Edna Possan, Mark Alexander