



The potential of carbon storage in bio-based solutions to mitigate the climate impact of social housing development in Brazil

Pedro Correa de Melo ^a, Lucas Rosse Caldas ^b, Gabriele Masera ^c, Francesco Pittau ^{c,*}

^a School of Architecture Urban Planning Construction Engineering (AUIC), Politecnico di Milano, Via Ampère 2, 20133, Milan, Italy

^b Universidade Federal Do Rio de Janeiro (UFRJ), Centro de Tecnologia, Ilha Do Fundão, Cidade Universitária, 21945-000, Rio de Janeiro, Brazil

^c Department of Architecture, Built Environment and Construction Engineering (ABCE), Politecnico di Milano, Via Ponzio 31, 20133, Milan, Italy

ARTICLE INFO

Handling Editor: Fu Zhao

Keywords:

Social housing
Brazil
CO₂
Carbon footprint
Biobased materials
Bioconcrete

ABSTRACT

The increasing demand of housing in the Global South requires effective solutions to cover the corresponding deficit in the next decades. In Latin America, Brazil is the most populated Nation, which accounts for one-third of the total population and is the main contributor to carbon emissions. This study estimates how bio-based construction solutions, implemented in the Brazilian housing stock as alternative to conventional systems, can contribute to limiting the carbon emissions. Five different construction archetypes were considered, and a Material Flow Analysis model developed to estimate the demand of construction materials by 2050 under multiple scenarios. A carbon footprint assessment, which considers the dynamic effect of biogenic carbon sequestration and uptake, was finally performed to estimate the net Global Warming Potential. The results indicate that, if fast implemented, bio-concrete solutions with short-rotation vegetal species as bamboo, coupled with the lowest material intensity scenario, can reduce the cumulative carbon emissions by 65%, equal to 118 Mt of cumulative CO₂-eq savings. Considering bamboo's widespread availability in Brazil's different climate zones, and in the Global South in general, such material presents a significant impact to mitigate the climate impact of social housing. However, the carbon saving intensity is largely affected by uncertainties on population growth and the type of biomass used in the concrete mixture. Therefore, further development of standards for the safe use of bio-concrete in construction is urgently needed, as well as the implementation of environmental policies to facilitate the market penetration of bio-based solutions in emerging economies.

1. Introduction

The influence of human activities on the environment and the climate crisis have been widely discussed throughout the past decades. Anthropogenic carbon emissions have been significantly increasing when compared to pre-industrial levels, directly impacting the global average temperature (IPCC, 2022). Such increase of temperature reverberates in the economy, biodiversity, and wellbeing on the whole planet, requiring urgent actions to avoid reaching critical tipping points which would make the change irreversible (Lenton et al., 2019). In that sense, the Intergovernmental Panel on Climate Change (IPCC) has estimated global carbon budgets, which indicate the remaining amount of carbon that can be emitted before reaching the global surface temperature critical thresholds.

The building sector represents an opportunity to address climate change mitigation, as buildings account for approximately 40% of

energy and process-related emissions in the world (IEA, 2019). World-wide initiatives address necessary changes within this sector, such as the New Green Deal, from the European Union, and the Sustainable Development Goals (SDGs) from the United Nations, that tackles climate change with a holistic approach, considering health, education, and inequality (United Nations, 2022). In addition, it is expected that the demand for new construction will intensify in emerging economies such as Africa, Asia, and Latin America, including Brazil (United Nations Environment Programme, 2020). Therefore, the adoption of climate change mitigation strategies in those emerging markets is a priority action toward the transition to a carbon-neutral society.

Past studies have investigated the global warming potential (GWP) from buildings in emerging economies (Kwon et al., 2018; Martin, 2013), including the housing sector (Satola et al., 2021). Future energy needs for emerging countries have also been estimated, considering the contribution of decent living standards to climate stabilization scenarios (Rao et al., 2019). In the Latin American context, Brazil presents a

* Corresponding author.

E-mail address: francesco.pittau@polimi.it (F. Pittau).

<https://doi.org/10.1016/j.jclepro.2023.139862>

Received 14 May 2023; Received in revised form 1 November 2023; Accepted 19 November 2023

Available online 24 November 2023

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Nomenclature			
BC	Bio-based Composition	GWP	Global Warming Potential
BIM	Building Information Model	IBGE	Instituto Brasileiro de Geografia e Estatística
BCON	Bio-concrete cast-in-place	IEA	International Energy Agency
BSM	Building Stock Model	IPCC	Intergovernmental Panel on Climate Change
CD	Conservative Distribution	LCA	Life Cycle Assessment
CFA	Carbon Footprint Assessment	LSF	Light Steel Frame
CLA	Clay blocks	LWF	Light Wood Frame
CON	Concrete blocks	MFA	Material Flow Analysis
CC	Conventional Compositions	nZEB	nearly-Zero Energy Building
DLCA	Dynamic Life Cycle Assessment	PNAD	Pesquisa Nacional por Amostra de Domicílios
ED	Extreme distribution	PpD	People per Dwelling
FJP	Fundação João Pinheiro	Sidac	Sistema de Informação do Desempenho Ambiental da Construção
GHG	Greenhouse gas	SDGs	Sustainable Development Goals
		USAID	United States Agency for International Development

potential market for sustainable construction, due to its socio-economical relevance in the region. Some scholars focused on investigating the residential sector, especially social housing programs (Paulsen and Spoto, 2022). Social housing is a common object of study in Brazil due to the efforts to implement a nationwide program to cover the housing deficit, supported by consolidated public policies and representing a potential benchmark for construction practices in the Country (Ministério do Desenvolvimento Regional, 2021).

The carbon emissions related to buildings are mostly investigated from an operative energy point of view (Andresen, 2017), but recent studies have demonstrated that embodied emissions of new low-energy buildings have become dominant in the whole life cycle (Röck et al., 2020). Considering that efforts towards nearly-Zero Energy Building (nZEB) standard are increasing worldwide due to governmental endorsements, the reduction of embodied emissions to achieve a carbon neutral construction is a crucial issue during the transition, in particular for those materials, such as concrete and cementitious, ceramic and steel products, which account for a massive annual demand and are affected by process-related emissions (Favier et al., 2018). A valuable approach for achieving climate-neutral construction is the combined application of circular economy concepts and the large implementation of bio-based materials (Carcassi et al., 2022). For a Country with continental proportions, such as Brazil, and others from the Global South, those concepts might lead to a significant carbon saving, also due to the reduced distances covered by trucks for transporting construction materials within internal regions (Caldas et al., 2021c). Furthermore, important carbon emissions saving were observed when applying biomaterials to energy and land systems, through an integrated assessment model, under energy transition scenarios in Brazil (de Oliveira et al., 2021).

Some studies have been proposing non-conventional bio-based construction systems for emerging economies in the Global South to reduce the carbon footprint (Caldas et al., 2020). Bio-based construction solutions, specifically bio-concrete, present a significant potential for enhancing the circularity of materials, as the biomass used in the mixtures is often collected from waste products (e.g., rice husks, wood shavings, bamboo fibers, etc.), but at the same time allow to continue using the most widespread material in the world, i.e. cast concrete, taking advantage of the existing infrastructure. Additionally, bio-based materials account for carbon sequestration, which store the carbon in long lifespan products while the CO₂ is reabsorbed in the land due to forest or crops regrowth (Guest et al., 2012). The use of bio-based materials as a mitigation strategy to reduce carbon emissions is not only limited to the construction sector, but has been examined on a global scale for replacing highly contributing materials such as plastics, presenting substantial impact reductions (Stegmann et al., 2022).

Therefore, it is important to adopt adequate methodologies to measure the potential of bio-based and circular materials to reduce GHG

emissions and CO₂ stock. Most of the studies (Caldas et al., 2020a; Liu et al., 2023; Mouton et al., 2023; Petrović et al., 2023; Satola et al., 2021) use Life Cycle Assessment (LCA) with focus on the GWP, performing a carbon footprint study, with special attention to bio-based materials. However, it is important to go further, to understand the real effects on climate from the use of bio-based solutions applied to building stocks. In this perspective, the Material Flow Analysis (MFA) integrated with LCA can be a powerful method/process, as presented in previous studies (Göswein et al., 2021a, 2021c; Imran et al., 2023). However, most of them are focused on the Global North, especially European and North American countries, while there is a large research gap in the Global South. This can be a serious problem, since most of the increment of housing stock in the world is expected in Asian, African and Latin America countries.

As most growing Countries in the Global South, Brazil registers a high level of housing deficit to cover, having reached a value of approximately 9% in 2019 (FJP, 2020). The social housing program is a direct response to this issue that aims to implement appropriate politic and economic policies to reduce the deficit and ensure a minimum standard of living. As the population in the country is expected to continue growing in the coming years (Vollset et al., 2020), the implementation of low-carbon construction materials may represent an opportunity to mitigate climate change.

Although many studies have already discussed social housing in Brazil, no specific studies were found in the scientific literature focusing on the carbon saving potential of bio-based solutions when used for covering the housing deficit in the Global South by combining LCA instruments with MFA models.

2. Aim of the study and scientific contribution

This study aims to evaluate the potential carbon saving when bio-based solutions are implemented in the Brazilian construction market to cover the housing deficit with the social housing program by 2050. A hybrid methodology, based on a combined bottom-up and top-down approach, was proposed to assess the annual construction material demand and the consequential carbon footprint. Five alternative construction archetypes for external walls were assessed, namely: i) clay blocks (CLA), ii) concrete blocks (CON), iii) light steel frame (LSF), iv) bio-concrete cast-in-place (BCON), and v) light wood frame (LWF). A novel integrated model which combines dynamic Life Cycle Assessment (DLCA) and Material Flow Analysis (MFA) was proposed for the first time in the Global South after preliminary tests in previous studies on European context (Göswein et al., 2021c; Pittau et al., 2019). This method allows to take into account the dynamic contribution of biogenic carbon and CO₂ uptake by biomass restoration in the land and define a Net-GWP value based on the type of biomass and storage period. The

proposed methodology is the main contribution of this research, which allows policy makers to benefit from the comparison of alternative scenarios and identify pathways for implementing low-carbon strategies in emerging economies and encourage the large use of bio-based construction solutions. In addition, the results presented here will serve as an important source of data for countries located in developing countries, which are still quite scarce in the literature (Röck et al., 2020).

3. Methodology

3.1. General framework

The methodology adopted in this research consists of the definition of a hybrid top-down/bottom-up approach, allowing to perform a Carbon Footprint Assessment (CFA) from technology implementation scenarios based on a Building Stock Model (BSM) and a Material Flow Analysis (MFA).

The BSM is defined considering the future projections of People per Dwelling (PpD) and the number of dwellings, according to Brazilian statistical data provided by Instituto Brasileiro de Geografia e Estatística (IBGE 2018a). The projection of the total number of dwellings in the country is then narrowed down to social houses, estimated by the housing deficit of the country, the main driver of the national social housing program. The number of social houses is distributed according to the main typologies found in the social housing program (Triana

et al., 2015). The MFA is calculated based on five building archetypes, based on the current market practice in the country and in bio-based alternatives, which are then applied to the social housing typologies under study, resulting in the material intensity for each typology. Therefore, the outcomes of BSM and MFA are then combined with emission factors, resulting from the CFA, measured as cumulative emissions. The CFA is based on the DLCA method that is considered an effective non-standard instrument to measure the effect of timing of emissions and uptake (Levasseur et al., 2010). Altogether, those three distinct models configure the final proposed methodology applied in the study, which is detailed in Fig. 1.

3.2. Building Stock Model

To estimate the social housing evolution in Brazil, the BSM simulates the expected number of dwellings by 2050 and their main geometrical characteristics. The model inputs are population, housing deficit and dwellings. Different projections for each input of the model were considered in order to estimate the cumulative social housing demand within the time horizon considered for the analysis (2020–2050). For additional details, see Supplementary Information (SI) - Annex A.2.

3.2.1. Population evolution

This study considers projected values of demographic evolution in Brazil by 2050, derived from two different sources: Censo Demográfico,

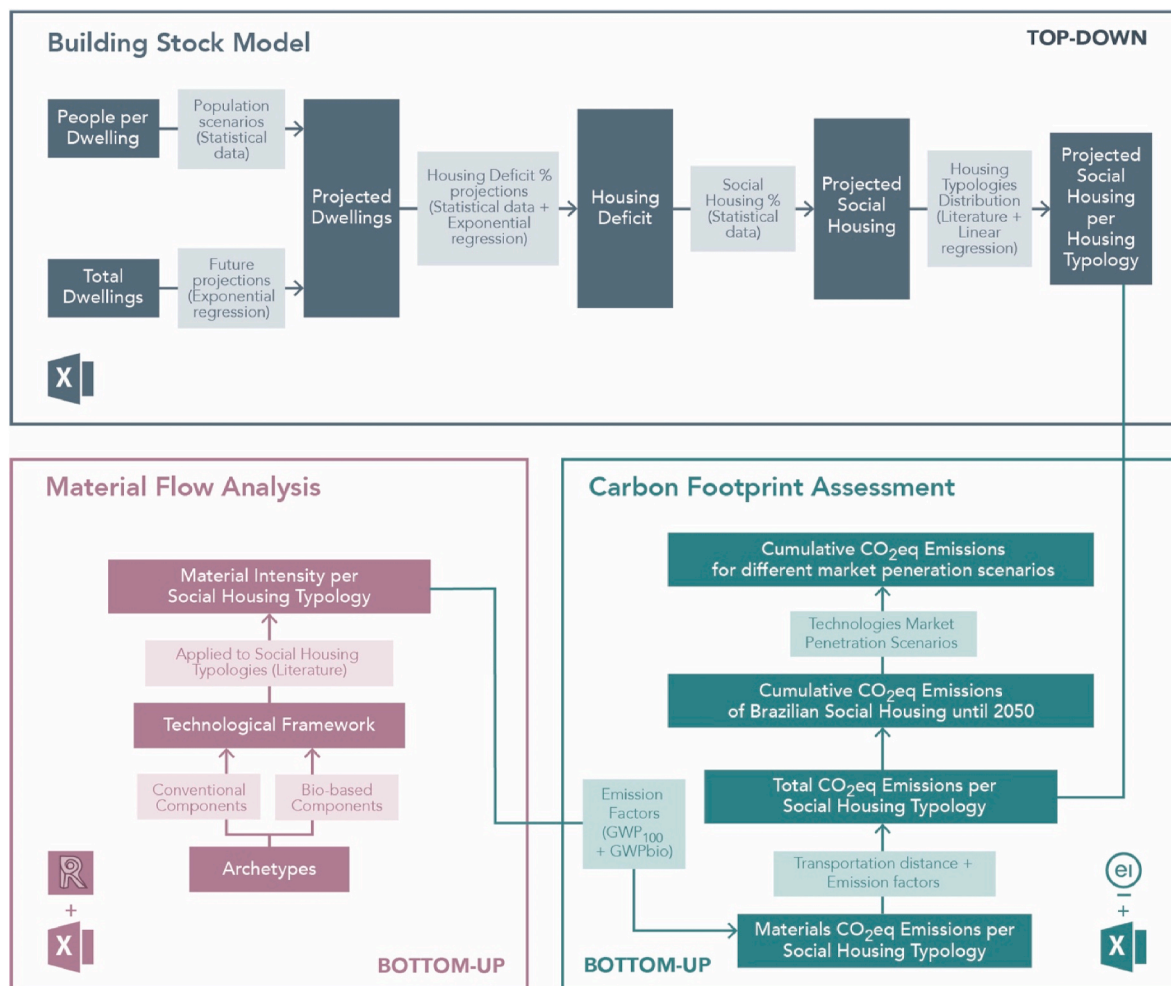


Fig. 1. Schematic framework of the proposed methodology in this study, divided into three parts: Building Stock Model – BSM (blue), Material Flow Analysis – MFA (pink) and Carbon Footprint Assessment - CFA (green). The main inputs of the CFA are the BSM and MFA, established through top-down and bottom-up approaches, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

provided by Instituto Brasileiro de Geografia e Estatística (IBGE 2018a), and a comprehensive global study of forecast population scenarios of 195 countries from Vollset et al. (2020). The projection values can be found in SI - Annex A.1. The population from the census reckons the trend of the estimated values from the dynamic demographics obtained in previous years, also considering birth and death rates. On the other hand, multiple scenarios are proposed, based on fertility, mortality, and migration conditions. However, for the present research, only two scenarios were adopted: a reference scenario with a high population growth rate, based on current trends of the population indicators, and an SDG scenario with a low population growth rate, which considers the SDGs for educational and contraceptive objectives met by 2030. Further details are found in SI - Annex E.

3.2.2. Housing deficit

Fundação João Pinheiro (FJP) is a research institute that conducts studies on statistics, generating economic, demography, and social indicators nationwide, including estimations of the Brazilian housing deficit (FJP, 2020). However, unlike the population data, there are no government records of future projections for such an indicator. Hence, a projection model was proposed based on historical data. The methodology adopted by FJP for the housing deficit calculation accounts for inadequate houses considering three conditions: i) precarious housing, ii) cohabitation, and iii) excessive charge on rent (FJP, 2020). Then, the housing deficit is given by the percentage of houses that do not meet the minimum standard of living from the total amount of dwellings in the Country. The study considers a data interval ranging from 2006 to 2019. In addition, the institute published previous surveys for earlier years, but with a different methodology. Therefore, for the sake of data consistency, only housing deficit values from 2006 onwards were taken into consideration. Further details are found in SI - Annex E.

3.2.3. Share of dwellings

IBGE conducts an annual survey entitled Pesquisa Nacional por Amostra de Domicílios (PNAD) that estimates the total number of dwellings in Brazil. It is an extensive collection of data that investigates housing conditions and the presence of minimum services, but for the purpose of this study, just the total amount of houses was considered. Although the PNAD survey started in the 1967, this study takes into account the data range 2001 ÷ 2019 to enhance the data accuracy. Socio-economic conditions in Brazil have changed significantly at the beginning of early 2000s, shaping the dynamics of the Country (IBGE, 2019). No government records are available for future projections of the

total amount of dwellings in Brazil. Therefore, the estimated scenarios are based on a regression analysis based on historical data.

In addition to the overall number of Brazilian dwellings, the study considers the social housing share. The Brazilian social housing program provides annual data since the beginning of the program in 2009 (Ministério do Desenvolvimento Regional, 2021). Due to inconsistent variations on the numbers, a regression analysis was unsuccessful to determine a representative curve for future scenarios. Hence, a conservative approach is used, in which the percentage of social housing in terms of inadequate dwellings remains constant until 2050, based on the arithmetic average of the values. The projection values can be found in SI - Annex E.

The social housing initiative aims to cover the national housing deficit while respecting the diverse realities found over the Country. Hence, the program proposes different housing typologies according to local needs and availability of sites and materials. The distribution of the social housing dwellings in this research considers five representative building typologies distributed all over the Brazilian territory, based on collected data of earlier projects carried out by the national program, as shown in Fig. 2 (Triana et al., 2015). The allocation of housing typologies occurs according to the income bracket of the recipients; therefore, two groups are identified: the first group for lower incomes and the second one for higher incomes.

3.2.4. Projected social housing

The BSM for the estimation of the social housing stock is based on the data presented in the previous sections and their respective projections. The main purpose of this model is to estimate the yearly stock change and the cumulative stock achieved by 2050, starting from the total amount of the residential buildings in the country. Two main factors characterize the housing stock change: the projections of the total amount of dwellings along a trend line and the change of population. To establish a relationship between the population and the housing stock, the People per Dwelling (PpD) indicator from the national survey PNAD was considered.

Once the housing stock evolution for each scenario is estimated, a corresponding annual housing deficit was correlated, based on the number of inadequate dwellings. The calculation considers two alternative approaches: a conservative approach and an extreme approach. On one hand, the conservative one assumes the housing deficit rate as a constant value until 2050, based on the average of the historical data for the assumed range. On the other hand, the extreme one considers the projection of the housing deficit with an increasing reduction of the rate

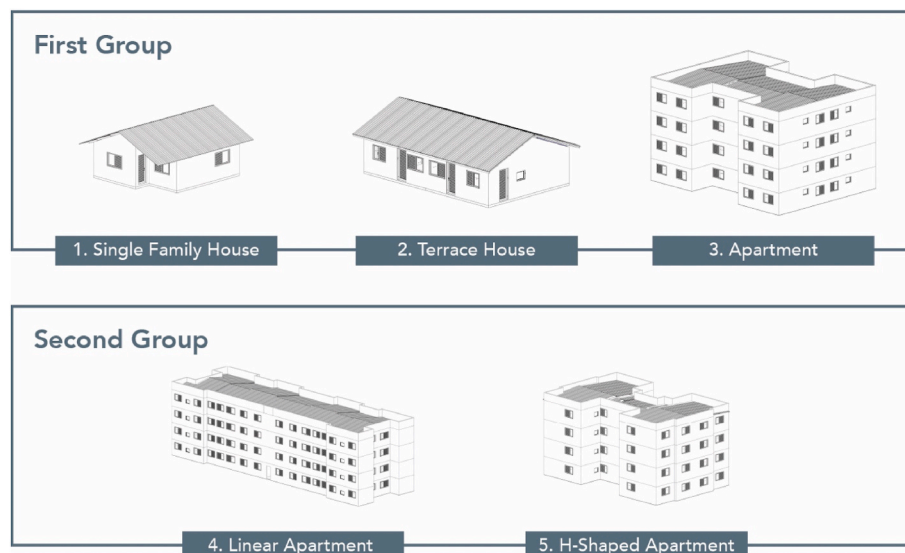


Fig. 2. Representative Brazilian Social Housing Typologies based on Triana et al. (Triana et al., 2015).

following the respective linear regression. The social housing stock was then estimated according to the percentual static value of social housing in terms of inadequate dwellings. Further details on the BSM can be found in SI - Annex A.1.

In addition, to define a range of cumulative social housing (CSH) stock change scenarios, it is necessary to consider how the different building typologies are shared in each scenario. This research proposes two approaches for the building typologies evolution. Considering the current distribution of typologies in the social housing stock, the first approach proposes a constant annual increment in the total stock for each typology until 2050 - the conservative distribution (CD). The second approach follows the assumptions of recent studies (Chandrakumar et al., 2019; Lavagna et al., 2018) and proposes a reduction of single-family housing share to enhance urban densification and limit the land use competition due to city expansion - the extreme distribution (ED).

The first approach considers the share of housing typologies from 2019 and assumes a constant rate in the period 2020–2050. The second approach considers a linear regression between 2019 and 2050, aiming to reduce the quantity of typologies 1 and 2, and increase the share of typology 3. A final target share of 5% for typologies 1 and 2 and of 20% for typology 3 for 2050 was proposed. The linear regression is applied to housing typologies within the same income group; therefore, only typologies 1, 2 and 3 were considered. The distribution of the housing typologies is based on data presented by statistic Brazilian reports (Ministério do Desenvolvimento Regional, 2021) as well as on the distribution of the typologies obtained from surveys (Triana et al., 2015).

The final configuration of the cumulative scenarios for Brazilian social housing is given by equation 1.

Equation 1. Cumulative scenarios of Brazilian social housings with typologies distribution

$$CSH_k = \sum_{i=2021}^{2050} (SH_{j,i} \times T_{1,i} + SH_{j,i} \times T_{2,i} + \dots + SH_{j,i} \times T_{5,i})$$

where.

- CSH_k is the cumulative number of social housings, for the distribution of typologies k
- $SH_{j,i}$ is the number of social housings, for the scenario j , in the year i
- $T_{n,i}$ is the share of typology n , in the year i

3.3. Material Flow Analysis

The MFA model proposed in this study aims to assess the material intensity from the annual demand of construction material required for Brazilian social housing implementation until 2050. Five different archetypes, which are mainly characterized according to the composition of the wall systems, were proposed in order to observe the potential impacts of technological changes in the construction sector on carbon emissions. The first two are representative of the conventional practices found in the Brazilian market, namely clay blocks (CLA) and concrete blocks (CON), while the other three are non-conventional wall systems solutions that either result at an early stage of development or account for a modest share of the market. Light steel frame (LSF) is one of the emerging technologies affecting the construction market in Brazil, as well as light wood frame (LWF). Finally, a bio-concrete cast-in-place (BCON) wall system, characterized by a mixture of low-carbon cement and wood shaves, is proposed as promising solution for envelopes, based on recent technology developments achieved at lab scale that is expected to be soon implemented in the market (Caldas et al., 2020). The current standard for thermal performances of external walls in Brazil requires a maximum U-value of 2.5 W/m²K (ABNT, 2013) for most climate zones. All the proposed archetypes meet such requirement and, therefore, a homogeneous application throughout the Brazilian territory, independent of different climate zones, was considered. This is a

conservative approach, since all Brazilian climate zones accept higher U-values, when compared with Global North countries, and therefore less material would be necessary to comply with the standards. However, this approximation was considered acceptable in view of foreseeable more stringent energy standards in the future and to allow the evaluation of real technologies the way they are used in the market practice. Furthermore, all the proposed wall systems meet the minimum requirements of mechanical, fire safety and other performance criteria required by Brazilian standards (ABNT, 2016, 2005; IFBQ, 2020; IPT, 2021) and have therefore been considered comparable for the purposes of this study. Solely for bio-concrete, that is a new material, it is assumed it reaches the minimal mechanical and fire resistance. For mechanical performance, several studies already showed that bio-concretes can reach adequate values, especially when supplementary cementitious materials (SCMs) are used (Caldas et al., 2021b). In terms of fire safety, Yew et al. (2021) already evaluated the behavior of bio-concretes for fire safety and verified that they can be used as building elements for non-structural applications. Aguiar et al. (2022) performed an experimental investigation of the fire behavior of wood shavings bio-concrete and verified that even with higher percentage of biomass fraction, the bio-concretes did not present ignition. In addition, the use of bio-based materials was also considered for complementary building components, such as partitions and roof. To avoid excessive iterations between materials, each wall composition was aggregated in two possible groups of complementary components characterized by a conventional composition (CC) or a bio-based composition (BC). Therefore, each archetype in this study is characterized by a wall system combined with two groups of complementary materials, resulting in ten possible combinations, as indicated in Fig. 3.

The construction systems included in this study are foundations, exterior walls, partitions, roof, and openings, disregarding the materials that account for less than 5% of the total mass, as considered in previous studies (Silva and Silva, 2015). For foundations, roofs and openings, the same construction solution was assumed for all archetypes: a raft system foundation in reinforced concrete and a grade system foundation in reinforced concrete, according to the housing typology. The doors and openings composition followed the social housing program common practice (Triana et al., 2015) and are mostly made of aluminum. Further details on the composition of the construction solutions are found in SI – Annex F. The technological framework of this research is defined by ten compositions, as shown in Fig. 3.

Therefore, to estimate the material intensity, the configurations observed in Fig. 3 were modeled for each social housing typology, following the indications of the social housing projects (Triana et al., 2015) described in section 3.2.3. The corresponding material demand for each housing typology was obtained by extracting geometric data from a Building Information Model (BIM) developed in Autodesk® Revit software (Autodesk, 2022).

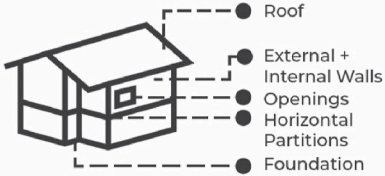
The final calculation for the material intensity of each housing typology is then given by equation 2. The material intensity, accounting for the different social housing typologies and the different archetypes, can be found in SI – Annex B.

Equation 2. Material intensity of each social housing typology

$$MI_{t,c} = \frac{\sum_i^n (q_{t,c} \times d)}{A_t}$$

where.

- $MI_{t,c}$ is the material intensity of the typology t with composition c , given in kg/m²
- $q_{t,c}$ is the quantity of each construction material of the typology t with composition c , given in m² or m³
- d is the density of each construction material, given in kg/m² or kg/m³



		ARCHETYPES				
		WALL SYSTEMS				
		Clay Blocks	Concrete Blocks	Light Steel Frame	Bio-concrete Cast-in-place	Light Wood Frame
CONVENTIONAL COMPONENTS	Horizontal Partitions Concrete slab Ceramic tiles Gypsum boards	CLA_CC	CON_CC	LSF_CC	BCON_CC	LWF_CC
	Roof Fibercement tiles					
BIO-BASED COMPONENTS	Horizontal Partitions Bio-concrete slab Laminate board Wooden boards	CLA_BC	CON_BC	LSF_BC	BCON_BC	LWF_BC
	Roof Bio-concrete tiles					

*For foundations, roofs and openings, the same construction solution was assumed for all archetypes, following the indications from Triana et al., 2015: concrete for foundations, steel framed windows and doors for the openings, and timber for the roofs.

Fig. 3. Technological framework of the archetypes in the study, represented by the combination of wall systems of Clay Blocks (CLA), Concrete Blocks (CON), Light Steel Frame (LSF), Bio-concrete cast-in-place (BCON) and Light Wood Frame (LWF) with either complementary conventional compositions (CC) or complementary bio-based compositions (BC). Each complementary composition is formed by horizontal partitions and roof elements.

- A_t is the net floor area of the typology t , given in m^2

3.4. Carbon footprint assessment

3.4.1. Global warming potential

The CFA proposed in this study focuses on the evaluation of the Global Warming Potential (GWP) according to the IPCC method (IPCC, 2013).

The GWP caused by the construction of social housing in the time-frame 2020–2050 were evaluated under a time horizon of 100 years (GWP100), in order to capture the long decay effect of the more relevant GHGs. Greenhouse gas (GHG) emissions are one of the main indicators of the impacts generated by anthropogenic activities. The main GHG are CO_2 , CH_4 , CO and N_2O , but for construction CO_2 and CH_4 are the main contributors to climate change (Pittau et al., 2018). All GWP100 results are measured in kg CO_2 equivalent (CO_2 -eq) for building components and Mt CO_2 -eq for cumulative emissions from the social housing stock. Considering the scope of the study, the CFA consists of two parts: construction materials and transportation.

3.4.2. System boundaries

Considering the scope and the limited timeframe (2020–2050), this study restricted the system boundaries to the pre-use phase, which according to EN 15978 corresponds to A1–3 – material production and A4 – transportation (CEN, 2011). Module A5 – on site installation was excluded from the calculation due to major uncertainties and lack of primary data. However, its contribution to the whole life cycle carbon of a building is generally marginal (Takano et al., 2014). The main processes are representative of raw materials extraction, transportation to

factories, manufacturing processes, and transportation to site. In the Brazilian residential context, most of the operational energy derives from electricity, with a national mix composed by 82.9% of renewable sources (Ministério de Minas e Energia, 2022). Therefore, considering the significantly low impact on emissions, the operational phase was not accounted for. The demolition phase was disregarded due to a shorter timeframe of the study compared to the service life of the social housings. Additional details about considered processes can be found in SI – Annex C.1.

A1–3 - Material production

The impacts of construction materials are obtained according to the material intensity for each social housing typology considered in this study and the corresponding emission factors, given in kg CO_2 -eq per kg or m^3 of material, as seen in SI – Annex C.1. Such factors account for all the manufacturing processes, including extraction and transportation to the factories, and are taken from the Ecoinvent 3.8 database (Ecoinvent, 2022) and previous Brazilian studies (Caldas et al., 2021a; Mahecha et al., 2020; Salles Ferro et al., 2018; Souza et al., 2016).

A4 - Transportation

In addition to the emissions related to material manufacturing, the present study also considers emissions from the transportation between factories and construction site. Twenty-five States and the Federal District were considered for modelling the social housings distribution over the country, disregarding just the Amapá State in the northern region. The neglect of this State is justified by insufficient data of transportation modalities, as the State is mainly accessed by waterways. The map showing the distribution of the factories can be found in SI – Annex G.

The calculation method considers the distances between the nearest

factory of each material to the city centers of the 26 capitals. In order to find one corresponding distance value for each material, a national weighted average was established, considering the housing deficit of the states in 2019 (FJP, 2020). An emission factor equal to 0.133 kgCO₂-eq/tkm was adopted in this study, obtained from the ecoinvent database as representative process of 'Transport, freight, lorry 16–32 metric ton, EURO3'.

3.4.3. Biogenic carbon

The choice of a method to include the biogenic carbon in CFA is a controversial argument since a standard accepted methodology does not exist yet (Hoxha et al., 2020). In this study, the GWP_{bio} method proposed by Guest et al. (2012) was considered. This method is based on a DLCA which takes into account in the GWP calculation at a time horizon of 100 years the storage period of the CO₂ in the biomass during the service life of the building and the rotation period needed for the biomass to be fully regenerated. Although the expected service life of buildings is assumed equal to 50 years, recent studies revealed that bio-concretes might present a much longer storage period as the biomass embedded in concrete is subjected to a mineralization process which avoids the release of the carbon into the air at the end of life (Durga et al., 2020). Hence, the storage period for all biogenic materials in this study is 50 years. The rotation period, on the other hand, varies according to the type of biomass used to process the material. In this study, the initial propositions of bio-based materials are assumed to be out of tropical timber, as detailed in SI – Annex B.1, with a rotation period equal to 10 years.

Additionally, alternative biomass typologies and rotation periods were considered to perform a sensitivity analysis. In particular, bamboo Moso particles were considered as replacement of wood shives in bio-concrete aggregates, as well as different rotation periods both for timber and bamboo. Finally, the Net-GWP was calculated as a sum of fossil-based GWP contribution from material production and transportation and the GWP_{bio} from biogenic CO₂, as indicated in equation 3. Additional information regarding the emissions calculation is found in SI – Annex G.

Equation 13. Net-GWP emissions per housing typology

$$GWP_{t,c} = CMGWP_{t,c} + TGWP_{t,c} + SGWP_{t,c}$$

where.

- $GWP_{t,c}$ is the total GWP emissions of the typology t with composition c , given in kgCO₂-eq/m²
- $CMGWP_{t,c}$ is the construction materials GWP emissions of the typology t with composition c , given in kgCO₂-eq/m²
- $TGWP_{t,c}$ is the transportation GWP emissions of the typology t with composition c , given in kgCO₂-eq/m²
- $SGWP_{t,c}$ is the bio-based contribution of the typology t with composition c , given in kgCO₂-eq/m²

3.4.4. Evolution of the stock under different market penetration scenarios

With the estimated values of carbon emissions for different scenarios of social housing typologies and materials compositions, it is necessary to establish how such configurations will evolve in the future, considering the market penetration of the proposed technologies. This study proposes three market scenarios: i) current scenario; ii) technology changes scenario, considering the three previously presented alternatives, and iii) bio-concrete implementation scenario. The first scenario is characterized by the continuity of Business as Usual (BAU) practices until 2050, consisting of clay and concrete blocks (Ministério do Desenvolvimento Regional, 2021). The second scenario proposes an initial share of 10% of one alternative material – bio-concrete, light steel frame or light wood frame – and 90% of BAU practices. Such rates follow linear regressions until 2050, when it is assumed that the alternatives material will represent 100% of the social housing market. Lastly, the

third scenario represents a full implementation of bio-concrete. The distribution follows a similar logic to the second scenario: initially, a 10% share of bio-concrete is proposed whilst there is a 90% share of BAU practices. The rates then follow linear regressions, in which the bio-concrete alternative will represent 100% of the market in three different timeframes, by 2030, 2040 and 2050. In addition, a sensitivity analysis is introduced, considering other inputs for the bio-concrete, following the same logic as the third scenario. However, two other types of bio-concrete are also studied: bamboo bio-concrete and timber bio-concrete with a rotation period of 40 years. The market scenarios result in a total of 20 possible combinations, as observed in SI – Annex G.

4. Results

4.1. Social housing stock

Multiple scenarios were calculated for the social housing projection in Brazil until 2050, but only the maximum and minimum values were considered. The maximum value corresponds to conservative scenarios of population growth and housing deficit, while the minimum value corresponds to extreme scenario for the same parameters. A range from 19.65 to 31.04 million dwellings represents the cumulative social housing stock for Brazil in 2050. The significant difference of approximately 58% in the number of houses reflects the investigation of extreme scenarios. Fundamentally, the projection with more dwellings considers a future with no proposition of change, following the current trends on population and housing deficit. On the other hand, the lowest value considers an increasing implementation of SDGs, reflected on the decline of population, and the reduction of housing deficit. In addition, the social housing projection predicts the distribution of the typologies throughout the years, according to the two types of distribution previously defined. The combination of conservative and extreme distributions with social housing stock scenarios resulted in 16 distribution combinations. In order to have a range that encompasses the extremes of the projection, the maximum and minimum values of cumulative social housing are the representative curves for the distributions. Fig. 4 shows the conservative curve and the extreme curve, according to housing typology share.

The curves present opposite propositions for the future of Brazilian social housing. Whilst the conservative approach shows an inclined curve, the extreme one shows a more subtle progression. The combination of an extreme approaches for both the social housing stock and the distribution of typologies reflects a future with a reduced need for social housing and less material-intensive housing typologies.

4.2. Material intensity

The material intensity was defined for the five typologies of social housing considered in the study, expressed in kilograms of material per square meter of floor area. For each typology, ten different scenarios were investigated, as observed in Fig. 5. The scenarios are named after the wall system of the archetype, which are clay blocks, concrete blocks, bio-concrete cast-in-place, light steel frame, or light wood frame, preceded by a suffix that indicates the type of the complementary construction components, either conventional (CC) or bio-based (BC).

Considering all the scenarios, typologies 1 and 2 are significantly more material intensive than the others. Such an outcome was expected, considering that the first two typologies have only one story, whilst the others have four and therefore a more favorable shape factor (lower ratio of external envelope to floor area). For the conventional archetypes' scenarios, such as CLA and CON, the material consumption per floor area for the one story typologies was 16% higher when compared to the multi-story typologies. This number increases up to 40%, when considering the light framing propositions. For the BCON archetype, the numbers are similar to the conventional materials, reaching up to 18%.

When comparing CC and BC within the same archetype, the latter

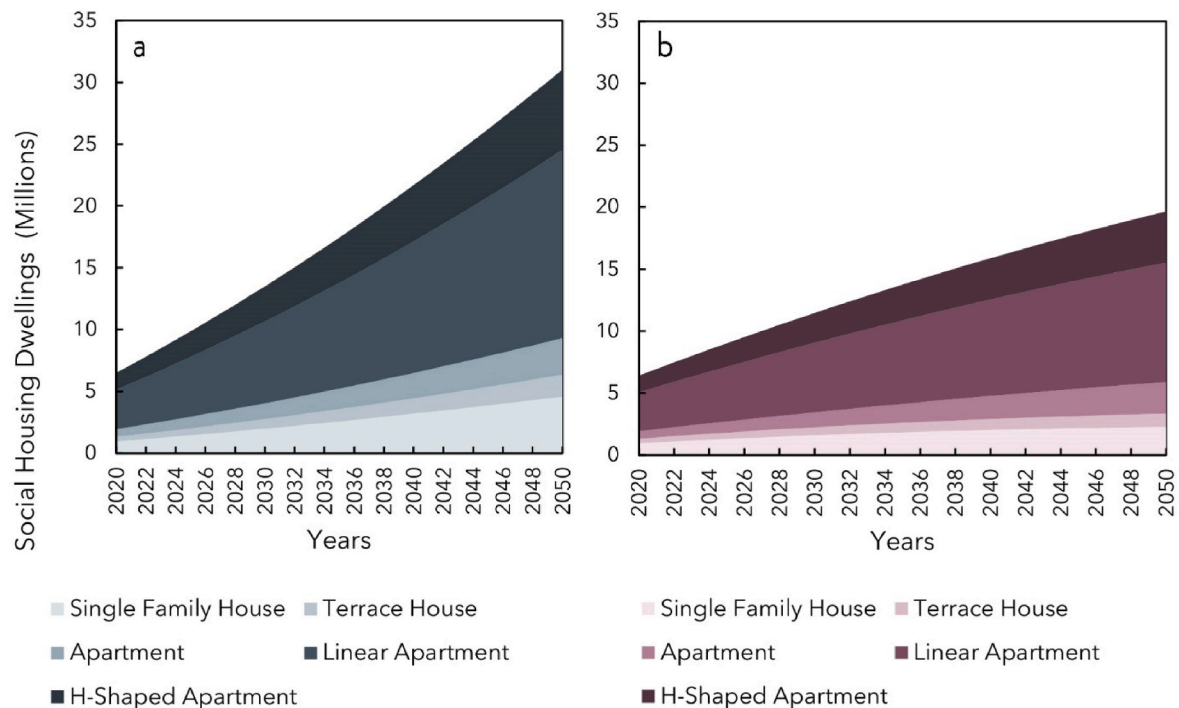


Fig. 4. Distribution of social housing dwellings based on two different approaches for typology distribution and population projection: conservative and high population growth distribution (a) and extreme and low population growth distribution (b).

presents more intensive scenarios for all the housing typologies. Such an outcome is explained by the substitution of expanded polystyrene (EPS) for BCON, which is 50 times denser, in the horizontal partitions.

In general, the behavior of the different compositions followed similar patterns for all the typologies. The most intensive scenario is the CON with BC, for all housing typologies, and the less intensive one is the LSF with CC. The highest difference amongst scenarios within the same typology is observed in typology 5, in which the application of LSF with CC represents a reduction of more than 1.2 tons of material per floor area, when compared to the CON with BC. The Apartment is the social housing typology with less material intensive scenarios, while the Single Family House is the most material demanding typology for any composition.

4.3. Carbon intensity

Once the social housing stock projection and the material intensity of the housing typologies are defined, the carbon emissions can be calculated. Considering the same ten compositions proposed in the material intensity section, the estimation of carbon emissions was carried out, with outcomes in kilograms of CO₂ equivalent per floor area (kgCO₂-eq/m²). The results are visible in Fig. 6.

Some results of the emissions follow similar patterns to those observed in Fig. 5. Typologies 1 and 2, for instance, present higher emission values per floor area, when compared to the multi-story typologies, with differences of up to 100 kgCO₂-eq/m² for the LSF. However, the differences between LSF and CON are not as large as the ones shown in the previous figure, mainly due to the significantly higher emission factor of steel. The conventional archetypes present worse scenarios of emissions for all the compositions in every housing typology, even with lower emission factors, because these are dominated by the intensive material demand of such archetypes.

The carbon emissions of each materials composition follow similar patterns for all the housing typologies. The scenario with largest emissions is the CON with CC, for all housing typologies, while the scenario with lowest emissions is the LWF with BC. The highest difference

amongst composition scenarios within the same typology is observed in typology 1, in which the application of LWF with BC represents a carbon saving of more than 117 kgCO₂-eq per floor area, when compared to the CON with CC. For most of the materials composition, the Apartment is the social housing typology with the lowest values of carbon emissions per square meter, while the Single-Family House is the typology that emits the most.

An important aspect of the Carbon Footprint Assessment is the consideration of the carbon storage capacity of bio-based materials, through the GWPbio emission factors. Taking this aspect into account, the resulting GWP of construction materials are significantly reduced. The LWF archetype with conventional components, for instance, presents an average reduction of nearly 19% of its carbon footprint, when the carbon sequestration is accounted for. The same archetype with bio-based components presents a reduction of roughly 36%. Similar outcomes are observed for the other materials compositions and housing typologies, in which the presence of bio-based components contributes to a significant reduction of carbon emissions. Furthermore, the carbon storage outcomes indicate that the use of bio-based materials might bring relevant improvements not only when applied to archetypes, but also when applied to other construction components. Conventional archetypes compositions, such as clay and concrete blocks, have their GWP reduced by at least 20%, as observed in the H-Shaped apartment. However, regarding the nature of the constructive components, the archetype with less emissions is the LWF, for all the housing typologies.

The values obtained in this study range from nearly 197 kgCO₂-eq/m² (best case – Linear Apartment with LWF and bio-based components) to nearly 388 kgCO₂-eq/m² (worst case - Single Family House with CON and conventional components). They are in the same magnitude of different carbon benchmarks observed in the literature and directives for different European countries. Minunno et al. (2021) found values from 260 kgCO₂-eq/m² to 610 kgCO₂-eq/m². Röck et al. (2020) presented the Swiss SIA benchmark limit of 450 kgCO₂-eq/m². The World Business Council for Sustainable Development report (WBCSD, 2021) presented limit values of 500 kgCO₂-eq/m² (until 2030) in United Kingdom, 500 ÷ 700 kgCO₂-eq/m² (until 2025) in Finland, 600 kgCO₂-eq/m² (until

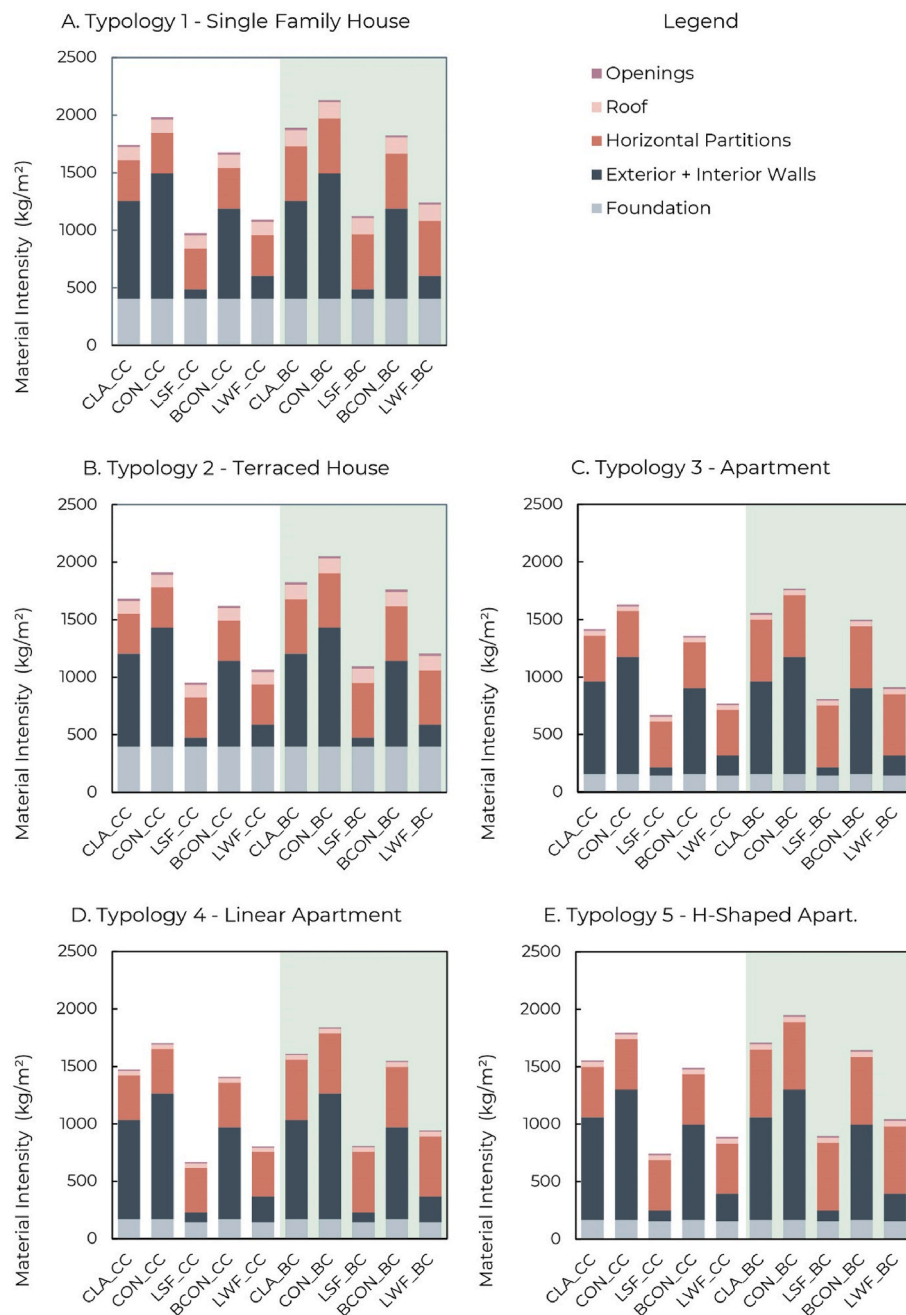


Fig. 5. Material intensity for each typology of social housing (Single Family House - 1; Terrace House - 2; Apartment - 3; Linear Apartment - 4; H-Shaped Apartment - 5) according to five archetypes (clay blocks - CLA; concrete blocks - CON; light steel frame - LSF; bio-concrete cast-in-place - BCON; light wood frame - LWF) combined with two sets of complementary components (conventional composition - CC, and bio-based compositions - BC).

2023) in Denmark and $640 \div 740 \text{ kgCO}_2\text{-eq/m}^2$ (until 2025) in France. This comparison shows that our results are consistent, with all the evaluated typologies and technologies below of most of those limits.

In terms of cumulative carbon emissions, according to the different archetypes' implementation, the LWF presents the best outcome with a potential reduction of 18%, when compared to the Business as Usual practices (CLA and CON), considering the conservative distribution for social housing typologies and a high population growth rate. Such a reduction is even more significant, nearly 23%, when considering the extreme approach. The differences of cumulative emissions between the alternative archetypes, applied with OD, are below 5%, as shown in Fig. 7.

4.4. Sensitivity analysis

4.4.1. Housing typology and population growth

Another sensitivity analysis was proposed to understand the population and the housing typologies influences. Fig. 8 indicates the differences between conservative and extreme housing typologies distribution, applied to the same population distribution, considering bio-concrete with wood shavings. The outcomes highlight marginal impacts when proposing the reduction of one story typologies. Since the distribution of multi-story typologies already represents a share of more than 70% for the current scenario, such an outcome was expected.

On the other hand, Fig. 9 demonstrates the differences between high population growth and low population growth distributions, applied to the same social housing typology distribution. The results present

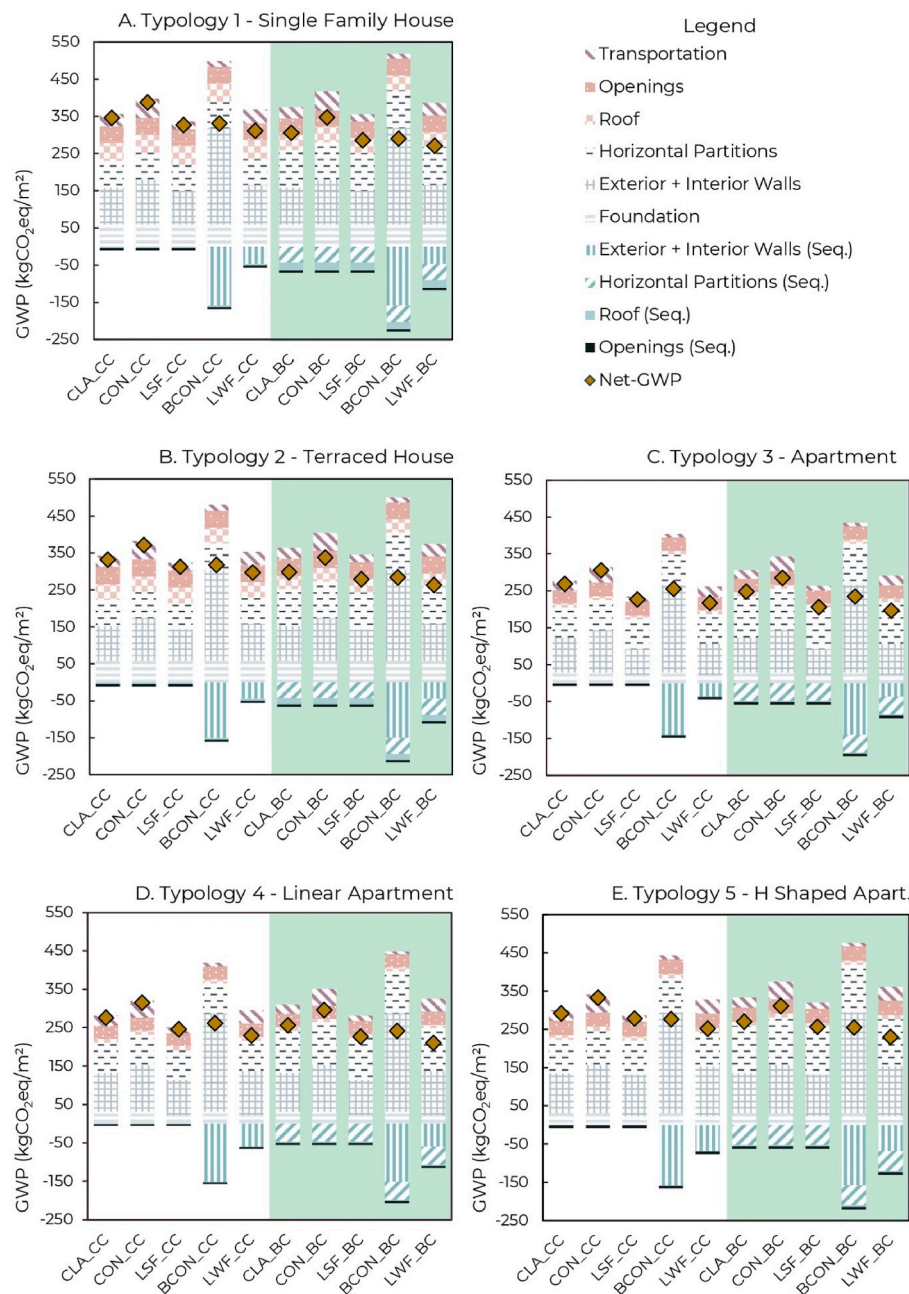


Fig. 6. Global Warming Potential (GWP) per typology of social housing (Single Family House - 1; Terrace House - 2; Apartment - 3; Linear Apartment - 4; H-Shaped Apartment - 5) according to five archetypes (clay blocks - CLA; concrete blocks - CON; light steel frame - LSF; bio-concrete cast-in-place - BCON; light wood frame - LWF) combined with two sets of complementary components (conventional - CC and bio-based - BC).

significant divergences, reaching a reduction of approximately 46% in carbon emissions, when considering the low population growth rate.

4.4.2. Type of biomass

In order to investigate the influence of different types of biomasses, a sensitivity analysis is proposed, as observed in Fig. 10. Bamboo, timber with 10 years of rotation period, and timber with 40 years of rotation period are the three configurations under investigation. Three market implementation scenarios for bio-concrete were considered, with a complete transition from conventional materials to bio-concrete within three different time frames: 2030, 2040 and 2050. For this analysis, only the ED of the dwellings was considered.

For all the time frames, the bamboo bio-concrete demonstrated better outcomes than the timber options. The difference between

bamboo and timber with 40 years of rotation period reaches up to 58% less cumulative carbon emissions for the 2040 scenario.

Considering different propositions for the rotation period of timber crops, the results indicate significant changes. As expected, all the scenarios for the 40-years timber present worse values of carbon emissions. When compared to BAU scenarios, the bamboo bio-concrete presents a potential reduction of nearly 65% of cumulative emissions. The higher climate benefit of bamboo technologies instead of timber, in terms of rotation period, is already verified in the literature: Carcassi et al. (2022) observed that the implementation of bamboo-based materials in European buildings is more advantageous when compared with timber and concrete.

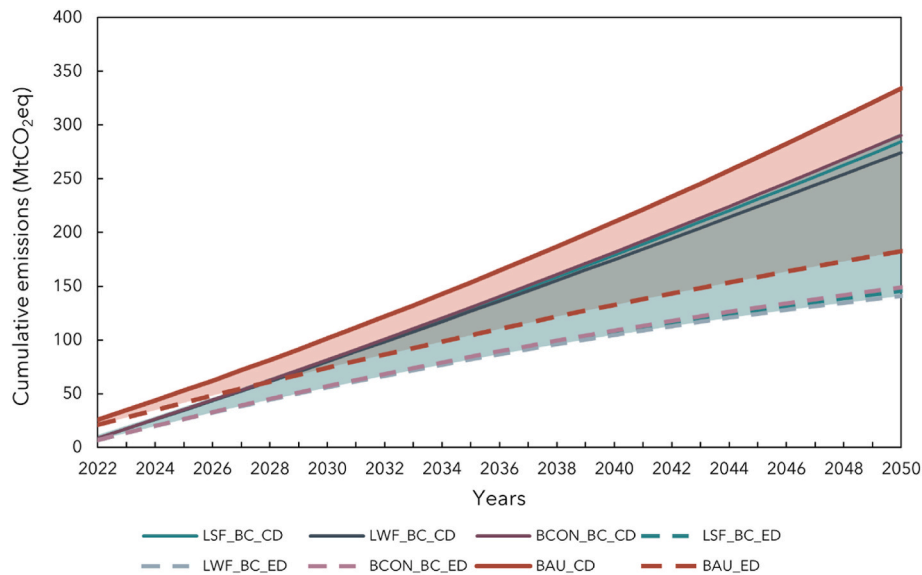


Fig. 7. Future projections of cumulative carbon emissions according to archetypes implementation. The red projections consider the distribution of dwellings following the Business as Usual (BAU) practices, employing clay blocks and concrete blocks population, while the green lines states for light steel frame (LSF), purple lines for bio-concrete cast-in-place (BCON) and blue lines for light wood frame (LWF), all combined with complementary bio-based components - BC. The continuous lines consider a conservative distribution (CD) of dwellings based on population and on social housing typologies and the dotted lines consider an extreme distribution (ED). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

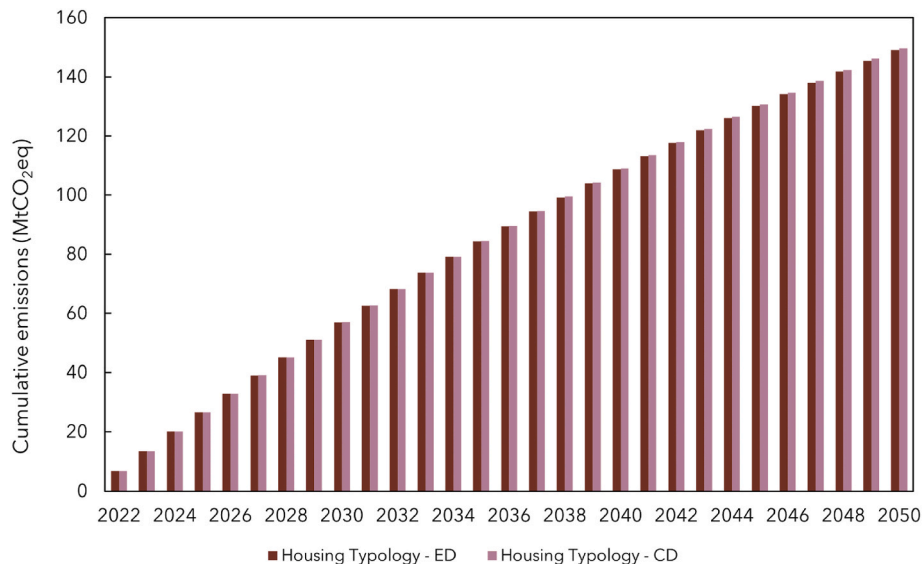


Fig. 8. Sensitivity analysis of cumulative carbon emissions of different distributions of housing typologies: extreme (ED) and conservative (CD). The distributions consider the same population projection.

4.4.3. Production processes

When the sensitivity analysis is performed with carbon factors exclusively applied to the Brazilian context (using Sidac database), instead of Rest of the World (RoW) values from ecoinvent, it is possible to observe a reduction of nearly 92% in the emission factor of a single material for the most critical case - light wood frame.

Overall, the combination of multiple materials with Brazilian emission factors results in a reduction of nearly 23% in cumulative emissions for a conservative distribution of dwellings, when the LWF archetype is applied. The lowest difference, around 14%, is observed in the application of the BCON archetype, with an extreme distribution of dwellings, as shown in Fig. 11.

It is expected that the carbon factors of building materials will tend to reduce in the coming years, especially due to the use of more

renewables for electricity production, reduced fuels consumption and the increasing use of low-carbon technologies. In terms of electricity, Brazil already benefit of a relative clean mix due to the high participation (more than 80%) of carbon-clean sources, mainly hydropower and biomass (Ministério de Minas e Energia, 2022). Therefore, the reduction of GHG emissions of electricity will not have a significant influence, especially for materials that are highly used in the Brazilian construction market such as cementitious components, where most of the CO₂ comes from the calcination process, and ceramic, that uses wood chips or natural gas as energy sources.

New technologies and innovations have also been studied in the past years, aiming for the reduction of GHG emissions of building materials, such as Carbon Capture and Storage – CCS. However, those technologies are mostly in a development stage of research, facing issues related to

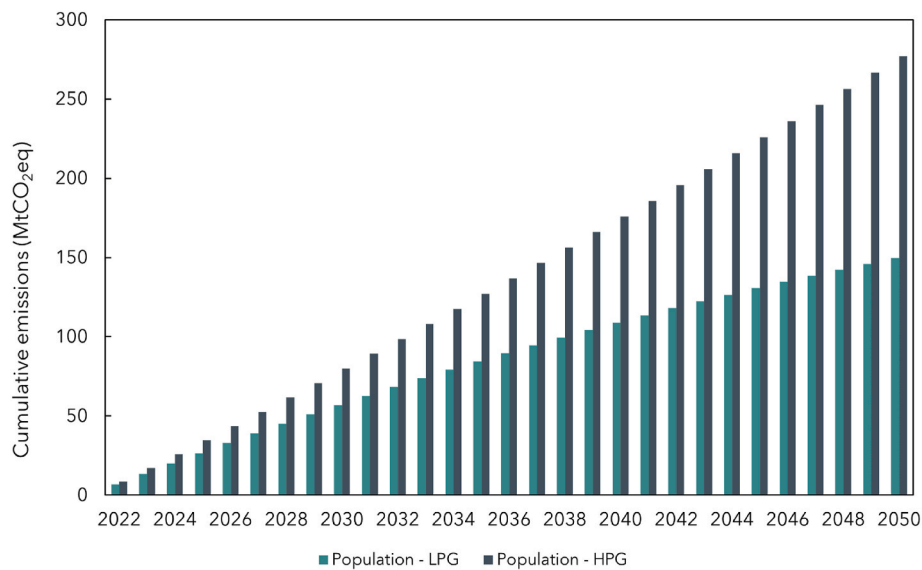


Fig. 9. Sensitivity analysis of cumulative carbon emissions of different distributions of population: low population growth rate and high population growth rate. The distributions consider the same housing typology share.

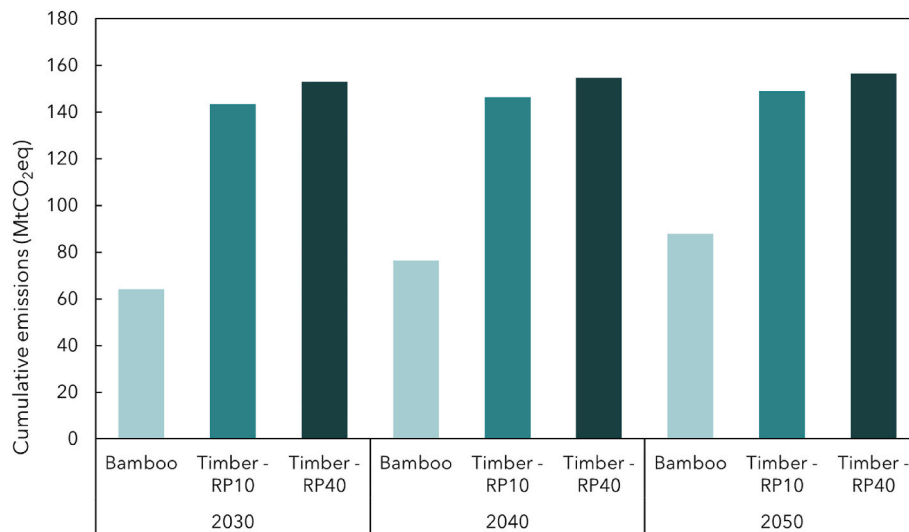


Fig. 10. Sensitivity analysis of cumulative carbon emissions of different types of bio-concrete applied to Brazilian social housings, with three targets of achieving a full market penetration: 2030, 2040 and 2050. Bamboo bio-concrete, Wood Shavings (Timber) bio-concrete with 10 years of rotation period and Wood Shavings (Timber) bio-concrete with 40 years of rotation period are the three types of bio-concrete analyzed.

logistics, production capacity and implementation at a large scale, which tend to be costly. Considering the social housing context, where building materials and technologies should keep a competitive price, future negative carbon technologies were not considered in this study.

5. Discussion

5.1. Resource scarcity and land use competition for biobased implementation

The availability of resources is one of the pivotal arguments when discussing climate change mitigation strategies. Within the construction sector, common practice technologies, such as concrete and steel, present a significant and growing share on global carbon emissions (IEA, 2019). The innovation of materials neglected the impacts of raw materials extraction, manufacturing, and transportation for a long period, but studies have already been stating the urgency of implementing circular

economy principles, emphasizing the local availability of resources (Caldas et al., 2021c).

Due to its continental proportions, transportation in Brazil is a key factor when discussing environmental impact mitigation and promoting its efficiency can be beneficial in terms of carbon emissions (Caldas et al., 2021c).

On these premises, bio-concrete technology has the potential to play a relevant role in the Brazilian market, especially in the case of bio-concretes using bamboo. The concrete market distribution is the most geographically balanced when compared to the other materials, being present in all the states. Therefore, if aligned with a fair distribution of biomass, bio-concrete might be a viable alternative to highly intensive materials, such as fired clay and concrete blocks. One of the proposed biomasses in the study is wood shavings, a by-product of woodworking operations. In Brazil, timber manufacturing occurs mostly in the south and southeast regions, that together encompass 49.4% of the housing deficit in the country (FJP, 2020). Hence, the promotion of wood

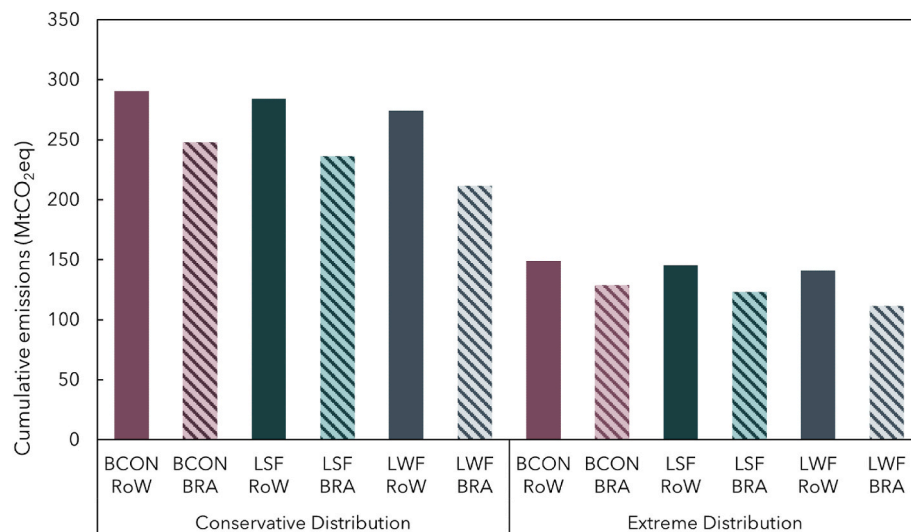


Fig. 11. Sensitivity analysis of cumulative carbon emissions of different emissions factors for the building components applied in the archetypes: Rest of the World (RoW) factors and Brazilian factors (BRA). The two emission factors scenarios are combined with conservative and extreme distributions of dwellings based on population and on social housing typologies.

shavings bio-concrete could address a great part of the housing demand, with a reduced impact from transportation (Caldas et al., 2021c).

In terms of bamboo, as another biomass proposition for bio-concrete, the availability of the material in Brazil is still restricted to specific regions, but the expansion of the crops is promising (Balduino Junior et al., 2016). Considering the weather conditions in the country, bamboo can be cultivated in every region, due to its adaptability to both cold and hot settings. Bamboo can be used in construction, both in a natural form as bamboo culms, that can be used mainly as structures and scaffolding, and as a more industrialized product, like bamboo mats or glued laminated bamboo that can be used as structures, claddings, partitions, etc. (Escamilla et al., 2016; Escamilla and Habert, 2014). In terms of scale production, the use as industrialized product tends to be the most effective. Bamboo in Brazil can be used for several other applications and not just as construction purposes, such as food (bamboo shoot), energy source (bioethanol, charcoal), industrial product (handmade products, furniture, fashion, etc.). All of these applications can generate a large amount of waste that can be recycled as bio-concrete aggregates (Gomes et al., 2022). Therefore, bamboo bio-concrete might be an effective circular economy strategy, if the distribution of the cultivations is promoted in the Brazilian territory. A progressive implementation of bamboo bio-concrete, whilst wood shavings bio-concrete is used, represents an opportunity to enhance the mitigation of climate change impacts, as bamboo has shorter rotation periods, indicating a significant increased potential for carbon sequestration, as observed in Fig. 11.

The demand of wood shavings might surpass the available supply, considering the timber industry in Brazil is limited to specific regions. In that case, an alternative solution is to manufacture wood shavings as a direct product from raw timber, instead of a by-product, as it already occurs in African countries (Göswein et al., 2021b). However, such proposition needs to address the land use distribution.

Göswein, Reichmann, Habert, et al. (2021a) investigated the impacts of a radical shift towards bio-based construction, considering land availability in Europe, and found promising scenarios for different construction technologies. Considering the Brazilian land use situation, some studies (Ferreira Filho and Horridge, 2014; Oliveira et al., 2020) have already discussed the need for land considering the increasing demand of biofuels in the countries. The main findings point out that food scarcity has not arisen, even with a high demand of land for biofuels, but emphasize the need to control deforestation in sensitive areas, such as the Amazon rainforest. Therefore, the land use for biomass available for construction might be potentially applicable in Brazil,

when properly controlled. de Oliveira et al. (2021) developed an integrated assessment model of energy, land, and materials in the context of the use of biomaterials for the energy transition. They verified that in period of 2010–2050 the variation of the change of agricultural area will be less than 1% and the price of average food basket will change less than 0.5%, suggesting that a big change in energy production will nearly not affect the land use competition, especially for food. However, in this kind of models the increase of biomaterials for construction and other high demanding goods should be considered. Fiorini et al. (2023) evaluated the influence of the production of large-scale bio-sustainable aviation fuels and the relation with land use change. They verified that these fuels could have an important role for the aviation sector decarbonization if deforestation rates are very well controlled. Moreover, data from the national census (IBGE, 2018b) distinguishes the agricultural land use in Brazil into three different types: crops, pastures and plantations, in which pastures represent the biggest share. In terms of crops, soy represents the largest area in Brazil and is a fundamental export commodity, which directly affects food security and land use (Martinelli et al., 2017). Hence, the land use dynamics in the country presents significant constraints that must also be accounted when proposing the diversification of uses, such as land for biomass and deforestation decrease. These possible constraints reinforce the need to consider circular bioeconomy, where waste from different uses of biomass (agricultural, energy and industrial) can be incorporated as raw material for the production of different types of bio-concretes, considering local availability. Then, integrated assessment models should be developed coupled with the MFA methodology.

Furthermore, bio-construction implementation in a large scale still needs to be consolidated in Brazil. Innovative constructive technologies in the country go through a technical evaluation and a documentation called 'Documento de Avaliação Técnica' (DATec) is emitted in the case of a positive outcome. This procedure fosters the development and the use of alternative technologies, such as bio-concrete. There are no records of a DATec for bio-concrete so far, as the technological development is at the moment at the experimental phases (Caldas et al., 2021b).

Finally, it is important to say that although countries of the Global South have their constructive and cultural specificities, the solutions evaluated in this research, including bio-concretes, may have a general application potential thanks to the widespread availability of the considered bio-based resources. Since Brazil is one of the biggest countries in the Global South, its decisions and policies to promote the

use of bio-based construction can positively influence nearby States towards a change of paradigm.

5.2. Urgent need of environmental policies for carbon targets and limitations of construction material demand

Considering the Brazilian social housing and the context of other Global South countries, public policies regarding carbon reduction targets within the construction sector should be proposed, in order to reduce its significant contribution to carbon emissions.

This study shows that, to be effective, public policies should tackle both societal and technical aspects.

Vollset, et al. (2020) stated that societies following United Nations SDGs have the tendency to considerably reduce the population growth rate, resulting in less housing demand and consequently less carbon emissions. Fig. 9 highlights the significant incidence of population growth on the GWP. This reinforces the concept that a reduction of global emissions can be achieved not only through an improvement of technological efficiency, but also, and possibly foremost, through the implementation at a global scale of sufficiency principles to reduce the resources consumption per capita in the Global North and secure an acceptable living standard in the Global South. A fair and sustainable use of space and resources should therefore be central to public policies aimed at remaining within the allowable carbon budget limits. On the other hand, it is also important to highlight that normally the social housing designs (considering the context of the Global South) already present very small area for occupants. Then, it should be evaluated in future studies if the reduction of spaces per person is still viable for this type of building, considering the low level of comfort and sanitary conditions often observed, or if this strategy has already reached its maximum potential.

In parallel, it is also necessary to promote and accelerate the transition to bio-construction. Röck et al. (2020) indicated the urgent need of diffusion of materials with lower embodied emissions and, at the same time, good performance for operational energy reduction. Caldas et al. (2020) showed that bamboo bio-concrete is a solution that can provide appropriate thermal performance in at least six of Brazil's eight climate zones, therefore demonstrating its suitability to reduce energy demand for HVAC in Brazilian residential buildings. The shift towards carbon-neutral solutions is therefore necessary, and Fig. 10 shows that a widespread adoption of bio-concrete for social housing in Brazil presents the best chances to significantly reduce carbon emissions when bolder market penetrations of bio-based materials (bamboo in particular) are projected. These outcomes highlight the urgent need for public policies promoting and regulating both the amount of construction and the adoption of bio-based solutions in the country.

6. Conclusions

This article proposed a hybrid methodology, based on Carbon Footprint Assessment (CFA) and Material Flow Analysis (MFA), to evaluate the carbon saving potential of bio-based technologies applied to the future Brazilian social housing development under different projections of the building stock evolution and material intensity scenarios. The methodology could be replicated in the contexts of other Global South emerging economies facing similar challenges.

The social housing stock was modeled until 2050 and then ten different construction technologies, using conventional and bio-based material compositions (CC-BC), were analyzed. Furthermore, future market penetration scenarios were investigated, applying the transition from conventional materials to alternative solutions, such as light wood frame (LWF) or bio-concrete (BCON).

Construction solutions based on light wood frame (LWF) for walls, complemented by bio-based components (BC) for the rest of the building, show a reduction of carbon emissions of up to 36% for the considered time frame when the carbon storage capacity is accounted for.

Compared to conventional construction solutions, they also show a reduction of 18% of cumulative carbon emissions during their operational life under a conservative housing demand scenario, becoming a 23% reduction when an extreme scenario (limited housing need) is considered.

While the mix of housing typologies does not affect significantly the net carbon emissions, a slower growth of the population, with the consequent reduction in the floor area needed to accommodate it, can reduce the cumulative carbon emissions by 46%.

Overall, the use of bio-based materials instead of carbon-intensive traditional ones significantly reduces the carbon emissions, thanks to the carbon sequestration. Such scenario would allow more time to find other solutions to limit the effects of climate change, but it requires aggressive policies to promote the widespread use of bio-based solutions in current practices across the country.

The study also shows that the use of short rotation biomass, as bamboo, used as aggregate in bio-concrete materials, presents a substantial positive impact, reducing carbon emissions of up to 65%, equal to 118 Mt of cumulative CO₂-eq savings, compared to the conventional solutions, thanks to the fast carbon regeneration in the land during bamboo regrowth. Such an outcome is a promising result considering bamboo's widespread availability in Brazil's different climate zones, and in the Global South in general.

Additional studies addressing land use, resources availability, and public policies implementation, are necessary to provide more conclusive answers about the viability of bio-concrete as a generalized construction material in Brazil and can be done by the inclusion of integrated assessment models with MFA. In addition, further investigations could include longer time horizons and encompass emissions from operational, maintenance and demolition phases, also evaluating how the different criteria performance of the chosen construction technologies and more accurate country-specific emission factors can influence the results. Although the present study focuses just on the case of the Brazilian context, the developed methodology and the assessed use of bio-concrete with short-rotation biomass as aggregate can be adapted for other Global South countries, such as the rest of Latin America, Africa and Asia, suggesting a possible roadmap to cover the housing deficit of growing populations whilst staying within the limited carbon budgets allowed by the ongoing climate crisis.

CRedit authorship contribution statement

Pedro Correa de Melo: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Roles, Writing – original draft, Writing – review & editing. **Lucas Rosse Caldas:** Conceptualization, Data curation, Supervision, Roles, Writing – original draft, Writing – review & editing. **Gabriele Masera:** Supervision, Roles, Writing – original draft, Writing – review & editing. **Francesco Pittau:** Conceptualization, Data curation, Funding acquisition, Methodology, Supervision, Roles, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

All data used are available in Supplementary Information.

Acknowledgments

The authors wish to thank the NEST International Program from the Department of Architecture, Built environment and Construction Engineering (ABC) of Politecnico di Milano which funded and supported the

research. The *Núcleo de Ensino e Pesquisa em Materiais e Tecnologias de Baixo Impacto Ambiental na Construção Sustentável* (NUMATS) which was the research group in Brazil, coordinated by professor Romildo Toledo Filho, responsible for the development of bio-concretes. Finally, a special thanks to the two anonymous reviewers who contributed with their constructive comments and recommendations to improve the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2023.139862>.

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