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Embodied residential building carbon emissions reduction in Nepal using linear optimization modeling

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ABSTRACT

The study of embodied residential carbon emissions has attracted significant attention in sustainability research amidst growing awareness of climate change. As Nepal experiences economic growth and urbanization, urban areas are witnessing a significant surge in carbon emissions, in contrast to past decades. Despite national level initiatives aimed at achieving net zero emissions by 2045, there is a noticeable gap in actionable approaches at provincial, ecological, and city levels regarding the tracking and mitigation of carbon emissions. This research combines building component data from the National Statistics Office (NSO) of Nepal and emissions data from literature in order to model three distinct emissions forecasting scenarios: (1) the current optimized, (2) a 50 % reduction emissions, and (3) a 75 % reduction in emissions. Based on these estimations, Bagmati province is found to exhibit the highest levels of embodied emissions, while Karnali province is found to have the lowest emissions. This can aid in the formulation of region-specific policy frameworks aimed at reducing emissions in high-emission areas. Additionally, the study highlights that urban emissions outweigh rural emissions by a factor of more than two, suggesting a need for policymakers to concentrate their efforts on urban areas.

1. Introduction

The world's primary energy source remains fossil fuels, significantly elevating atmospheric carbon dioxide and contributing to climate change [1,2]. In response, global efforts are increasingly focused on green technologies such as renewable energy, green buildings, etc. [3,4]. The evolution of housing and construction materials has been influenced by shifts in societal needs and safety standards. Nepal's construction history stretches back a few thousand years as evidenced from the time of Buddha [5]. Kathmandu, Nepal's largest city, dating to the 13th century, predominantly employed brick, timber, mud mortar, and stone to construct historic buildings and palaces [6]. With industrialization came the mass production of steel, cement, brick, etc., quickly becoming the preferred material (and production) choice for construction [7]. While natural stone was the most common building material for centuries, with the development of Portland cement in the 19th century, concrete quickly became the dominant construction material for modern

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buildings. Mass production also made bricks more affordable and popular [8]. However, industrialized materials in construction have also significantly contributed to emissions compared to native materials.

In Nepal's villages, adobe, wooden frame housing, and rubble stone masonry remain prevalent; meanwhile, reinforced concrete (RC) construction is prevalent in urban and suburban areas [9]. In rural settlements, construction technology and materials have seen limited change, while urban areas have experienced a surge in RC in the 1980s. Concerns revolve around the environmental impact of RC homes, particularly related to carbon emissions from concrete and brick production and transportation [10]. Social and cultural shifts, particularly after the democratization of Nepal in 1990, have influenced the choice of building materials, driven by factors such as the Maoist movement and labor migration [11]. Remittance from overseas workers have played a significant role in the development, particularly of RC buildings [12] as they send money home. The mass migration from rural to urban areas escalated causing urban sprawl [13]. In 2011, Nepal had a population of approximately 26 million, with 17 % in urban areas [9]. By 2021, the population reached 30 million, with 66 % in urban areas (a 49 % increase compared with previous decades) [14]. Traditional materials like mud, clay, and thatch became scarcer in urban areas, prompting a shift to modern materials such as cement, bricks, and steel [15]. Traditional materials such as mud, clay, and thatch became scarcer in urban areas, prompting a shift towards modern materials such as cement, bricks, and steel [16]. Remittances often funded the construction of RC homes, reflecting a broader shift toward modern building materials [12].

The 2015 earthquake in Nepal significantly impacted the need for more stringent building codes and better enforcement, especially in urban areas due to higher buildings and urban density [17]. A revised code included stringent earthquake-resistant construction requirements [18,19]. As these codes encourages the construction of RC or cement based construction. The embodied carbon emissions associated with cementitious materials significantly affect a building's overall carbon impact [20,21]. Striking a balance between seismic resilience and environmental sustainability is a complex task, but integrating sustainable building practices and materials can help reduce embodied and operational carbon while ensuring that buildings remain resilient to seismic [22]. Understanding embodied carbon (emissions associated with material production, transportation, and disposal) and operational carbon (ongoing emissions from product use and maintenance) is crucial for addressing climate impact [23,24].

Household carbon emissions refer to the release of carbon dioxide and other greenhouse gases resulting from household activities such as the consumption of goods and services as well as energy usage for heating, cooling, cooking, and transportation [25]. These emissions exhibit substantial global variations, with higher-income countries generally having higher emissions per household [26]. However, considerable disparities exist within countries, influenced by factors such as urbanization, household size, and lifestyle choices [27]. While operational energy usage tends to be the primary contributor to household carbon in many developed countries [24], in the context of Nepal, embodied carbon emissions originating from building materials assume particular significance [28]. This is largely attributed to the prevalent use of natural ventilation and the absence of mechanical heating and cooling systems in many residential buildings. In a comparative context, household residential embodied carbon emissions in Nepal are relatively lower than

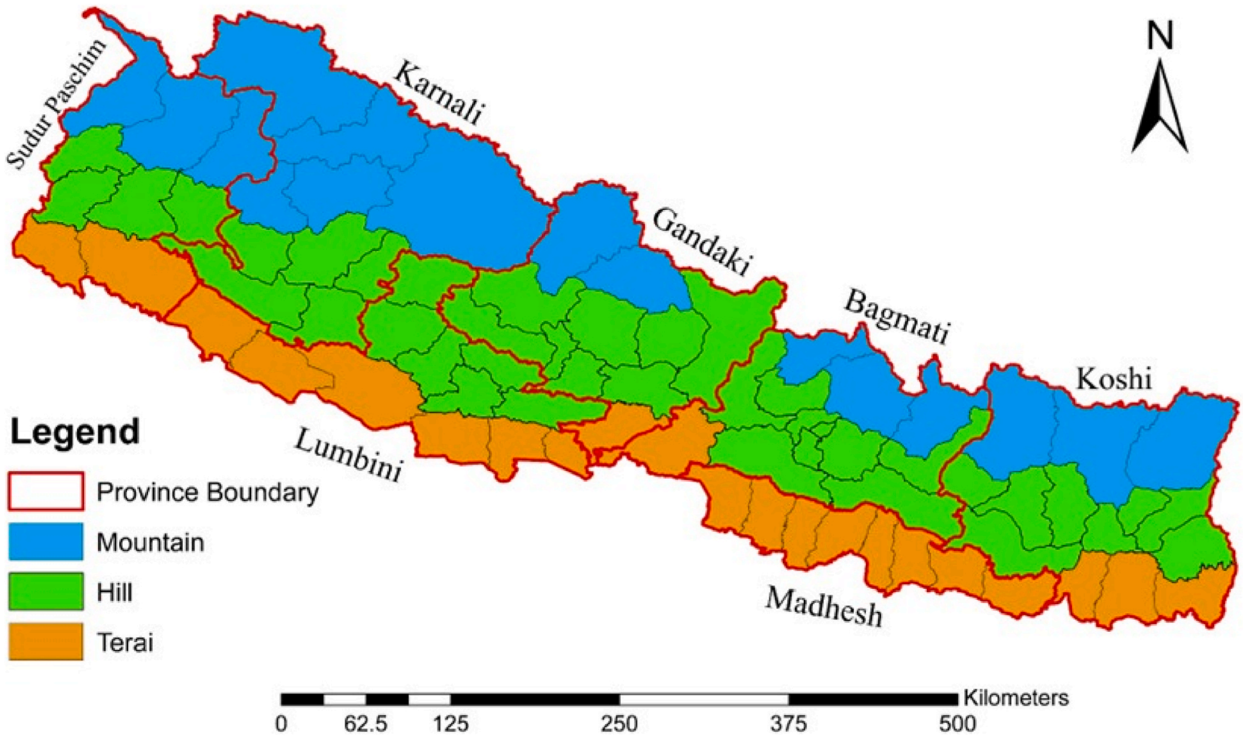

Fig. 1. Map of Nepal showing ecological boundary and provinces.

those in developed countries owing to the country's low level of industrialization [29].

Numerous studies have been conducted that specifically examine embodied emissions in the context of residential construction. For example, Zhixing et al. introduce a model for calculating embodied carbon emissions in building design, emphasizing the importance of reducing materials like steel and concrete for a more environmentally friendly construction approach [30]. Teng and Pan address uncertainties in evaluating embodied carbon emissions in prefabricated high-rise buildings, offering a framework to improve reliability in assessments [31]. In China, a study estimates the annual embodied carbon dioxide emissions in the building sector, highlighting the significant impact of residential buildings and the need to consider embodied carbon in future emission control plans [32]. Life cycle assessment is employed to analyze embodied emissions in interior partition wall systems, emphasizing the importance of extending service life and improving material selection and production processes to reduce environmental impact [33]. These studies primarily focus on life cycle-based assessments. However, there is a need to explore LP and its application in optimization of emissions in buildings.

The existing body of research has made significant contributions to understanding embodied carbon emissions in construction and building materials, focusing on specific aspects like material reductions and construction practices. However, a notable research gap exists in the examination of household embodied emissions on a national, regional, or city scale. The emissions disparity within the specific geo-region of the country is an essential step for the targeted policy intervention. This study aims to bridge this research gap by exploring the current patterns of embodied carbon emissions in residential households on a macro-level, encompassing urban and rural areas, ecological zones, and provincial levels within Nepal. Additionally, the study will delve into what-if scenarios using a linear optimization model, considering reduction scenarios of current optimized, 50 %, and 75 %. By gaining insights into current emission trends and exploring a range of optimization scenarios, this research seeks to provide a foundation for formulating actionable policies that target regional variations while aligning with the overarching national emissions target, with the goal of achieving carbon neutrality in the residential sector.

2. Method

Nepal is divided into three ecological regions Mountain, Hill, and Terai, and has seven provinces: Koshi, Madhesh, Bagmati, Gandaki, Lumbini, Karnali, and Sudur Paschim as shown in Fig.1. With about 30 million populations, Nepal has experienced rapid urbanization in recent decades and the trend continues to grow.

For this study, the number of building components data (count) is obtained from the National Statics Office of Nepal, and emission coefficients are obtained from the various literature sources. While specific Nepal-centric emission intensity data is lacking, the best suitable emissions value from the literature is used.

Although the emissions coefficient of materials obtained from the literature not precisely correspond to Nepal's residential construction materials, we have adopted material coefficients with similar characteristics, rendering them applicable within the Nepali context. Table 1 shows the comparison of emissions coefficients from various literature, an empty cell signifies the absence of data in the literature.

Further, embodied carbon emissions linked with materials are computed by multiplying the emissions intensity, structural material quantities, and the number of building components. The estimated emissions originating from Nepal's residential sectors are projected to serve as the baseline. In order to propose strategies for reducing emissions, we examine three different scenarios: current optimized scenario, 50 %, and 75 % reduction in carbon emissions. These alternative scenarios offer policymakers flexibility, as areas with lower carbon footprint may require less stringent policy interventions compared to high carbon-intensive regions. Fig. 2 outlines the methodology employed in this research from data collection to the optimized scenarios.

2.1. Data collection

2.1.1. Census data

The quantity of building materials utilized in residential construction in Nepal is obtained from the National Statistics Office's (NSO) of 2021 data [14]. The data obtained from the only provides the counts of materials utilized in each household with detailed breakdown of building components used by the foundation, wall, floor, and roof. To track changes over time, the annual trends in

Table 1
Emissions coefficient of materials obtained from various literatures.

Materials	ICE [21] (kg CO2/Kg)	SYKE [36] (kg CO2/Kg)	Others
Baked Bricks	0.21	0.22	0.195 Kg CO2/kg; reference [37]:
Bricks + Cement Mortar	0.23	0.28	–
Concrete	0.149	0.24	–
Wood	0.493	0.2	–
Unbaked Brick	0.005	0.005	–
Galvanized sheet		12	–
Reinforced cement concrete	0.149	0.24	–
Thatch/straw	–	0.1	–
Tile	0.480	0.66	–
Stone/slate	0.073	0.06	–
Wood/planks	–	0.083	0.083 kg Co_2/kg; reference [38]:
Mud	–	–	0.05 kg Co_2/kg; reference [38]:

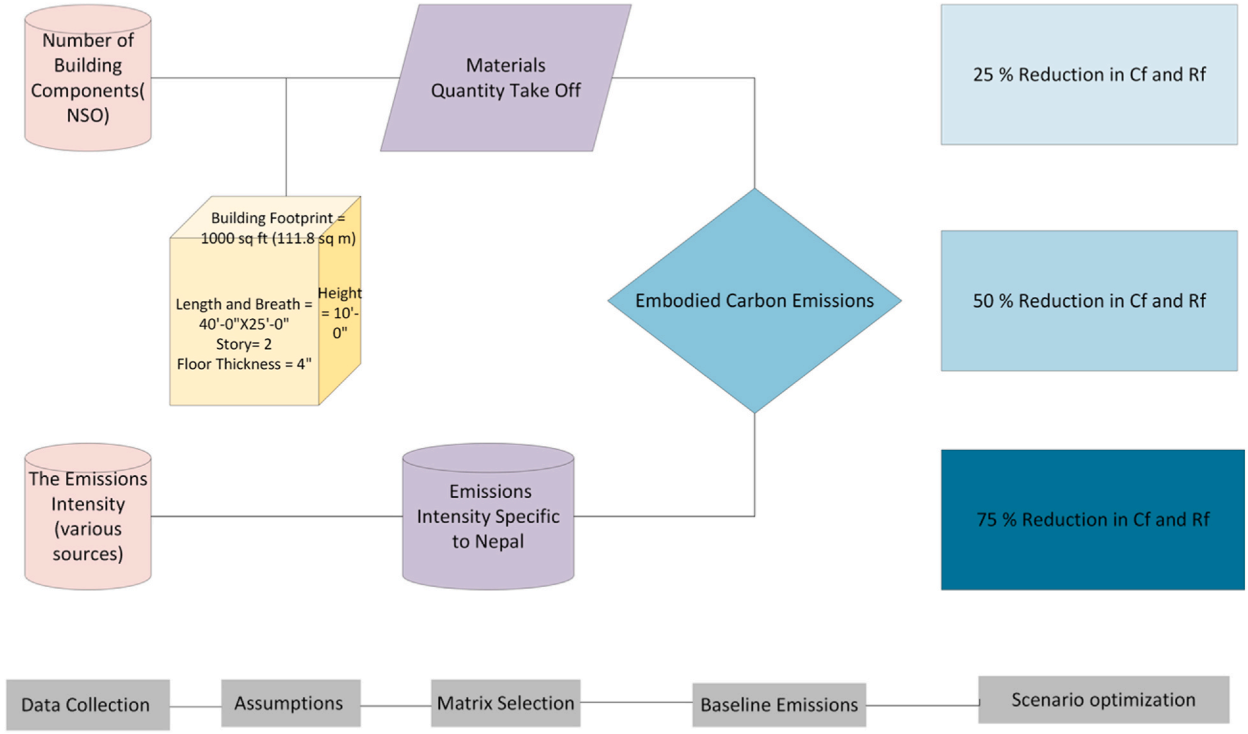

Fig. 2. The Methodological Framework Used in this Research.

building components are derived by analyzing the census data from 2011 [9] and 2021 [14].

Based on the design catalog of the Nepal Government Department of Urban Development, various applicable details are assumed for both rural and urban areas. For instance, SMM 1.1 is used for stone masonry in mud mortar, and BMC technical details are utilized for brick masonry in cement mortar [34]. In the case of residential reinforced concrete buildings in Kathmandu, the literature suggests a floor area of 111.8 m^2, with 55.02 m^2 on each floor [35]. However, for the purpose of simplified calculations and to accommodate residential building sizes from various regions of Nepal, we assume an area of 111.8 m^2 (1000 sq ft) While there is no specific documentation available on the sizes of rural homes, it is reasonable to assume that rural residential homes might be smaller in size. Nonetheless, given that rural homes are generally low in carbon emissions, a slightly larger area for the calculations should not significantly impact the study.

Table 2
Building Components and its Corresponding CO_2 e Emissions for 1000 sq ft built-up area.

Building Components	Materials	Emission coefficient (kg CO2/Kg)	Emissions (CO_2 e tons)
Foundation	Mud-bonded bricks/stone (Mf)	0.22	3.03
	Cement-bonded bricks/stone (C_f)	0.28	4.55
	Reinforced Cement Concrete with pillars (Rf)	0.24	4.57
	Wooden pillars (Wf)	0.2	1.05
Wall	Mud-bonded bricks/stone (Mw)	0.22	45.47
	Cement-bonded bricks/stone (Cw)	0.28	68.25
	Wood/planks (Ww)	0.083	6.55
	Bamboo (Bw)	0.083	0.73
	Unbaked bricks (Uw)	0.005	1.03
	Galvanized sheet (Gw)	12	175.61
Floor	Mud	0.05	1.86
	wooden plank/bamboo	0.083	0.56
	brick/stone	0.22	16.50
	ceramic tiles	0.66	4.84
Roof	Galvanized sheet (Gr)	12	67.54
	Reinforced Cement Concrete (Rr)	0.24	8.35
	Thatch/straw (Tr)	0.1	0.23
	Tile (Lr)	0.66	2.42
	Stone/slate (Sr)	0.06	0.32
	Wood/Planks (Wr)	0.083	0.28
	Mud (Mr)	0.05	0.93

2.1.2. Carbon emission coefficient

In this research the carbon emissions coefficient, we extracted data from several sources such as the Inventory of Carbon and Energy (ICE), Finish Environmental Institute (SYKE), and other sources such as Intergovernmental panel on climate change (IPCC). The empty cell indicates the absence of data or information in the literature.

2.2. Analysis

2.2.1. Carbon forecast equation

The calculation of embodied carbon emissions utilizes equation (1) which simply multiplies structural material quantities with embodied carbon coefficients [39].

$$ECE = SMQ_i \times ECC_i \tag{1}$$

where i is a specific component or material in the building structure i = 1, 2,3, 4, etc., n; ECE is embodied carbon emission (CO_2 equivalent); SMQ is structural material quantities, and ECC is embodied carbon coefficients. Emissions results are based on the assumptions of a building footprint of 1000 sq ft and building size of length = 40′-0″, breath = 25′-0″, and height = 10′-0″ assuming the entire area of foundation, wall, or roof is constructed with only one material are presented in Table 2. All the materials are converted into kilograms by multiplying surface area, thickness, and density. For example, 130 sq ft of the area of the foundation is made of mud-bonded bricks/stones, and 2600 sq ft of surface area for a wall (exterior and infill) is made of cement-bonded bricks.

In this study, the emissions coefficients employed are a combination of those derived from the SYKE database. In instances where the SYKE database did not provide the necessary emissions data, alternative literature sources were consulted to obtain the relevant coefficients, as outlined in Table 2. The emissions data from the ICE and SYKE databases, both originating from European region may not accurately reflect the emissions scnerios in Nepal. This is noted as a major limitations, and highlights the need for future efforts to develop databases tailered to Nepali context. As indicated in Table 2, the materials Cf and Rf in the foundation, Cw and Gw in the wall, and Gr and Rr in the roof have the highest emissions among the materials within each respective group of building systems. To assess three different scenarios, namely the optimized current scenario, 50 % reduction goal, and 75 % reduction goal, two materials with the highest emissions in the foundation, wall, and roof were identified. However, the floor was excluded from the analysis due to insufficient data availability.

equations (2)–(4) respectively for the foundation, wall, and roof are utilized as the objective function to be minimized and the number of building components per year are treated as decision variables. Fig. 3 illustrates graphical representation of emissions equation.

$$E_f = 3.03{*}M_f + 4.55{*}C_f + 4.57{*}R_f + 1.05{*}W_f \tag{2}$$

$$E_w = 45.47{*}M_w + 68.25{*}C_w + 6.55{*}W_w + 0.73{*}B_w + 1.03{*}U_w + 175.61{*}G_w \tag{3}$$

$$E_r = 67.54{*}G_r + 8.35{*}R_r + 0.23{*}T_r + 2.42{*}L_r + 0.32{*}S_r + 0.28{*}W_r + 0.93{*}M_r \tag{4}$$

The annual demand for each material in all building components as shown in Table 3 was determined by subtracting the demand in 2021 from the demand in 2011, and then dividing the result by 10. This approach was applied because census data in Nepal is released every 10 years, implying an assumption of consistent year-over-year demand.

2.2.2. Linear optimization model

Optimization involves the process of identifying the most favorable solution to a problem by selecting values for decision variables that minimize or maximize a specific quantity of interest. One widely utilized optimization technique is Linear programming (LP),

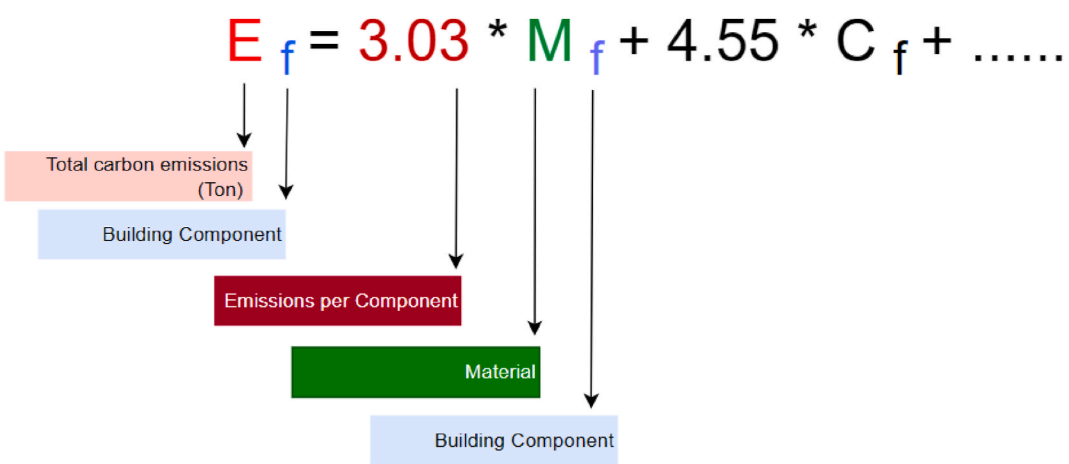

Fig. 3. Graphical illustration of emissions equations.

Table 3
Variables per year demand for building components.

Building Component	Variables per year demand					
Foundation	Mf	Cf	Rf	Wf		
Unit = number	−19655.5	103132.7	95368.9	−40600.3		
Wall	Mw	Cw	Ww	Bw	Uw	Gw
Unit = number	−20113.4	191613.4	−7716.5	−31706.6	−3317.6	8098.9
Roof	Gr	Rr	Tr	Lr	Sr	Wr	Mr
Unit = number	126053.8	129603.3	−77227.6	−25727	−17004.5	−2587.9	−1138.7

which provides a straightforward and efficient approach to addressing intricate problems. In this study, carbon reduction equations have been developed for building components (specifically foundation, wall, and roof) by using a linear optimization model. The primary objective was to construct a linear programming (LP) minimization model to ascertain the optimal level of annual embodied carbon emissions linked to residential buildings in Nepal. This was achieved through the application of Python programming and the PuLP package which offers a versatile and customizable framework for modeling and solving LP problems. Furthermore, PuLP supports a variety of open-source solvers.

This research explored three different optimization scenarios 1) optimized current scneraio 2) 50 % reduction scneraio 3) 75 % reduction scnerios, each with its associated carbon reduction strategies. The outcome of each scenario provides a comprehensive overview of emission reduction, facilitating policymakers' ability to make informed decisions for promoting equitable carbon reduction across regions.

Optimized current scenario: Our goal in the optimized current scenario was to determine the minimum attainable carbon emissions by converting the existing negative demand for certain building component types (Mf and Wf in the foundation, Mw, Ww, Bw, and Uw in the wall, and Tr, Lr, Sr, Wr, and Mr in the roof) with notably low carbon coefficients into non-negative values.

50 % reduction scenario: In this scenario, our aim was to decrease the demand for the two materials with the highest emissions in building components (Cf and Rf in the foundation, Cw and Gw in the wall, and Gr and Rr in the roof) by 50 %. This reduction was achieved by adjusting the remaining variables in each category to meet the total foundation demand per year.

75 % reduction scenario: Our objective in this scenario was to reduce the demand for the two materials with the highest emissions in building components (Cf and Rf in the foundation, Cw and Gw in the wall, and Gr and Rr in the roof) by 75 %. To meet the total foundation demand per year, adjustments were made to the remaining variables in each category.

3. Results

Based on the Linear Programming (LP) model, emissions trends are estimated. These estimated emissions serve as the baseline from which linear optimizers are employed with the objective of reducing the embodied emissions from the residential sector of Nepal.

3.1. Emission trends

Urban areas mostly use bricks for construction walls, which contributes to higher emissions compared to rural areas, where local stone and mud as the primary building materials, as identified in Fig. 4. Wall materials make a significant contribution to the embodied emissions in residential buildings. To reduce the emissions in urban areas, it is essential to reduce the use of bricks as wall material. Furthermore, urban areas contribute up to twice as much as rural areas to emissions from foundations, walls, or roofs. To lower emissions in urban areas, policymakers can consider discouraging the use of high-emissive materials such as brick and concrete through taxation or similar measures while providing incentives to promote low-embodied materials.

Moreover, the hilly region of Nepal exhibits a notable increase in embodied carbon emissions, as depicted in Fig. 5. This phenomenon could be attributed to the larger cities such as Kathmandu, Bhaktapur, and Lalitpur, in hilly areas. In these urban centers, a

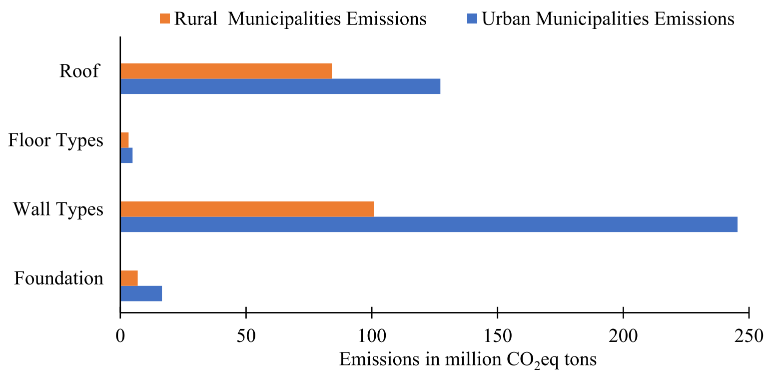

Fig. 4. Embodied carbon emission patterns in urban and rural areas.

substantial portion of homes are constructed using high-emission materials such as concrete and bricks. Contrarily, many hilly areas remain primarily rural and would typically have lower emissions. Additionally, the Terai region, characterized by a high-density of population and migration of people from the mountains to the Terai, has seen a surge in residential construction. A significant number of these residential buildings in Terai are built with brick and concrete, further contributing to the overall emissions.

Furthermore, Nepal is divided into seven provinces, with the capital city situated in Bagmati Province. Consequently, Bagmati Province exhibits a significant carbon footprint, as indicated in Fig. 6. However, it's noteworthy that other provinces, particularly Lumbini and Koshi also make substantial contributions to emissions ranking as the second and third highest emitters, respectively. Interestingly, Karnali province emits the least carbon and is nearly five times lower than that of Bagmati province.

The emission patterns identified above offers valuable insights that can serve as pivotal milestones in shaping national, regional, and local carbon policies and framework. For example, given the higher emissions in urban areas, there's a compelling case for more stringent regulation to curtail carbon emissions. This could involve penalties for the use of specific high emission materials or the provision of incentives for the adoption of low-emission materials.

3.2. Carbon reduction using linear optimization modeling

This research has considered three different optimization scenarios and associated carbon reduction in each scenario. The goal of these scenarios is to provide a high-level overview of the potential results/outcomes of the policy interventions for equitable carbon reduction. Equation (2) to equation (4) are derived, the emission coefficient used in the equations refers to the overall emissions associated with the materials. The other variable represents the number of building materials in the foundation, wall, and roof. In our study, 'prob' is an optimization problem variable that defines the problem, encompassing the objective function and constraints. It is subsequently utilized by optimization algorithms to identify the optimal solution.

3.2.1. Carbon emission of foundation

The foundation has four materials: mud-bonded bricks/stone, cement-bonded bricks/stone, reinforced cement concrete with pillars, and wooden pillars. The materials Cf and Rf were found to have higher emissions than the other two materials in the foundation. The emissions associated with the foundation are calculated and considered baseline. In addition, equation (2) is used as the objective function to be minimized and the four building materials used per year were treated as decision variables. The total carbon emissions per year due to foundation were calculated to be 802903 CO_2 equivalent tons based on equation (2).

$$E_f = 3.03*M_f + 4.55*C_f + 4.57*R_f + 1.05*W_f \tag{2}$$

Linear optimization found that the implementation of the optimized current scenario led to a reduction in nationwide carbon emissions from foundations by 21 %, equivalent to 172560 CO_2 equivalent tons. In the optimized scenario, our objective was to identify the minimum carbon emission attainable by modifying the existing negative demand of Mf and Wf, both of which have considerably low carbon emissions, to non-negative values. Furthermore, by reducing the demand for the two highest emission foundation materials, Cf and Rf by 50 % and meeting the total foundation demand per year by increasing Mf and Wf, we can achieve about 34 % reduction in carbon emissions accounting for 270810 CO_2 equivalent tons. Similarly, in the third scenario, by reducing the demand for Cf and Rf by 75 % and increasing Mf and Wf to meet the total foundation demand, a 49 % reduction which is equivalent to 395848 tons is achievable as shown in Table 4.

3.2.2. Carbon emission of wall

The wall is constructed from six different materials: mud-bonded bricks/stone, cement-bonded bricks/stone, wood/planks, bamboo, unbacked bricks, and galvanized sheet. Two of these materials, Cw and Gw, were found to have relatively higher emission coefficients than the others. The emissions associated with the wall are calculated and considered baseline. In addition, equation (3) is used as the objective function to be minimized and the six building materials used per year were treated as decision variables.

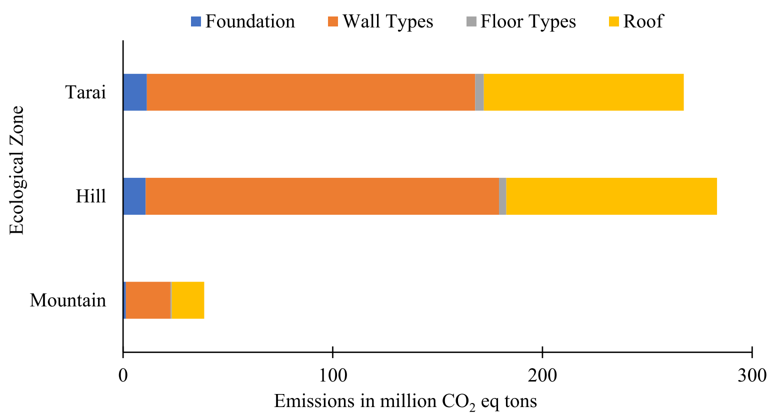

Fig. 5. Household carbon emission patterns in ecological areas.

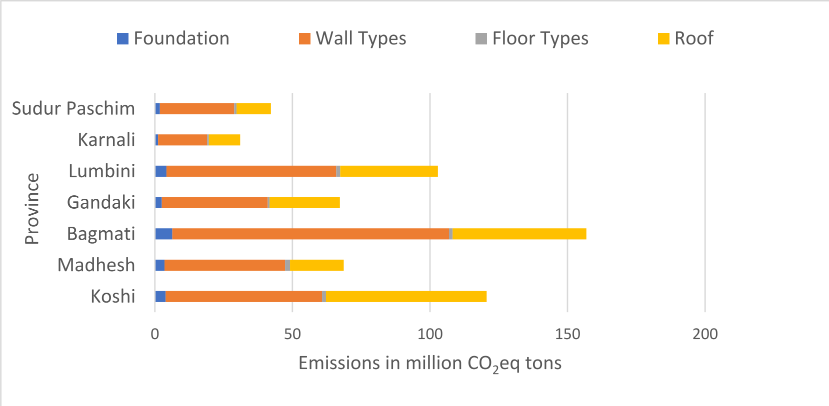

Fig. 6. Household carbon emission patterns by provincial level.

Table 4
Optimized carbon emissions scenarios for foundation.

Building Component	Optimization	Optimized Current Scenario	50 % Reduction in Cf & Rf demand	75 % Reduction in Cf & Rf demand
Foundation	Objective Function	Equation 2	Equation 2	Equation 2
	Constraints	3.03*Mf + 4.55*Cf + 4.57*Rf + 1.05*Wf≤802903 prob + = Mf + Cf + Rf + Wf≤138246 prob + = Cf≤71826 prob + = Rf≤66419 prob + = Mf≥0 prob + = Wf≥0	3.03*Mf + 4.55*Cf + 4.57*Rf + 1.05*Wf≤802903 prob + = Mf + Cf + Rf + Wf≤138246 prob + = Cf≤51566 prob + = Rf≤47684 prob + = Mf≥19498 prob + = Wf≥19498	3.03*Mf + 4.55*Cf + 4.57*Rf + 1.05*Wf≤802903 prob + = Mf + Cf + Rf + Wf≤138246 prob + = Cf≤25783 prob + = Rf≤23842 prob + = Mf≥44310 prob + = Wf≥44310
	Number of Cf and Rf	Cf = 71826 & Rf = 66419	Cf = 51,566 & Rf = 47,684	Cf = 25,783 & Rf = 23,842
	Emissions Reduction	172560 CO_2 Equivalent tons	270810 CO_2 Equivalent tons	395848 CO_2 Equivalent tons
	Emissions Reduction %	21 %	34 %	49 %

Table 5
Optimized carbon emissions scenarios for wall.

Building Component	Optimization	Optimized Current Scenario	50 % Reduction in Cw & Gw	75 % Reduction in Cw & Gw
Wall	Objective Function	Equation 3	Equation 3	Equation 3
	Constraints	prob + = 45.47*Mw + 68.25*Cw + 6.55*Ww + 0.73*Bw + 1.03*Uw + 175.61*Gw≤13508200 prob + = Mw + Cw + Ww + Bw + Uw + Gw≥136858 prob + = Cw≤131308 prob + = Gw≤5550 prob + = Mw≥0 prob + = Ww≥0 prob + = Bw≥0 prob + = Uw≥0	prob + = 45.47*Mw + 68.25*Cw + 6.55*Ww + 0.73*Bw + 1.03*Uw + 175.61*Gw≤13508200 prob + = Mw + Cw + Ww + Bw + Uw + Gw≥136858 prob + = Cw≤95807 prob + = Gw≤4049 prob + = Mw≥11275 prob + = Ww≥11275 prob + = Bw≥11275 prob + = Uw≥11275	prob + = 45.47*Mw + 68.25*Cw + 6.55*Ww + 0.73*Bw + 1.03*Uw + 175.61*Gw≤13508200 prob + = Mw + Cw + Ww + Bw + Uw + Gw≥136858 prob + = Cw≤47903 prob + = Gw≤2025 prob + = Mw≥21733 prob + = Ww≥21733 prob + = Bw≥21733 prob + = Uw≥21733
	Number of Cw and Gw	Cw = 131308 & Gw = 5550	Cw = 95807 & Gw = 4049	Cw = 47903 & Gw = 2025
	Emission reduction	3571793 CO_2 Equivalent tons	5651958 CO_2 Equivalent tons	8714409 CO_2 Equivalent tons
	Emission reduction %	26 %	42 %	65 %

$$E_w = 45.47*M_w + 68.25*C_w + 6.55*W_w + 0.73*B_w + 1.03*U_w + 175.61*G_w \quad (3)$$

The analysis revealed that implementing the optimized current scenario reduced nationwide carbon emissions from walls in Nepal by 26 % equivalent to 3571793 tons. Our aim in the optimized current scenario was to identify the minimum carbon emission achievable by transforming the existing negative demand of Mw, Ww, Bw, Uw, all of which have relatively low carbon coefficients, into non-negative values. Moreover, by decreasing the demand for the two highest emission wall materials, Cw and Gw, by 50 % and increasing Mw, Ww, Bw, and Uw to meet the total wall demand per year, a 42 % reduction in carbon emissions from walls per year, amounting to 5651958 tons is obtained. Similarly, in the third scenario, 65 % of nationwide carbon emissions reduction from walls totaling 8714409 tons, by reducing the demand for Cw and Gw by 75 % and increasing Mw, Ww, Bw, and Uw to meet the total wall demand every year as shown in Table 5.

3.2.3. Carbon emission of roof

There are varieties of roofing materials in Nepal, including galvanized sheet (Gr), reinforced cement concrete (Rr), thatch/straw (Tr), tile (Lr), stone/slate (Sr), wood/planks (Wr), and mud (Mr). However, Gr and Rr have been identified as having particularly high emission coefficients compared to the other materials. Equation (4) is used as the objective function to minimize, with the five building materials used for the roof per year treated as decision variables.

$$E_r = 67.54*G_r + 8.35*R_r + 0.23*T_r + 2.42*L_r + 0.32*S_r + 0.28*W_r + 0.93*M_r \quad (4)$$

The analysis shows that implementing the optimized current scenario led to a nationwide reduction of carbon emissions stemming from roofs in Nepal by 48 %, equivalent to 4555154 tons. Our objective in the optimized current scenario was to ascertain the minimum attainable carbon emission by converting the existing negative demand values of roofing materials, such as Tr, Lr, Sr, Wr, and Mr, which possess relatively low carbon coefficients, into non-negative ones. Furthermore, by reducing the demand for the two roofing materials with the highest emissions, Gr and Rr, by 50 % and simultaneously increasing the demand for Tr, Lr, Sr, Wr, and Mr to meet the total roof demand per year, a 50 % reduction in carbon emissions equivalent of 4707208 tons, can be achieved. Similarly, in the third scenario, 74 % of reduction from roofs amounting to 7052783 tons, by reducing the demand for Gr and Rr by 75 % and evenly increasing the demand for Tr, Lr, Sr, Wr, and Mr to meet the total roof demand, as indicated in Table 6.

4. Residential embodied carbon emissions and strategies for reduction

In this section, we have discussed the existing policies that support residential carbon reduction. However, based on the study and literature review results, a few policy-related implications have been suggested in the following strategies to reduce the embodied residential buildings' carbon emissions in Nepal.

4.1. Review of the residential household carbon emissions

Total household carbon emissions are influenced by various determinants, including income, household size, age, education level, location, gender and rebound effects, etc. [40]. Government agencies globally have implemented abatement policies to reduce residential emissions. In high-income countries, demand-side policy instruments such as carbon taxes, cap-and-trade systems, and subsidies, are commonly used. In contrast, low-income countries primarily rely on supply-side policies, which involve regulations and standards for emissions, investment in renewable energy infrastructure, and promoting energy-efficient technologies [40]. Additionally, the geographic location within a nation plays a crucial role in selecting appropriate policy instruments, as different regions

Table 6
Optimized carbon emission scenarios for roofs in Nepal.

Building Component	Optimization	Optimized Current Scenario	50 % Reduction in Gr & Rr	75 % Reduction in Gr & Rr
Roof	Objective Function	Equation 4	Equation 4	Equation 4
	Constraints	prob + = 67.54*Gr + 8.35*Rr + 0.23*Tr + 2.42*Lr + 0.32*Sr + 0.28*Wr + 0.93*Mr≤9508614 prob + = Gr + Rr + Tr + Lr + Sr + Wr + Mr≥131971 prob + = Gr≤65070 prob + = Rr≤66902 prob + = Tr≥0 prob + = Lr≥0 prob + = Sr≥0 prob + = Wr≥0 prob + = Mr≥0	prob + = 67.54*Gr + 8.35*Rr + 0.23*Tr + 2.42*Lr + 0.32*Sr + 0.28*Wr + 0.93*Mr≤9508614 prob + = Gr + Rr + Tr + Lr + Sr + Wr + Mr≥131971 prob + = Gr≤63027 prob + = Rr≤64802 prob + = Tr≥829 prob + = Lr≥829 prob + = Sr≥829 prob + = Wr≥829 prob + = Mr≥829	prob + = 67.54*Gr + 8.35*Rr + 0.23*Tr + 2.42*Lr + 0.32*Sr + 0.28*Wr + 0.93*Mr≤9508614 prob + = Gr + Rr + Tr + Lr + Sr + Wr + Mr≥131971 prob + = Gr≤31513 prob + = Rr≤32401 prob + = Tr≥13611 prob + = Lr≥13611 prob + = Sr≥13611 prob + = Wr≥13611 prob + = Mr≥13611
	Number of Gr and Rr	Gr = 65070 & Rr = 66902	Gr = 63027 & Rr = 64802	Gr = 31513 & Rr = 32401
	Emission reduction	4555154 CO_2 Equivalent tons	4707208 CO_2 Equivalent tons	7052783 CO_2 Equivalent tons
	Emission reduction %	48 %	50 %	74 %

have varying climates [41]. For instance, a study in China uncovered substantial differences in carbon emissions across rural/urban households and regional and income groups, recommending the implementation of incentives to encourage green l lifestyles and consumption behavior [42]. Another study conducted in the United States found that carbon emissions in typical households were lower in metropolitan areas with a higher concentration of college graduates living downtown [43]. Moreover, technological innovation and adaptation of renewable energy technologies were observed to mitigate carbon emissions [25]. In Europe, a voluntary carbon offset measure has been introduced, particularly in regions with high electricity costs. This measure, despite a relatively small share in total electricity costs, does significantly burden household budgets and can effectively contribute to achieving carbon neutrality through the use of voluntary carbon offsets [44].

Several studies have explored the embodied energy and carbon associated with various building materials and types, primarily from a micro perspective [28,45,46]. However, there remains a notable absence of a comprehensive macro-level assessment of the total embodied carbon emissions stemming from residential buildings. Rural building materials are vastly vernacular and typically exhibit significantly lower emissions when compared to urban building materials. Despite the inherently lower emissions in rural areas, the process of rapid urbanization in Nepal has led to a substantial increase in carbon emissions. These emissions have risen from approximately 26 to 54 Mt CO_2e between 1990 and 2016; with an expected further increase of 31–36 % by 2030 under current policies [47]. While the government has made some progress in implementing mitigation policies, the current efforts appear insufficient to meet the emissions reduction targets, particularly concerning emissions associated with residential embodied carbon. As depicted in Fig. 7, the Climate Change Governance Action Plan Timeline has been put into effect by the government to address carbon emissions. However, it is evident that specific attention is required for the monitoring and control of emissions within the built environment.

4.2. Strategies for carbon emission reduction

Reducing carbon emissions from residential buildings is an important goal to mitigate climate change. Incorporating the characteristics of Nepal's national conditions and development needs is crucial for the successful implementation of strategies in this context. Below are several strategies that can be considered:

First, policy-level intervention is needed to establish and enforce green building standards that can have a positive impact on the environmental performance of buildings. However, the effectiveness of such standards relies heavily on strict enforcement. Loose implementations of the mandates tend to have a limited impact on construction practice [48]. In India, Leadership in Energy and Environmental Design (LEED) and Green Rating for Integrated Habitat Assessment (GRIHA), have been widely adopted to promote environmentally-friendly construction practices [49]. A recent study in Ghana also [50] identified mandatory regulations, standards, and policies as drivers for green buildings. Adoptation of technology such as Building Information Model and Artificil Intelligence can optimize the reduction of emissions [51–53]oo.In contrast, Nepal currently lacks green building standards, though some buildings have certified LEED certification. Therefore, setting up green building standards that address various aspects, including, green infrastructure, low carbon transport, zero energy buildings, energy retrofits, and other environmental protection policies. The implementation of stringent green building standards in urban areas has the potential to significantly reduce emissions originating from the residential sectors. Furthermore, the development of emission coefficients that account for regional variations will greatly enhance the accuracy of carbon tracking efforts.

Next, raising awareness through technology-assisted means is crucial for reducing carbon emissions, as technology can play a significant role in fostering low-carbon design and construction. Initiatives such as low carbon city pilot have been successful in promoting technological innovation in pilot cities and neighboring cities [54]. A study conducted in China identified that low-carbon and zero-carbon technologies are not yet fully mature, technology can help in raising awareness and fostering innovation in low-emission materials [55]. A pilot study in China emphasized the significant role of technology in promoting innovation, particularly in small, medium, and non-provincial capital cities, and cities in high-carbon provinces [56]. In the context of Nepal, launching a pilot project for a zero-carbon city with a robust technological framework can make a substantial impact to reduce the carbon emissions from household emissions.

Third, enhancing consumer behavior through the simulation of the impact of demand-side policies on low-carbon technology facilitates the rapid adaptation of low-carbon technologies but there are noticeably diminishing marginal effects; even if subsidies are only employed on the demand side, they can still effectively promote low-carbon technology through the interaction of demand-supply interaction [57]. In the context of Nepal, the use of low-carbon technology in residential construction can be effective.

Fourth, increasing energy efficiency can yield substantial long-term economic benefits, and modifying consumer behavior is a key means to reduce greenhouse emissions [58]. In the context of Nepal, encouraging consumers to use energy-efficient devices, and low carbon-density electricity for producing building materials are crucial. Consumer behavior is a vital tool to promote market-driven innovation in low-carbon technologies.

Fifth, incentives and promotion of low-carbon materials are essential to scale up zero-carbon housing development [59]. Market demand is greatly influenced by investment in the promotion of low-carbon products and emissions reduction efforts [60]. Policymakers should allocate more research and development funds for green technologies and establish a regionally integrated system for reducing low-carbon emissions [61]. Nepal can effectively implement incentives to encourage low-carbon construction practices, preferably on a city to regional scale.

Furthermore, green buildings often face a huge investment deficit, carbon offsets and pricing offer viable solutions for bridging this gap. Green finance can assist researchers, policymakers, and practitioners in promoting green buildings and low-carbon construction [62]. The government can encourage households to purchase carbon offsets to offset their carbon emissions. This can provide a financial incentive for households to reduce their emissions and support carbon reduction projects. In addition, governments can implement carbon pricing policies, such as carbon tax or cap-and-trade systems, to discourage fossil fuel use and incentivize the

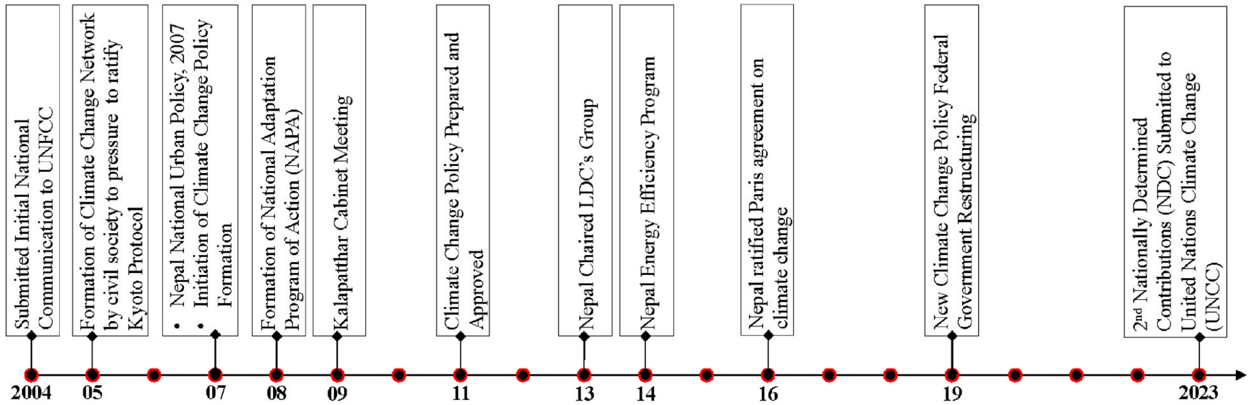

Fig. 7. Climate change governance action plan timeline in Nepal.

adaptation of low-carbon alternatives. In the context of Nepal, high-carbon-intensive regions can be taxed and support low-carbon regions for their sustainable infrastructure projects.

Finally, by implementing circular economy principles, the building industry can contribute to the establishment of a waste-related economy where wasted materials are considered valuable assets rather than ordinary waste. This shift promotes innovative approaches to material recovery, fosters the development of recycling infrastructure, and creates a market for secondary raw materials. In Nepal, households can efficiently reduce their carbon footprint by adopting this circular model, enhancing the overall sustainability and resilience of the built environment.

5. Limitations

This study is subjected to several limitations. The foremost limitations pertain to the critical issue of data reliability, which is crucial in the quantification of embodied carbon emissions. Acquiring detailed and accurate data, particularly in the context of developing countries such as Nepal, can be a challenging endeavor. Consequently, this study resorts to employing emissions intensity data from various literature sources, primarily from non-Nepali contexts. Additionally, the research relies on a 1000 sq ft building footprint for both urban and rural areas, which may not fully capture the diversity of architectural archetypes. The study also omits the consideration of microclimate factors and does not encompass a comprehensive life cycle assessment, which could yield more comprehensive insights into carbon emissions. Furthermore, the emissive coefficients used in this study are not specific to Nepal, highlighting the need for further research aimed at identifying emissions coefficients tailored to different geographic regions within Nepal. Given the change in administrative zones in Nepal in 2015, where certain rural municipalities were reclassified as urban municipalities, future studies examining emissions trends in these evolving urban areas could provide valuable insights for policy recommendations. Lastly, this study excludes emissions stemming from building openings, furniture, mechanical, electrical, and plumbing (MEP) systems, among other factors. Conducting emissions analyses of individual residential units in both urban and rural areas may yield more meaningful findings, aiding designers in selecting low-carbon materials and practices for reduced environmental impact.

Lastly, In the formulation of LP, the minimum amount of material required for the structural feasibility of buildings is not considered. It is important to acknowledge that future studies should address this aspect. Diverse constraints parameters should be taken into account for rigorous emissions analysis for the practical use, and further research on various building typologies is recommended to incorporate structural feasibility requirements as constraints in future emissions estimation.

6. Conclusion

The study of residential carbon emissions in Nepal holds significant potential for informing and guiding crucial policy-level interventions aimed at reducing embodied emissions. The study's emission trend results serve as valuable insights for policymakers, enabling them to identify regions for targeted interventions, such as urban-rural areas, and provincial zones. Furthermore, the research incorporates the analysis of three different distinct scenarios of carbon reduction through linear optimization, offering a spectrum of intervention levels tailored to specific regions. For instance, in urban areas, recommendations include reducing the use of concrete and bricks, while rural areas may continue utilizing locally sourced materials. To underpin these scenarios, data on the number of building components is sourced from the National Statistics Office, Nepal, while emission intensity data is drawn from reliable sources. The study's findings substantiate that Bagmati Province exhibits the highest levels of embodied carbon emissions in the residential sector, whereas Karnali Province demonstrates the lowest emissions. Additionally, urban areas are found to be approximately three times more carbon-intensive than their rural counterparts. The outcome of this study provides policymakers with the prioritize their efforts, starting with high carbon emitting regions, and implementing stringent regulations and measures in low carbon emitting areas. In doing so, they can work toward reducing carbon emissions to maintain their current carbon level. The results from the linear optimization model demonstrate substantial potential for carbon emissions reduction in various building components within Nepal. In the case of foundations, the optimized current scenario led to a 21 % reduction in nationwide carbon emissions, with further reductions of

34 % and 49 % achieved by decreasing the demand for the highest-emission materials and increasing the use of alternative materials. For walls, the optimized current scenario resulted in a 26 % reduction, while more aggressive scenarios achieved reductions of 42 % and an impressive 65 %. In the case of roofs, the optimized current scenario led to a 48 % reduction, with additional reductions of 50 % and a remarkable 74 % achieved by changing material demand. These findings underscore the potential for significant carbon emissions reduction through strategic material selection and utilization, offering valuable insights for promoting sustainable construction practices in Nepal.

CRediT authorship contribution statement

Suman Paneru: Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – original draft. **Prashnna Ghimire:** Methodology, Validation, Visualization, Writing – review & editing. **Ayushma Kandel:** Formal analysis, Methodology, Software. **Sagar Kafle:** Methodology, Visualization, Writing – review & editing. **Christopher Rausch:** Supervision, Validation, 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

Data will be made available on request.

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