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Carbon Footprint Estimation in Road Construction: A Case Study of Pokhara-Mugling Road, Nepal

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ABSTRACT. Road construction is a significant contributor to greenhouse gas emissions within the transport sector. This study attempted to quantify the Green House Gases (GHGs) emission of Pokhara - Mugling Road using Life Cycle Assessment (LCA). A Gate-to-Gate LCA was conducted to quantify emissions. Sensitivity analyses were conducted to assess the differential impacts of bitumen and aggregate on emissions during construction. The Relative Importance Index (RII) was calculated by distributing a questionnaire to experts and environmental safeguard specialists to gather insights on the most suitable mitigation measures for reducing emissions in Nepals' road sector. The findings revealed that the total carbon equivalent emissions from the construction of the Pokhara - Mugling Road amounted to 33.73 kilotons of CO_2e. Notably, 60.78% of these emissions were attributed to the materials used in the construction process. Fuel consumption by the Hot Mix Asphalt (HMA) plant contributed 70% of the emissions from the total fuel consumption, surpassing the emissions from all other plants and equipment involved in the pavement construction. Sensitivity analysis results indicated that changes in bitumen content have a more significant effect on GHG emissions compared to variations in aggregate. This suggests that the construction of a national highway substantially contributes to carbon emissions, and therefore, requires careful consideration to minimize its environmental footprint. Based on the RII analysis, optimizing construction and quality management plans is essential for reducing greenhouse gas emissions in road construction. Equally important is using electricity as a fuel source for heating in asphalt production can lower emissions compared to traditional fossil fuels. Implementing warm mix or cold asphalt technologies and incorporating recycled materials such as Reclaimed Asphalt Pavement (RAP) and crumb rubber in asphalt mixtures can significantly reduce emissions. Transitioning to low-emission equipment, including electric or biodiesel-powered machinery, and adopting alternative energy sources such as natural gas or biomass-based fuels in asphalt plants also can minimize the environmental impact. By integrating these sustainable practices, road construction in Nepal can significantly decrease its contribution to greenhouse gas emissions.

Keywords: Gate to Gate, Green House Gas, Hot Mix Asphalt, Life Cycle Assessment.

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1. Introduction

Global warming is causing more frequent extreme weather events and the ongoing melting of the polar ice caps, which is being caused by an increase in greenhouse gas emissions. As a result of these negative effects of global warming, it is now urgently necessary to control and reduce greenhouse gas emissions in order to protect human life [1, 2, 3]. One of the primary global sources of carbon emissions is the road transportation sector [4]. Therefore, reducing the carbon emissions produced during construction is a crucial area for research to combat global warming. Infrastructure construction projects, especially road construction, are responsible for significant emissions [5]. Over the course of their entire life cycle, including the manufacturing of raw materials, building, operation, maintenance, and road repair, road infrastructure produces significant amounts of greenhouse gases (GHGs) [6, 7]. By 2050, it is anticipated that more than 25 million kilometers (a 60% increase from 2010) of new roads will have been constructed worldwide, 90% of which is anticipated to be constructed in the developing nations[8]. The World Bank study estimates that in 2018, around 17% of global greenhouse gas emissions came from the transport sector. Over the past 50 years, transport emissions have grown faster than nearly any other sector. If no measures are taken, these emissions are expected to rise by 60% by 2050 [9].

Nepal is among the most vulnerable nations to climate change and is at significant risk, due to its delicate topography, peoples' climate sensitive and subsistence lifestyles, and their limited potential for adaptation [10]. Despite its insignificant emissions, Nepal is committed to accelerating climate action while upholding the common but distinct obligations and unique capacities set forth in the Paris Agreement. Nepal's Nationally Determined Contribution (NDC) 3.0, submitted to the UNFCCC Secretariat in 2025, aims to reduce net GHG emissions by 8,866.53 Gg CO_2e (17.12%) by 2030 and 16,627.80 Gg CO_2 (26.79%) by 2035 through the implementation of quantified mitigation targets. Of the total expected reductions, the energy sector is projected to contribute around 53%, with the transport subsector accounting for 16% of the reduction by 2030 [11]. Nepal is committed to its long-term climate goals, based on recent reports from the Intergovernmental Panel on Climate Change (IPCC) and other scientific evidences. Nepal is strategically addressing climate change, aiming to achieve minimal or zero emissions and attain sustainable net-zero emissions by 2045 [10]. In Nepal, energy sector has a major share in the GHG emission among all other sectors (about 65% of the total emission of the year 2022 including removals from the land use sector). Of 25.014 Gg CO_2 equivalent GHG emissions from the energy sector, 19.04% is contributed by transport sub-sector [12]. Thus, to check the adverse environmental impacts and to help the country achieve net zero emission goals, transportation sector which contributes significantly to Nepal's GHGs emission, should be given due consideration. Reducing the environmental impact of the road sector has become international as well as national concern.

The construction sector is recognized as one of the leading contributors to environmental pollution. Traditional construction practices and management struggle to address emerging challenges including carbon emissions. These challenges underscore the necessity for professionals to reevaluate and enhance construction processes and technologies. This highlights the significant potential of the construction sector in advancing sustainable development, addressing economic, social, and environmental concerns. Embracing sustainable construction practices offers the opportunity to reduce overall energy consumption, maximize the utilization of renewable energy sources, minimize waste generation, conserve water resources, reduce vulnerability to flooding, decrease harmful emissions into water, air, and soil, and mitigate noise and light pollution[13]. While there has been considerable focus on new construction materials and technologies, there has been relatively little attention given to the examination of the construction phase itself. This phase warrants closer examination to determine if improved construction process management can indeed result in reduced GHG emissions from projects. Upon close monitoring of several highway construction projects, it becomes evident that inadequate management practices during the construction phase are causing a notable increase in GHG emissions associated with these projects [14].The essential goal for achieving sustainable infrastructure project construction lies in finding a crucial balance between economic considerations and the potential for emissions reduction [15].

2. Literature Review

2.1. **Global Warming Potential.** Greenhouse gas emissions are quantified using the unit of carbon dioxide equivalents (CO_2e) [16]. A key impact category to consider in these analyses is the Global Warming Potential (GWP). The GWP outlined by the IPCC in the 2014 Climate Change Comprehensive Report was used to determine the ratio of various greenhouse gases to equivalent carbon dioxide. According to this report, the GWP of CO_2 is 1, CH_4 (methane) is 25, and N_2O (nitrous oxide) is 298 [17].

2.2. **Carbon Emission Factors.** As defined by Environmental Protection Agency (EPA) AP-42 (Compilation of Air Pollutant Emission Factors), an emission factor represents a value that correlates the quantity of a pollutant released into the atmosphere with the activity that generates it [18]. Emission factors translate activity data, such as material usage, production volumes, or energy consumption, into corresponding emission estimates. The list of carbon emission factor as obtained from various literature are shown in Table 1.

Table 1. CO2 Emission Factors for Different Construction Materials and Fuel

Component	Value	Unit	Source
Sand	0.0025	$kgCO_2/kg$	[19]
Aggregate	0.0028	$kgCO_2e/kg$	[19]
Bitumen	0.426	$kgCO_2e/kg$	[19]
Cement	0.8207	$kgCO_2e/kg$	[19]
Fuel (Diesel)	2.71	$kgCO_2e/liter$	[20]

2.3. **LCA in Evaluating Environmental Impact.** Given the importance of carbon footprint due to global warming, it's crucial to understand that a lower carbon footprint doesn't necessarily mean better environmental performance. Therefore, it's recommended to conduct carbon footprint studies alongside broader tools like LCA (Life Cycle Assessment) for a more comprehensive evaluation [21]. LCA and CF may appear similar, but the key difference is that CF evaluates using a single indicator, whereas LCA considers multiple indicators to assess environmental impacts [22]. LCA is gaining popularity as a tool to analyze the environmental effects of construction activities and identify strategies for impact reduction [23].

LCA in the field of transportation offers a thorough method for assessing the full environmental impact of a specific product (like a ton of aggregate) or more intricate systems (such as a transportation facility). It evaluates key environmental inputs and outputs throughout the product's life cycle, from the production of raw materials to its eventual disposal [24]. The life cycle of the product begins with the acquisition of raw materials, progresses through various distinct phases (such as material processing, production, and usage), and ends at the end-of-life (EOL) stage.

2.4. **Relevant Studies.** Several studies have focused on methods for calculating carbon emissions in road construction and have explored various measures to mitigate these emissions. The GHGs emissions related to transportation infrastructure are calculated widely using the LCA method [25]. Horvath et al. [26] studied the environmental consequences of asphalt and steel-reinforced pavements in United States. LCA conducted in this study suggested that asphalt pavements can be a more environmentally sustainable option when they are effectively recycled. White et al. [19] examined various pavement types' carbon emissions throughout road material production and construction; and developed a carbon emission calculation model that took into account calculation parameters such as road width, material properties, road thickness, and service life. Santos et al. [27] used LCA model to investigate the effects of in-place recycling procedures on the construction and repair of pavement. And found a 75% reduction in environmental impacts during raw material extraction and mixture production was achieved by opting for recycling-based maintenance and rehabilitation (M&R) activities instead of traditional reconstruction methods. Barandica et al. [28] evaluated the GHG emissions of Spanish road constructions throughout the entire life cycle. Their results showed emissions range from 8,880 to 50,300 t CO_2e/km, mainly from construction activities, with the maintenance stage playing a minor role. Earthworks dominate emission in construction stage (60–85%), driven primarily by off-road machinery (61.5–84.9%), followed by material-related emissions (9.5–32.9%). Kim et al. [29] calculated the GHG emissions from the production of the materials used in road construction. Wang et al. [30] described that the majority of CO_2 emissions from highway construction comes from the production of raw materials. Results indicated that, mixture mixing phase generates the highest GHG emissions, contributing approximately 54% of the total, while the production of raw material is the second highest. In asphalt course construction, 95.04% of emissions came from mixture mixing, and 2.38% from raw material and mixture transportation, excluding raw material manufacturing. Peng et al. [31] calculated the GHG emissions from asphalt roadways, using LCA method. The results showed that road length, type, material use, and technology are key factors in high GHG emissions. Asphalt roads emit 39–63% less GHG than cement roads. Ma et al. [32] studied the construction of asphalt-paved highways into three layers asphalt course, cement stabilized aggregate base and cement stabilized gravel sub base based on the life cycle inventory method. The results indicate that the mixture mixing phase generates the highest greenhouse gas emissions, accounting for approximately 54% of the total, followed by the raw material production phase as the second largest contributor.

Noland and Hanson (2015) carried out an in-depth life-cycle assessment of greenhouse gas emissions for highway re-construction project in New Jersey. Their study took into account the emissions from material extraction, construction, and maintenance phases [33]. A study by Gulotta et al. [34] in Italy, which analyzed the life cycle of various pavement technologies for urban roads, found that material production is responsible for more than 60% of the total carbon emissions. This analysis considered all stages; extraction of material, construction, maintenance, and end-of-life. Huang et al. [35] developed a life cycle assessment tool specifically for evaluating the construction and maintenance of asphalt pavements in UK. Their study utilized this tool to assess the environmental consequences of asphalt pavement construction. A study considering the key impact categories – human health, ecosystem quality, and resource consumption – found that the total impact value for rigid pavement is 78.90 kPt, which is 45% of the 175.50 kPt impact for flexible pavement. This indicated that rigid pavement is more sustainable in long term [36].

A study in [37] found that bitumen contributed between 38% and 39% of the total GHG emissions, taking into account the stages of raw material extraction and the construction and the operation of the Hot Mix Asphalt (HMA) plant was the largest contributor to GHG emissions; also, the study found that the energy used to operate the plant was insignificant, primarily due to the use of renewable energy. A study in [38] found that asphalt production at the plant is the most energy-intensive process. A study conducted in expressway construction in China found that the aggregate and asphalt heating are the main sources of energy consumption and can be lowered by utilizing natural gas [4]. A case study in China by [15] examined seven stages of road construction, finding that subgrade construction contributed the most emissions than pavement construction.

As discussed in [39], the carbon emission from asphalt pavement on a second-class road considering the material usage, construction, maintenance, and renovation phases was found to be 1,754 tons per kilometer. As discussed in [40], four different pavement structures were responsible for 121.86, 116.66, 104.54, and 100.59 tons of CO_2e emission from 1 km of road, during the stages of extraction, production, transportation, and construction. The different pavement structures constituted: aggregates, bitumen, and cement; aggregates, bitumen, and polymer-modified asphalt; aggregates and bitumen; and aggregates with recycled asphalt, respectively. Similarly, a study in [32] assessed and calculated emissions, considering various phases such as raw material production, mixing, transportation, laying, compacting, and curing. The total CO_2e emissions for the 20 km asphalt pavement construction was found to be 52,264,916.06 kg.

A study [41] found that the construction management plan is the most critical criterion for achieving green highway development, followed by quality management. According to [42], emission reduction technologies for materials include using recycled materials like rubber asphalt and reclaimed asphalt pavement, and replacing traditional materials with alternatives like bio-bitumen. For the construction phase, emissions can be reduced by adopting warm, half-warm, or cold asphalt manufacturing techniques, substituting energy sources such as using natural gas as fuel for asphalt plants, and using biodiesel or hybrid and electric-powered construction equipment. Recycling technologies like hot-in-place and cold-in-place recycling also contribute to emission reduction. As discussed in [43] use of Reclaimed Asphalt Pavement (RAP) and recycled concrete as alternative materials are acceptable in various pavement systems and applications. Incorporating RAP in asphalt base and sub-base layer construction can significantly lower environmental impacts, including a 20% reduction in global warming potential and 16% in energy use [44]. Also, a study [45] found that asphalt mixed with 18% crumb rubber using wet technology showed a carbon emission reduction of 36% to 44% compared to standard asphalt mixtures. Another study [46] demonstrated that incorporating RAP with HMA could lower CO_2 emissions by 6.8%. As discussed in [47] the Hot Mix Asphalt (HMA) requires high production temperatures (155–165°C), leading to increased greenhouse gas emissions, which contribute to global warming and harm workers' respiratory health. Warm Mix Asphalt (WMA) technology lowers the mixing and compaction temperature by about 30°C compared to HMA, offering benefits such as fuel savings. Another study [48] showed that WMA can reduce GHG emissions by 20% compared to HMA. Also, study [49] found that using biomass-based fuel for construction equipment can reduce carbon emissions by 36% to 90%, while electrified construction equipment can achieve a 67% to 95% reduction in GHG emissions.

3. Methodology

3.1. **Study Area.** The Pokhara-Mugling Road, chosen for this study, is a section of the Prithvi Highway, classified as National Highway H04 according to Department of Roads (DoR)(see FIGURE 1). The road plays a crucial role in enhancing tourism in the western regions of Nepal. This route starts at the right bank of the Trishuli River, near the new bridge site in Mugling, Tanahun District, and extends approximately 88.810 kilometers to Sahid Chowk in Pokhara Bazar, Kaski District. However, for this study two sections of road were considered from Ch. 8+250 to Ch. 49+700 (section-01) and from Ch. 49+700 to Ch. 88+583 (section-02), totaling 80.333 km. The geometric design standard for this road generally has been followed as for the Class II Road under Nepal Road Standard (NRS) 2070. This road is being designed for a speed of 60 kilometers per hour (kmph) based on the terrain. Road is a four-lane highway. The pavement material is asphalt concrete.

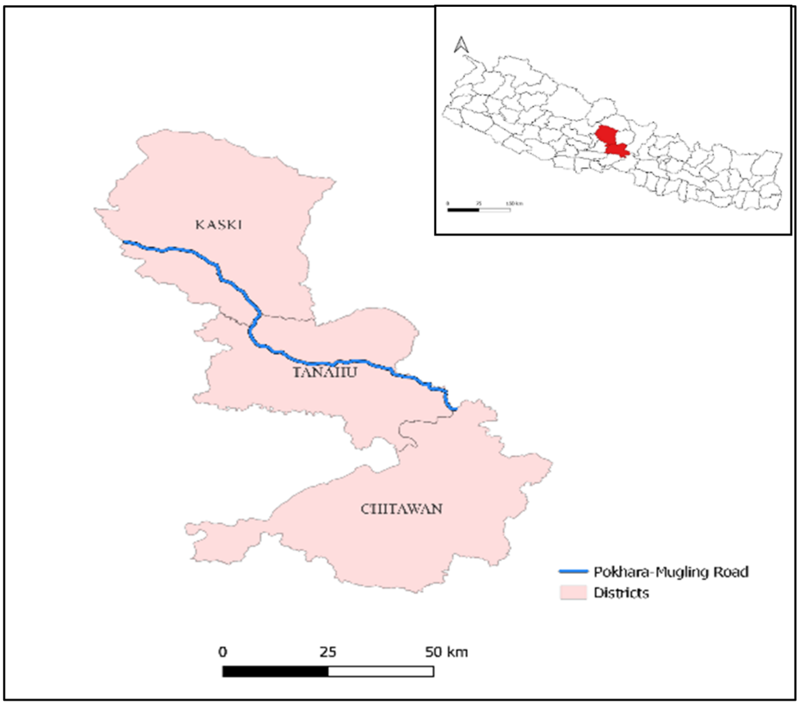

FIGURE 1. Pokhara-Mugling Road.

3.2. **Data Analysis.** LCA method was employed to analyze and quantify GHG emissions associated with the road construction project. LCA provides a detailed framework for assessing the environmental impacts of the project by considering relevant stages from material extraction to construction. The analysis focuses on the gate-to-gate system boundary, which encompasses emissions related to material use and construction activities. Emissions from the material extraction and transportation from the extraction to the construction sites are not considered for this study. LCA includes the following stages:

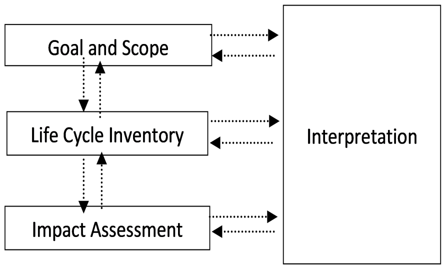

FIGURE 2. Life cycle assessment frame work [50]

3.2.1. *Goal and Scope Definition.* In the case study, GHG emissions were regarded as the primary environmental indicator. Therefore, the scope of the study has been designed to incorporate GHG emissions as the environmental indicator. For this stage of the Pokhara-Mugling road project, the LCA method will focus exclusively on the construction phase. To align with the objective of evaluating the environmental impacts of highway construction, the study considers GHG emissions within a gate-to-gate system boundary. Within this system boundary, the case study takes into account GHG emissions related to materials and construction machinery. The gate-to-gate LCA approach focuses specifically on the construction stage, capturing emissions generated from the production, as well as the energy consumed by construction equipment. In this study, lane-kilometer was chosen as the functional unit, and the total greenhouse gas emissions were quantified in tons of CO2e per lane-kilometer.

3.2.2. *Life Cycle Inventory Analysis.* The Life Cycle Inventory (LCI) stage of an LCA for the Pokhara-Mugling road involves a comprehensive identification and quantification of all environmentally relevant inputs and outputs throughout the construction process using mass and energy balance approaches. This phase includes a detailed collection of data on material inputs (such as aggregates, bitumen, and fillers), energy use (including fuel consumption for machinery and electricity for operations), and outputs like air emissions. The inventory captures data specifically during the construction stage of the road's life cycle that is it includes on-site activities.

3.2.3. *Impact Assessment.* In LCA study of carbon emissions for the Pokhara-Mugling road construction, the impact assessment is limited to environmental aspects. The evaluation specifically targets the GWP, which measures the road's contribution to climate change by assessing the greenhouse gas emissions associated with various construction stages and materials used.

3.3. **Calculation Formula.** The standard method for estimating GHG emissions used in this inventory involves applying the formula provided by the IPCC in its 2006 guidelines [51]:

$$\text{Emission} = \sum_{i=1}^{n} (Ac \times EF)_i, \tag{1}$$

Where,
EF = emission factor

Ac denotes the activity i, with i indicating various activity types (1, 2, 3, ..., n).
EF represents the amount of GHG emissions generated per unit of activity.
Ac represents the activity level measured in units that match the emission factor. Activity data indicates the extent of human activity that leads to emissions or removals over a specific period.

3.4. **Relative Importance Index.** This approach facilitates the identification of the most suitable options for minimizing greenhouse gas emissions in road construction by systematically assessing the relative significance of each alternative. The Relative Importance Index (RII) was employed to evaluate and prioritize various methods, techniques, and alternatives that can effectively reduce emissions in road construction. For the RII analysis, a questionnaire was sent to experts selected based on their experience in road construction, construction management, and environmental sustainability. The respondents included environmental specialists, highway engineers and consultants, with some directly involved in the Pokhara–Mugling road project. Responses were received from 15 respondents and used for RII analysis. The formula for calculating RII is outlined by [52, 53] as follows:

$$\text{RII} = \frac{\sum W}{A \times N} = \frac{5N_5 + 4N_4 + 3N_3 + 2N_2 + 1N_1}{5N}, \quad (2)$$

Where,
W represents the weight assigned to each variable by respondents, on a scale ranging from 1 to 5.
N_1, N_2, N_3, N_4, and N_5 represent the number of respondents for strongly disagree, disagree, neutral, agree, and strongly agree, respectively.
A is the maximum weight assigned, which is 5.
N represents the total number of respondents.

4. Results and Discussion

4.1. Carbon Emission During the Construction of Road.

4.1.1. *Material Specific Emission.* Among primary materials used in asphalt road construction, aggregate was the most extensively used, with a total consumption of 3,115.88 kilotons, followed by bitumen, which amounted to 27.61 kilotons. Filler materials were utilized in the smallest quantity, totaling only 5.39 kilotons. The analysis demonstrated that aggregate constituted approximately 99% of the total weight of the materials used in pavement construction. However, despite its dominant presence by weight, aggregate was responsible for only 42.50% of the total greenhouse gas (GHG) emissions associated with these materials. In contrast, bitumen, which represented just 1% of the total weight, accounted for a substantial 57.40% of the total GHG emissions, as presented in Table 2. This disparity highlighted the significant environmental impact of bitumen relative to its weight in the asphalt mix. It is crucial to note that this study does not include considerations for the use phase, maintenance phase, or end-of-life stage of the pavement.

4.1.2. *Emission from Use of Plants and Equipment.* **The figure** shows the fuel consumption for hot mix asphalt plants and other equipment as well as total fuel consumption by plants and equipment for Pokhara - Mugling road construction. Hot mix asphalt plants consumed the largest portion of the total fuel usage (hot mix asphalt plant consumed a

TABLE 2. GHG emission from the materials based on their consumption for pavement construction.

S.N.	Materials	GHG Emission ($ktCO_2e$)	Percentage Contribution
1	Aggregate	8.724	42.50%
2	Bitumen	11.76	57.40%
3	Filler	0.015	0.10%
	Total	**20.499**	

TABLE 3. GHG emission from plants and equipment used in pavement construction.

S.N.	Plants and Equipment	Total GHG Emission ($ktCO_2e$)	Percentage
1	Hot mix asphalt	9.28	70%
2	Other equipment	3.95	30%
	Total	**13.23**	

total of 3425.42 kilolitres of fuel). This significant consumption highlighted the energy-intensive nature of asphalt production, where fuel was required for heating and mixing materials. In comparison, all other construction equipment collectively consumed 1,457.15 kilolitres of fuel. Among these, rollers (vibratory, pneumatic, and smooth-wheeled) were the dominant consumers at 552.27 kl, followed by motor graders (281.75 kl), loaders (174.21 kl), and paver finishers (132 kl). Other machinery, including generators, tractors with rippers, bitumen distributors, air compressors, boilers, mechanical broomers, and tippers, contributed comparatively smaller amounts. Notably, the hot mix asphalt plant was responsible for 70% of the total emissions from plant and equipment operation. In contrast, all other equipment involved in asphalt pavement construction collectively contributed for the remaining 30% of the emissions (Table 3). These findings highlighted the substantial impact of the hot mix asphalt plant on the overall carbon footprint of the construction process.

4.1.3. *Total Carbon Emission.* The emissions from material usage were found higher than those generated by the operation of plants and equipment during construction. The total emission from the pavement construction was found to be 33.73 kilotons of CO_2 equivalent ($ktCO_2e$) as shown in Figure III. A substantial portion of these emissions, 20.50 $ktCO_2e$ (accounting 60.78% of total emission), originated from the materials used, underscoring their considerable impact on the overall carbon footprint. In contrast, the emissions resulting from the use of plants and equipment were found to be 13.23 $ktCO_2e$; accounting for about 39.22% of the total emission during pavement construction. The results show that the material consumption contributes significant GHG emission in total for pavement construction compared to the emissions from the use of plants and equipment.

The gate-to-gate analysis for the Pokhara-Mugling road construction revealed that the total emissions amounted to 419.9 tonnes of CO_2e per kilometer of road. This assessment considers the emissions generated from the material use and operation of plants and equipment during the pavement construction but excludes any emissions from the use phase, maintenance activities, and the road's end-of-life stage. The per km emission from Pokhara-Mugling road compared to the study conducted by Araújo et al. [40] is relatively higher even without considering the material extraction, production and transportation

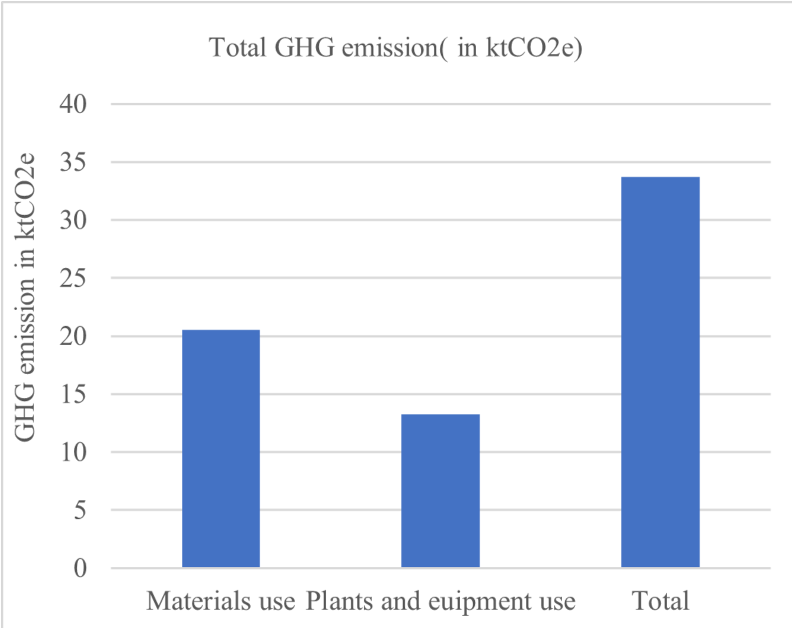

FIGURE 3. Total GHG emission from pavement construction of Pokhara Mugling Road.

TABLE 4. Carbon emission in different phases of asphalt surface construction

Phase	**Mixing Phase**	**Laying Down Phase**	**Compacting Phase**
CO_2e Emissions (kg)	22,668,564.44	588,189.39	641,448.20

stages.

4.2. **Emission from the Different Stages of Pavement Construction.** The total greenhouse gas emissions, measured across different stages of road construction, showed that the emissions from subgrade preparation amounted to 2.84 KtCO_2e, making it the stage with the lowest emissions. The sub-base and base stage followed with emissions of 6.99 KtCO_2e. However, the binder and wearing course stages contributed the highest emissions at 23.90 KtCO_2e. This indicates that binder and wearing courses, particularly due to the use of HMA plants and bitumen, have the most significant impact on the overall carbon footprint of road construction. In the construction of asphalt binder and wearing course, however, the largest CO_2e emission was found during the mixing phase, followed by the compacting phase and least during the laying phase, as shown in Table 4. This high emission level during the mixing phase is largely attributed to the energy-intensive processes involved in heating and mixing the materials (aggregates and binder). The machinery and fuel consumption needed for this stage are considerable, leading to its large environmental impact. The compacting phase comes second in terms of emissions, while the laying down phase has the least environmental impact.

4.3. **Sensitivity Analysis.** Sensitivity analysis was conducted to assess how variations in bitumen and aggregate content affect total GHG emissions. The findings of this study indicate that a 10% reduction in bitumen percentage results in a 3.49% decrease in total

TABLE 5. Probable mitigating measures with RII value and their rank

Probable Mitigating Measures	RII	Rank
Optimizing construction and quality management plans is essential for reducing GHG emissions in road construction.	0.853	1
Using electricity as a fuel source for heating in asphalt production could substantially lower emissions compared to traditional fossil fuels.	0.813	2
Adopting warm mix or cold asphalt mix technologies in current road construction practices is practical and beneficial for reducing emissions.	0.747	3
The use of recycled materials like Reclaimed Asphalt Pavement (RAP) and crumb rubber in asphalt mixtures is feasible in Nepal's road construction projects.	0.747	3
Transitioning to low-emission equipment such as electric or biodiesel-powered machinery is achievable in large-scale projects like the Pokhara-Mugling road.	0.733	5
Using alternative energy sources, such as natural gas or biomass-based fuels, for asphalt plants could significantly reduce carbon emissions.	0.720	6

GHG emissions (33.73 ktCO_2e). Conversely, increasing the bitumen percentage by 10% and 20% leads to increases in total GHG emissions of 3.49% and 6.97%, respectively. Similarly, changes in the aggregate percentage were examined for their impact on GHG emissions. A 10% decrease in aggregate percentage corresponds to a 2.59% reduction in total GHG emissions. On the other hand, increasing the aggregate percentage by 10% and 20% results in increase in GHG emissions by 2.59% and 5.17%, respectively. Overall, the sensitivity analysis clearly demonstrates that variations in bitumen content have a significantly larger impact on total GHG emissions compared to changes in aggregate content, with bitumen adjustments causing nearly 1.35 times the percentage change in emissions. This finding highlights the critical role of bitumen in influencing the carbon footprint of road construction.

4.4. **Probable Mitigating Measures.** The RII analysis identified and ranked the most effective measures for reducing GHG emissions in the Pokhara-Mugling road project. Optimizing construction and quality management plans ranked highest, followed by using electricity for asphalt heating as a cleaner alternative to fossil fuels. Adopting warm or cold asphalt mix technologies and incorporating recycled materials such as RAP and crumb rubber were equally ranked in third place. Transitioning to low-emission equipment was placed fifth, while alternative energy sources like natural gas and biomass for asphalt plants ranked sixth. These results highlight that improving construction management, shifting to cleaner energy, and promoting material reuse are key strategies for minimizing emissions in road construction projects in Nepal.

5. Conclusion and Recommendations

5.1. **Conclusion.** The study reveals that materials contribute significantly more to GHG emissions compared to the plants and equipment used in the pavement construction process. Among the materials, bitumen emerges as the primary source of emissions compared to aggregate and filler materials. The analysis revealed that the total carbon emissions per lane km from the Pokhara-Mugling Road construction are higher compared to similar studies conducted in other countries where electricity was used as source of energy to heat asphalt or alternative pavement structures such as aggregates and recycled asphalt was used. The sensitivity analysis results emphasized the significant impact of bitumen on the carbon footprint of road construction, underscoring the importance of implementing targeted reduction strategies specifically aimed at minimizing bitumen usage. To address this, exploring alternative materials such as aggregate with recycled asphalt could be an effective strategy for lowering overall emissions. Additionally, the analysis indicates that the hot mix asphalt plant is the largest contributor to GHG emissions among all the equipment and plants involved in the construction process, as they consume more fuel. And the RII analysis indicated that the most effective measures are optimizing construction and quality management plans and using electricity for asphalt heating as a cleaner alternative to fossil fuels.

5.2. **Recommendations.** To mitigate the emissions from road construction, this study recommends exploring alternative energy sources, such as renewable energy, natural gases for the operation of hot mix plants or adopting WMA technology. Transitioning to low-emission construction equipment, such as biodiesel or electric-powered machines, might also contribute to emission reductions. Moreover, this study also finds effective construction and quality management plans as essential measures for minimizing environmental impacts. Implementing these approaches can be key to reducing the overall greenhouse gas emissions from road construction and promoting sustainable road infrastructure development in Nepal.
Future research should extend beyond construction phase to include the full life cycle of highways, encompassing maintenance, operation, and end-of-life phases. Likewise, the alternative construction such as rigid pavement should be explored in terms of their environmental impact in the future.

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