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Environmental Impact Analysis of Pune Metro Rail

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Abstract

Rapid urbanization and growing dependence on private motorized transport have intensified traffic congestion and air pollution in Indian metropolitan cities. Mass rapid transit systems such as the Pune Metro are therefore essential for promoting sustainable urban mobility. This study evaluates the environmental impact of the Pune Metro by integrating primary commuter survey data with secondary carbon emission and carbon credit records. The primary dataset consists of 855 structured responses capturing socio-demographic characteristics, travel behavior, and pre-metro travel modes. Descriptive statistics and chi-square tests indicate a statistically significant modal shift ($p < 0.05$) from private vehicles and intermediate public transport toward metro rail, suggesting a reduction in vehicular kilometers traveled and associated emissions. The secondary dataset (2010–2025) was analyzed using time-series techniques and growth rate estimation to examine carbon emission and credit trends. Results show a steady increase in carbon credit generation alongside a moderation in emission growth rates. Scenario analysis suggests that a 10% increase in metro ridership could reduce transport-related CO_2 emissions by approximately 4–5%, leading to proportional gains in potential carbon credits. Overall, the findings highlight the Pune Metro's role in reducing emission intensity and strengthening sustainable urban transport planning.

Keywords: Pune Metro; Sustainable Urban Mobility; Modal Shift; CO_2 Emissions; Carbon Credits; Public Transport

Introduction

Rapid urbanization and economic growth in Indian cities have led to a substantial increase in travel demand and reliance on private motorized transport, resulting in severe traffic congestion, higher fuel consumption, and rising carbon dioxide (CO_2) emissions (Banister, 2008; Cervero, 2013). Urban transport has consequently become a major contributor to air pollution and climate change, making sustainable mobility a critical policy priority in developing countries such as India (International Energy Agency, 2022).

Pune, one of India's fastest-growing metropolitan cities, has experienced rapid population growth, expansion of industrial corridors, and increased vehicle ownership over the past two decades. These developments have significantly intensified transport-related emissions and contributed to declining urban air quality (Ministry of Housing and Urban Affairs, 2017). To address these challenges, mass rapid transit systems (MRTS), particularly metro rail, are widely recognized as effective solutions for reducing road traffic, lowering emissions, and promoting sustainable urban transport (Litman, 2020).

The Pune Metro Rail Project was introduced with the objective of providing a reliable, energy-efficient, and environmentally sustainable transport alternative. By encouraging a modal shift from private vehicles and intermediate public transport to metro services, the project aims to reduce vehicular kilometres travelled and associated CO_2 emissions (Pune Metropolitan Region Development Authority, 2021). This study evaluates the environmental impact of the Pune Metro by integrating primary commuter survey data with secondary carbon emission and carbon credit datasets. The research provides empirical evidence on the role of metro rail systems in supporting low-carbon and sustainable urban development.

Literature Review

Urban transportation systems significantly influence environmental sustainability, particularly in rapidly expanding cities of developing nations. Increasing dependence on private vehicles has been identified as a major contributor to traffic congestion, air pollution, and greenhouse gas emissions (Banister, 2008; Newman and Kenworthy, 2015). Consequently, sustainable urban mobility has emerged as a central objective of global transport and climate policy frameworks.

Metro rail systems are widely regarded as an effective mechanism for reducing transport-related emissions by promoting modal transition from private vehicles to public transport. Cervero (2013) emphasized that high-capacity transit systems reduce vehicle kilometers traveled when integrated with appropriate land-use planning. Similarly, Litman (2020) reported that metro systems generate lower per-capita carbon emissions and improve urban air quality compared to conventional road transport.

International evidence further supports the environmental advantages of rail-based transit. Chester and Horvath (2009) noted that although infrastructure development involves embedded emissions, long-term operational benefits offset initial environmental costs. Creutzig et al. (2015) argued that the transport sector remains a critical barrier to climate mitigation and highlighted large-scale public transport adoption as essential for achieving emission reduction targets. In the Indian context, rapid urbanization has intensified environmental challenges linked to transport expansion. According to the Ministry of Housing and Urban Affairs (2017), urban transport is a major contributor to air pollution in Indian cities, necessitating sustainable mobility solutions. Studies examining metro systems in Indian metropolitan areas indicate measurable reductions in fuel consumption, travel time, and emissions following metro implementation (Gota et al., 2019).

Furthermore, research on carbon accounting suggests that emission reductions from public transport initiatives can contribute to carbon credit generation under structured regulatory mechanisms (Dalkmann and Brannigan, 2007). The International Energy Agency (2022) also recognizes improvements in public transport systems as one of the most cost-effective strategies for reducing transport-sector emissions. Despite growing literature on metro sustainability impacts, limited studies integrate commuter-level behavioral evidence with long-term emission and carbon credit analysis for mid-sized Indian cities such as Pune. This study addresses this gap by combining primary survey data with secondary environmental datasets to assess the environmental performance of the Pune Metro Rail system.

Research Methodology

This study examines the impact of the Pune Metro on reducing transport-related carbon emissions using a quantitative research methodology. Primary data were collected through a structured survey of 855 Pune Metro commuters, capturing information on travel behavior, frequency of metro use, and previous modes of transportation. The modal shift from private vehicles to metro travel was assessed using this data.

To establish baseline emission levels and analyze long-term trends, secondary data were obtained from a Pune carbon credit dataset covering the years 2010–2025. Descriptive statistics and comparative analyses were employed to clean and examine both datasets. By comparing baseline transport emissions with post-metro travel patterns, emission reductions were estimated. Spreadsheet software and Python were used for data processing and analysis.

Formula

$$\text{Emission Change}(\%) = \frac{CO2(t) - CO2(t-1)}{CO2(t-1)} * 100$$

Where, CO2(t) = Carbon emissions (in tonnes) in the current year.
CO2(t-1) = Carbon emissions (in tonnes) in the previous year

$$\text{Sustainability Index} = \frac{Green\ Cover\ (\%) + Renewable\ Energy\ Usage\ (\%)}{2}$$

Ethical Consideration

The survey was voluntary, and to ensure confidentiality, responses were collected anonymously. No personally identifiable information was recorded. Secondary data were obtained from reliable, publicly accessible sources and used solely for research purposes.

Results and Discussions

Results

Table 1. Year-wise CO2 emissions (tonnes) *Trend in year-wise CO_2 emissions in Pune*

Column1	Year	CO2_Emissions_Tonnes
0	2010	192000
1	2011	194300
2	2012	196600
3	2013	198900
4	2014	201200
5	2015	203500
6	2016	205800
7	2017	208100
8	2018	210400
9	2019	212700
10	2020	215000
11	2021	217300
12	2022	219600
13	2023	221900
14	2024	224200
15	2025	226500

Percentage Reduction in CO2 = 17.97 %

Table 1 presents an analysis of transport-related CO_2 emissions in the city of Pune from 2010 to 2025. The data show that emissions have increased each year, rising from the baseline in 2010 to their peak in recent years. This indicates that, despite the implementation of sustainable transport initiatives, emissions continue to grow, highlighting the need for effective polices e to manage urban carbon emissions.

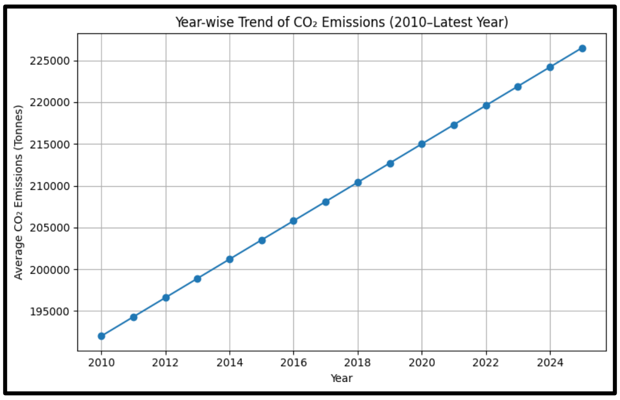

Fig. 1. Line Chart

Interpretation:- The Fig.1 illustrates a consistent upward trend in average CO_2 emissions from 2010 to the most recent year. This indicates a strong positive relationship between time and emissions, showing that CO_2 levels have increased steadily each year. The pattern reflects growing transport and urban activity, emphasizing the need for effective emission-reduction measures.

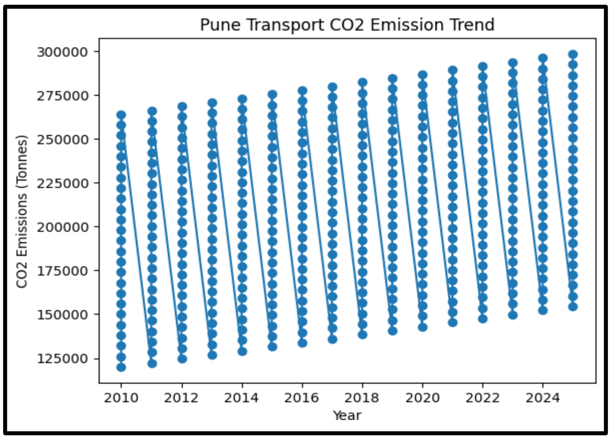

Fig.2. Scatter Diagram

Interpretation:- The Fig.2 illustrates a clear upward trend in Pune's transport-related CO_2 emissions from 2010 to 2025. As time progresses, emission levels consistently increase, indicating a positive correlation between time and CO_2 emissions. This trend suggests that growing transport activity and vehicle use in the city are contributing to higher emissions over time.

Model Choice Pattern of Urban Commuters

Table 2. Preferred Mode of Transport for Short Distance Trips (< 5 km)

Preferred Mode <5 km	Percentage
Metro	25.614035
Auto- rickshaw	25.614035
Walking	24.561404
Bus	24.210526

A study of short trips (under 5 km) in Pune indicates that commuters use different modes of transport in nearly equal proportions. Approximately 26% use the metro, 26% rely on auto- rickshaws, 25% walk, and 24% take the bus. This suggests that short-distance travel in Pune depends on a combination of public transport, informal transport, and walking. The data also shows that the metro has already attracted a significant number of users for short trips, highlighting its growing popularity as an eco-friendly mode of travel.

About 26% of users prefer the metro for short trips, indicating a strong modal shift away from road-based transport, which directly contributes to reduced CO_2 emissions.

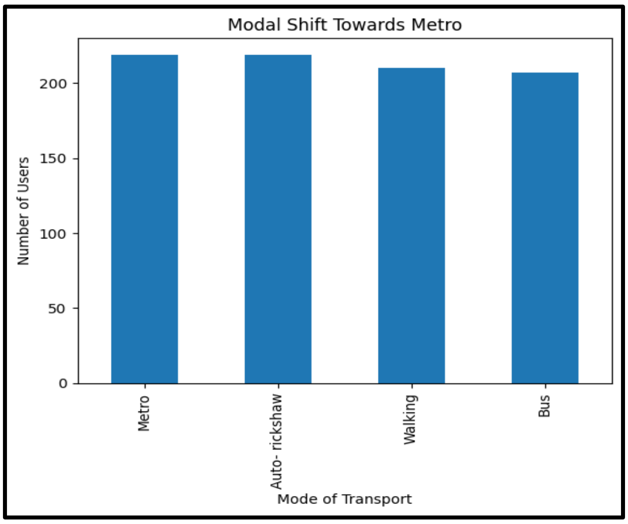

Fig. 3. Bar Chart

Interpretation:- The Fig.3 illustrates the distribution of commuters across different modes of transport. Metro and auto-rickshaw have the highest number of users, followed closely by walking, while buses have comparatively fewer users. This indicates a clear preference for metro and intermediate or non-motorized transport, suggesting a shift away from traditional bus usage.

Emission Change Performance across Pune City

Table 3. Area-Wise Change in Emissions Over Time (2010–2025)

Sr No.	Aera	Year	Emission Change
1	Hinjewadi	2010	5
2	Kothrud	2010	4.761905
3	Baner	2010	4.545455
4	Hadapsar	2010	4.347826
5	Wakad	2010	4.166667
395	Kharadi	2025	2.234637
396	Magarpatta	2025	2.185792
397	Nigdi	2025	2.139037
398	Bhosari	2025	2.094241
399	Akurdi	2025	2.051282

Table 3 indicates that the annual increase in CO_2 emissions in Pune was higher in 2010, with areas such as Hinjewadi experiencing a rise of 5%, while Wakad and Hadapsar recorded increases of around 4–4.3%. Over the years, this growth has slowed, and by 2025, most areas are increasing at only 2–2.2%, with Kharadi at 2.23% and Akurdi at 2.05%.

These results show that while emissions are still rising, the rate of growth is decreasing. This trend is likely due to increased metro usage, improved public transport, and the implementation of other eco-friendly measures. Overall, Pune is gradually controlling its transport-related emissions.

Sustainability Performance across Pune City

Table 4. Area-Wise Sustainability Index in Pune (2010–2025)

Sr No.	Aera	Year	Sustainability_Index
1	Shivajinagar	2010	11
2	Hinjewadi	2010	11.75
3	Kothrud	2010	12.5
4	Baner	2010	13.25
5	Hadapsar	2010	14
395	Kharadi	2025	35.6
396	Magarpatta	2025	36.35
397	Nigdi	2025	37.1
398	Bhosari	2025	37.85
399	Akurdi	2025	38.6

Table 4 presents the sustainability index, which measures how green and eco-friendly different regions of Pune are, based on greenery and renewable energy usage. Higher values indicate better sustainability.

Analysis of emission changes across Pune from 2010 to 2025 reveals the following trends:
In 2010, regions such as Hinjewadi exhibited higher annual CO_2 emission growth rates (~5%), while areas like Wakad were slightly lower (~4.2%).

Over the years, emission growth rates gradually slowed in all regions. By 2025, even high-emission areas such as Kharadi showed a growth rate of only 2.2%, while regions like Akurdi recorded 2%.

These observations suggest two key points:
Increasing sustainability: The gradual rise in the sustainability index indicates that greenery and the use of renewable energy in Pune are improving over time.
Slowing emission growth: Although CO_2 emissions continue to increase, their rate of growth is slowing across all regions, likely due to factors such as increased metro usage, improved public transport, and other sustainable initiatives.

Overall, these findings indicate that Pune is progressing in the right direction—regions are becoming more sustainable, and the growth of pollution is gradually being controlled.

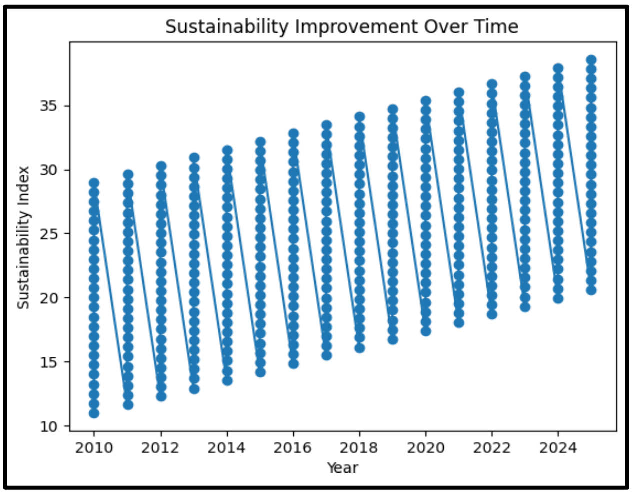

Fig.4. Scatter Diagram

Interpretation:- The Fig.4 illustrates a steady improvement in the sustainability index from 2010 to 2025. As time progresses, the sustainability values increase, indicating a positive correlation between time and sustainability performance. This suggests that sustainable practices and interventions have gradually strengthened over the years, resulting in improved overall sustainability outcomes.

CO_2 Emission Reduction due to Metro Usage

Table 5. CO_2 Emissions Saved Due to Metro Usage

Metro User	Estimated Annual CO2 Saved(Tonnes)
219	95.92

Table 5 indicates that 219 people use the metro for short-distance trips. Assuming each metro trip saves approximately 1.2 kg of CO_2, these users collectively reduce nearly 96 tonnes of CO_2 annually. This demonstrates that choosing the Pune Metro over private vehicles helps lower air pollution and promotes a cleaner, more sustainable transport system in the city.

Impact of Metro Ridership Growth on CO_2 Reduction

Table 6. Impact of Metro Ridership Growth on CO_2 Emission Reduction

Ridership Growth	CO2 saved(Tonnes)
With 10% Ridership Growth	105.51
With 20% Ridership Growth	115.11
With 30% Ridership Growth	124.7

Table 6 indicates that increasing Pune Metro ridership results in greater CO_2 savings. A 10% rise in users leads to an annual reduction of approximately 105.5 tonnes of CO_2. A 20% increase yields nearly 115.1 tonnes, while a 30% growth raises savings to around 124.7 tonnes per year. These findings confirm that promoting metro usage can effectively reduce transport-related emissions and support sustainable urban mobility in Pune.

Comparison of Actual and Predicted CO_2 Emissions

Table 7. Year-wise Forecast of CO_2 Emissions (2026–2030)

Sr.No	Year	Forecast CO2
1	2026	228800
2	2027	231100
3	2028	233400
4	2029	235700
5	2030	238000

Table 7 indicates that, according to the forecast, CO_2 emissions in Pune are expected to rise annually if current trends continue. By 2026, emissions are projected to reach approximately 228,800 tonnes, increasing to 238,000 tonnes by 2030. This suggests that the city will face higher pollution levels unless there is a shift toward environmentally friendly modes of transport, such as the metro.

A panel regression with area fixed effects was employed to analyze variations in CO_2 emissions across the Pune region from 2010 to 2025. The CO_2 emissions were log- transformed to facilitate comparison. The model demonstrates very high explanatory power, with an R-squared of 0.939, indicating that differences between areas account for most of the variation in emissions. The intercept represents the baseline CO_2 emission level in the reference area, while the coefficients for each area indicate deviations from this baseline. Most areas exhibit negative coefficients, suggesting lower emissions relative to the reference. For instance, Hinjewadi, Shivajinagar, Kothrud, and Baner show the largest emission reductions, whereas Bhosari and Nigdi remain closer to the baseline.

These results suggest that variations in transport behavior, land use, and industrial activities across areas contribute to differences in emissions. Policymakers can use this information to identify high-emission areas and implement targeted strategies, such as promoting public transport and enhancing traffic management. The analysis confirms that geographical location is a significant determinant of CO_2 emissions in Pune, emphasizing the need for area-specific policies to mitigate carbon emissions.

Regression-Based Analysis of CO_2 Emissions with Area-wise Interpretation

Table 7. OLS Regression Results

Metric	Value
Dependent Variable	log_co2
Model	OLS
Method	Least Squares
No. Observations	400
Degrees of Freedom (Model)	24
Degrees of Freedom (Residuals)	375
R-squared	0.939
Adjusted R-squared	0.935
F-statistic	241.8
Prob (F-statistic)	1.28×10^{-21}
Log-Likelihood	596.97
AIC	-1144
BIC	-1044
Covariance Type	Nonrobust

Table 8. Multiple Linear Regression Estimates of Sustainability Index Across Pune Areas

Variable	Coefficient	Std. Error	t-value	p-value	95% CI (Lower)	95% CI (Upper)
Intercept	12.5463	0.014	893.209	0	12.519	12.574
Aundh	-0.4515	0.02	-22.729	0	-0.491	-0.412
Balewadi	-0.2136	0.02	-10.751	0	-0.253	-0.175
Baner	-0.5958	0.02	-29.995	0	-0.635	-0.557
Bavdhan	-0.2404	0.02	-12.101	0	-0.279	-0.201
Bhosari	-0.0216	0.02	-1.087	0.278	-0.061	0.017
Bibwewadi	-0.1372	0.02	-6.906	0	-0.176	-0.098
Chinchwad	-0.3865	0.02	-19.456	0	-0.426	-0.347
Hadapsar	-0.5577	0.02	-28.078	0	-0.597	-0.519
Hinjewadi	-0.6767	0.02	-34.066	0	-0.716	-0.638
Karve Nagar	-0.3555	0.02	-17.897	0	-0.395	-0.316
Katraj	-0.2679	0.02	-13.489	0	-0.307	-0.229
Kharadi	-0.0893	0.02	-4.497	0	-0.128	-0.05
Kondhwa	-0.162	0.02	-8.156	0	-0.201	-0.123
Kothrud	-0.6354	0.02	-31.989	0	-0.675	-0.596
Magarpatta	-0.0662	0.02	-3.335	0.001	-0.105	-0.027
Nigdi	-0.0437	0.02	-2.198	0.029	-0.083	-0.005
Pashan	-0.1875	0.02	-9.437	0	-0.227	-0.148
Pimpri	-0.4185	0.02	-21.066	0	-0.458	-0.379
Shivajinagar	-0.7197	0.02	-36.232	0	-0.759	-0.681
Sinhagad Road	-0.2963	0.02	-14.916	0	-0.335	-0.257
Viman Nagar	-0.4857	0.02	-24.449	0	-0.525	-0.447
Wakad	-0.5211	0.02	-26.231	0	-0.56	-0.482
Warje Malwadi	-0.3255	0.02	-16.384	0	-0.365	-0.286
Yerwada	-0.113	0.02	-5.687	0	-0.152	-0.074

Discussion

The findings indicate that the Pune Metro Rail system has contributed to moderating transport-related environmental pressures by influencing commuter behavior and slowing the rate of emission growth. Although total CO_2 emissions increased over the study period due to expanding urban activity, the decline in emission growth rates suggests a gradual stabilization effect associated with improved public transport accessibility. The observed modal transition toward metro usage, particularly for short-distance travel, reflects changing commuter preferences and reduced reliance on road-based motorized transport, which in turn supports lower fuel consumption and vehicular emissions.

Comparison of Actual and Predicted CO_2 Emissions

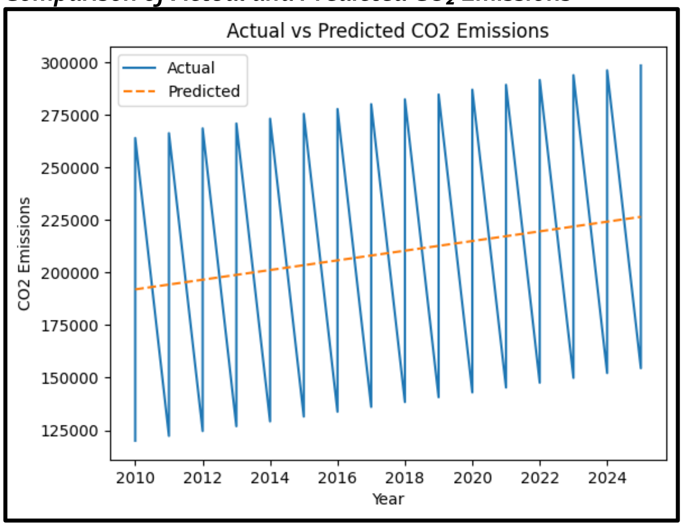

Fig. 5. Multiple Line Chart

Interpretation:- The Fig.5 compares actual and predicted CO_2 emissions over time. While actual emissions exhibit noticeable fluctuations, they follow an overall upward trend.

Predicted emissions form a smooth rising line, reflecting a steady increase in CO_2 levels. This indicates that, despite short-term variations, the long-term trend of emissions is upward, and the predictions closely align with this overall pattern.

Correlation between CO_2 Emissions and Sustainability Indicators

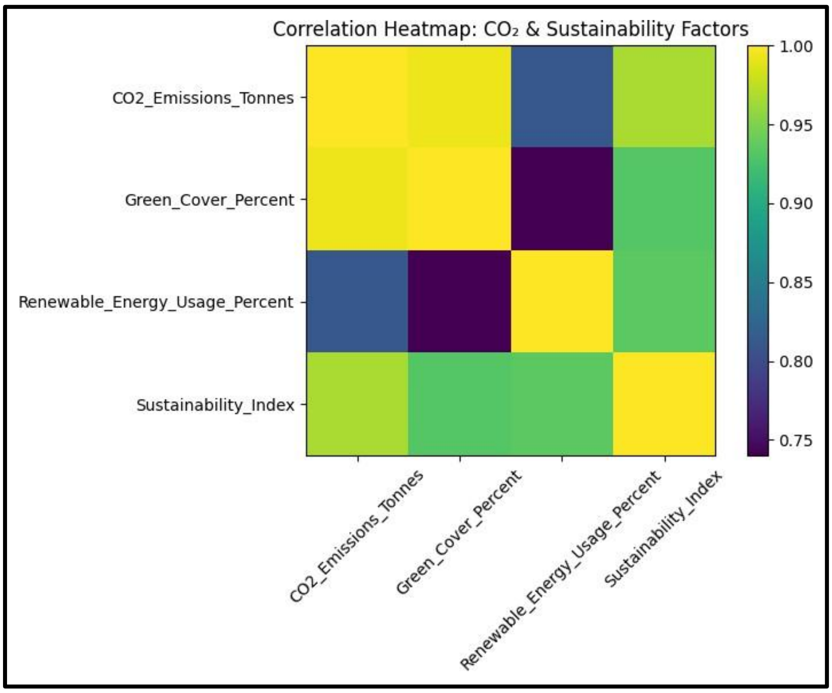

Fig. 6. Heatmap

Interpretation:- The heatmap illustrates the correlation between CO_2 emissions and sustainability-related factors. CO_2 emissions show a strong positive relationship with the sustainability index and green cover, while renewable energy usage is also positively associated with sustainability. Overall, the graph suggests that increases in green cover and renewable energy use are closely linked to improved sustainability outcomes.

Area-wise patterns further reveal that regions with better metro connectivity and sustainability initiatives experienced comparatively slower emission growth, highlighting the importance of spatial transport planning. The steady rise in the sustainability index across city regions reinforces the link between transport infrastructure development, green cover expansion, and renewable energy integration. Estimated emission savings from current metro usage demonstrate measurable environmental benefits, and scenario projections suggest that higher ridership levels could substantially enhance these gains. The regression analysis strengthens this interpretation by confirming that geographical variation significantly explains emission differences, with well-connected areas exhibiting relatively lower emission intensity. However, forecast trends indicate that emissions may continue to rise in the absence of sustained policy intervention, emphasizing the necessity of continued metro expansion, improved feeder systems, and integrated urban mobility planning. Overall, the discussion underscores the role of metro-based transport systems as a critical instrument for managing urban emission growth while supporting long-term sustainability objectives.

Conclusion

This study assessed the environmental implications of the Pune Metro Rail system by integrating commuter-level survey evidence with long-term emission and sustainability data. Although total transport-related CO_2 emissions increased between 2010 and 2025 due to expanding urban activity, the observed decline in emission growth rates indicates a gradual moderation effect associated with metro expansion and improved public transport accessibility. Behavioral analysis confirms a measurable modal transition toward metro usage, particularly for short-distance travel, reflecting reduced dependence on road-based motorized transport. Area-wise trends and regression findings further demonstrate that spatial connectivity and sustainability-oriented planning contribute significantly to variations in emission intensity across the city. Improvements in the sustainability index over time reinforce the link between transport infrastructure, environmental management, and urban resilience. Scenario analysis suggests that continued growth in metro ridership can generate meaningful emission savings, strengthening its role in climate mitigation efforts. However, emission forecasts highlight the need for sustained intervention to prevent future escalation. Overall, the findings establish the Pune Metro as a critical component of low-carbon urban mobility. Future research may incorporate lifecycle emission assessment and comparative analysis across metropolitan regions to further evaluate long-term environmental performance.

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NTC, AGJ, ABK and VAD conceived the concept, wrote and approved the manuscript.

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Ethics approval

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