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Riding the Green Rails: Pune Metro's Journey Towards Sustainable Transport

Abdulwahhab Jasim Mahdi[1], Anagha Vasant Somalkar[2]*, Saad Kadhim Ala Allah Al-Kalidy[3], Ashish Vilas Mane[4]
[1,3]Environmental Pollution Department, College of Environmental Sciences, Al-Qasim Green University, Babylon 51013 (Iraq)
[2,4]Department of Environmental Science, Fergusson College (Autonomous), Pune 004 Affiliated to Savitribai Phule Pune University, Maharashtra (India)
*Corresponding Author: anaghasomalkar25@gmail.com

Abstract: This paper ponders over the effect of development of modern metro system in Pune to decrease the air pollution and reduce the traffic congestion. The feasibility and effectiveness evaluation of Pune Metro project is carried using the data of online survey and statistical analysis of Pune Metro project. In addition, this focuses on the development of the metro systems and environmental problems of Pune, additionally, it argues for an improvement in transportation alternative. This work employs an online survey of the public to measure the public opinion in regards to the impact of the metro, and analyses of secondary data addressing the trends of ridership and cost of construction that are utilized in determining the environmental and economic outcomes. It also goes further and reachable that the Pune Metro has been very satisfied and has also perceived environmental benefits from it. However, the network and expanding to having an ambitious level of connectivity were still identified by the research where improvement is warranted. However, there is some insight in the comparative statistical analysis as regards to the various metro lines, their efficiency, costs, and consistency which propel further development. Therefore, it concludes that the Pune Metro has been able to meet some extent towards sustainable urban transport, yet a large number of network expansion with better connectivity needs to be improved upon in future.
Keywords: Congestion, Air pollution, Effectiveness, Feasibility, Environmental benefits, Network expansion

1.0 INTRODUCTION

Urban transportation plays a significant role in shaping the environmental, economic and social development of the cities, thus sustainable development of cities relies heavily on it (Moroke et al., 2019). Besides, the fast urbanisation process additionally overburdens existing transport systems in the fast-growing Indian cities including Pune (Rehena and Janssen, 2019). The industrial, educational and tourist development provided the boost to the population and spatial spread in Pune over the years 2001 to 2007 resulted in rapid increase in the population and spatial spread (Gawade, 2021). Though fast urban growth has spurred economic developments, at the same time it has contributed to the fast-growing problems of congestion, insufficient parking space, deterioration of air condition and dependence of private transport (Zhang et al., 2022). The majority of these issues stem from a denial between urban expansion and transportation planning (Zhou et al.,2019). However, infrastructure here have managed to withstand a lot of strain as the city increasingly included more private vehicles and less public transport (Gawade, 2021), nonetheless, was also able to roll out high carbon emissions and even worse, air quality. So, metro rail systems are one of the ways of transportation through urban transit that are sustainable and efficient. The fact that the design and planned extension of metro networks are not supposed to resolve mere the current transit problems but also have a capacity to serve as an appropriate response for the future urban mobility, as indicated by Chounde & Darade (2008), only makes design more important.

On this, the India is planning to develop metros in the urban places following the design based on which Kolkata, Delhi, Mumbai, Bengaluru and others have built their metros in their major cities. But building sustainable transport far exceeds a building: It is integrated with land use, financing schemes and the way commuters are picked up. But the land acquisition, the cost escalations and the modal integration remain

weak issues. One such promising strategy for the development of a metro is the Transit Oriented Development (TOD). At usage, TOD facilitates walkability and high density developments around these transit stations and thereby helps reducing a car use and corresponding fall in the emissions (Mithe & Patil, 2013). Though unevenly implemented in India, it has all the makings of an idea with great potential. Metros are also perceived globally to boost the environmental health, road safety and public welfare. According to Lin et al., (2024) and Ortúzar, (2019), these are policies that discourage too much of car use and makes public transit more attractive. This paper investigates Pune metro's potential of delivering sustainable mobility via an evaluation of metro's environmental, infrastructural and societal implications within integrated planning framework.

Table 1: Insights from other Studies and Key Findings

Study Title	Key Findings
Strategic Management of Metro Systems: Enhancing Sustainability	Metro systems encourage e-scooters and e-bikes integration to promote sustainable transport as they help provide last mile connectivity (Tiwari, 2024), though there are problems arising out of lack of infrastructure and other regulatory challenges that hinder its success. The strategy of 'avoid shift improve' is to reduce the use of private vehicles in
Transition Towards Sustainable Mobility: The Role of Transport optimization	Urban centers by encouraging adoption of public transport and other non-motorized modes of transport which the metro systems are to play a major role as these are efficient and low emission travel alternatives (Turan et al., 2024).
Smart Travel and Sustainable Mobility for Green Transport Cities	The other model achieves better urban sustainability in linking Bike, Bus, Metro as well as Walking (BBMW) methods to transit oriented development and demand management (Chang & Hsu, 2014).
The Transition Pathways to Sustainable Urban Mobility: Could They Be Extended to Megacities	The need of a holistic planning and an integrated transport system in which metro systems are involved is to achieve sustainable mobility, reduce environmental impact in the process and improve the urban life (ReyTienia et. al, 2024).
Improving Metro Access in India: Evidence from Three Cities	The paper explores commuter profiles and last mile choices in Indian metro networks, and second, it swipes a degrowth perspective on Indian urban mobility networks. (Mukherjee et al., 2023).
Metro Systems and Urban Development: Impacts and Implications	This research looks into optimization of metro infrastructure from the perspective of sustainability, the research topic is about how the metro systems have effects on the urban growth (Dong Lin et al., 2022).

1.1 Scope of the Study

Tthis paper provides contribution towards an effective urban transport planning in spite of rapidly growing cities like Pune. Thus, the urbanization grows, and the sustainable transport solutions are required. Based on a research, efficient metro systems improve congestion and air pollution, attract citizens to dwell in the urban areas in a sustainable way (Li, Tian, & Li, 2023). Pune Metro has been evaluated in terms of the effectiveness through case studies and the data of surveys done online. If well connected, metro really helps improve commute, lower emissions, and being an enriching learning source for Pune (Shinde et al., 2018). These results are of use to policymakers as a basis with which to formulate policies on sustainable transport policies. Based on previous studies, it is also found that Metro can be effective for the enhancement of last mile connectivity and finding the reduction in travel time. In terms

of efficiency of the project, theoretical and practical appraisal was made; and in terms of feasibility and cost effectiveness, statistical analysis of the project was conducted. From research on other metro system, it is shown that well planned metro systems are key in improving accessibility and a sustainable urban area (Lin et al., 2022). Finally, the study will help shape policies towards attainment of an efficient, an environmentally friendly transport, and a more accessible one.

2.0 METHODOLOGY

Mass transit system in Pune is built to highly cut down potential traffic congestion by reducing pollution emissions, producing a low carbon dioxide atmosphere which is minus nitrogen oxides and particulate matter. Public transportation usage can serve as a way that the city can improve air quality by the city shifting away from depending largely on private vehicles. Impact on Pune air pollution is studied on a comprehensive level for the system. Data Collection and analysis is done for the emission level and the historical trends based on the information that we get from local environmental agencies, transportation authorities, Pune municipal corporation and we also collect information about the usage patterns of transportation. Comparison of data of Pune is also compared with the case studies of other such cities that have already implemented the said transit systems. Then data are applied by statistical methods to derive meaningful insights and strong conclusions.

2.1 Primary Data

In this study a structured survey approach is used which is an effective quantitative tool for primary data collection (Nardi, 2018). The research was aimed at exploring the role of metro systems for sustainable urban transport and investigates environmental and social impacts of metro systems. The study was carried out in Pune city wherein the metro system operates and total of 204 respondents were sampled. Google Forms was used to conduct the survey and participants were collected using a cross section in all different times of the day to ensure diverse pool of participants. The topics of the questionnaire involved cleanliness, station and train maintenance, affordability, traffic reduction and commuter satisfaction. Respondents also provided their views of sustainability and connectivity as well as commented their opinion of metro fares compared to other transport modes. The fieldwork entailed making preparations for the survey tool, approaching the commuters, observing the usage patterns of the metro and collect the responses onsite. Later it used for statistical analysis to identify trends, assess impact and the performance area.

2.2 Secondary Data

The research approach of the research is scientific and the research analyzes primary survey responses with the help of secondary information from research papers, government reports and authoritative studies. Dual method analysis is advantageous for the study results as an analyst would get local detailed knowledge and overall databases on the Urban systems towards sustainable transportation. The ridership records and the metrics of metro line development and construction expenditure are analysed in order to assess the operational effectiveness as well as monetary feasibility of metro systems. This evaluation is based on the environmental effects which are determined by emission reductions of the greenhouse gases and air quality improvements and traffic congestion minimization. In this research, a complete and data driven analysis of metro systems is made as it merges the information from various sources to prove its vital place in the sustainable built transit structures. (Shaikh & Deulkar, 2015)

3.0 Result & Discussion

Table 2: Key Operational Features of the Aqua and Purple Line Metro

Alignment	Corridor	Rail Lengths	Number of stations	Construction cost
Line 1 (14 stations)	**PCMC – Swargate**	**17.4 km**	Underground -5 Elevated -9	**4911 cr**
Line 2 (16 stations)	**Vanaz – Ramwadi**	**15.7 km**	Underground -0 Elevated-16	**2217 cr**

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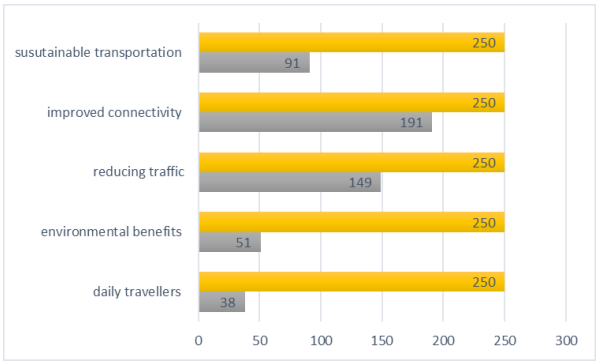

Fig 1: Positive Impact of Metro

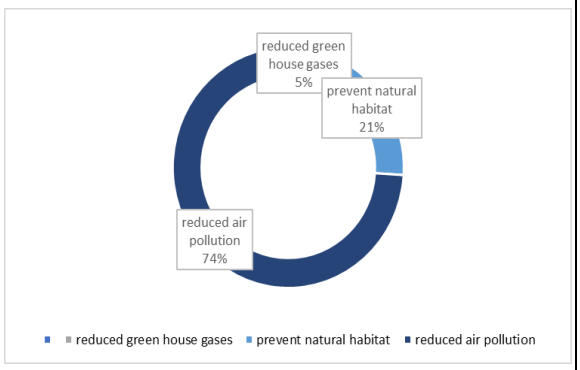

Fig 2: Environmental Benefits

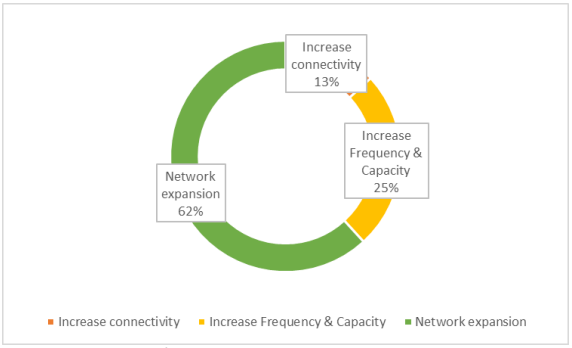

Fig 3- Area of Improvement

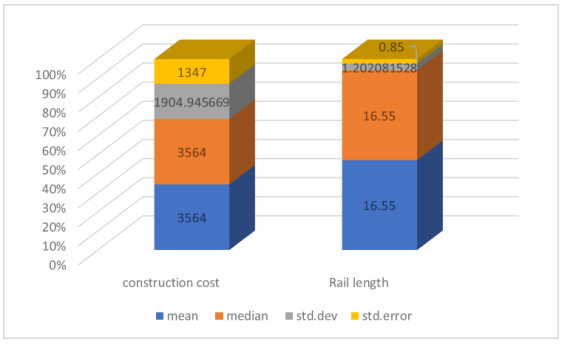

Fig 4- Descriptive Statistics

The primary data analysis indicates that the usage of metro is reasonable (47.1 %respond going occasionally, while 13.7 % never go to the metro), so the latter has still potentials for expanding usage. Time Saving (44.1%) is the factor with the highest influence in the use of metro, and secondly, followed by Cost Effectiveness (17.2%), indicating the fact that Good Convenience (Time Saving) and Good Affordability indicates are in play. In the apartments, 42.2% of the respondents feel very satisfied and 34.8% satisfied with a very good cleaniness. Its contribution to decreasing the air pollution is realized by 50.3% of the people, the same number of 72.8%, seemingly greater, are also aware of its contribution in reducing the traffic congestion. With 53.4% marking it as affordable and 40.2% very likely to call it very affordable, it does not have a lot of significance in affordability. The assertion that improved connectivity is widely noted as improving the situation is believed by the majority of respondents (see Fig. 1), as 93.1 % of those surveyed agree with having improved connectivity. In addition, 74 per cent recognise the metro as the cause of reduced air pollution while 21.1 per cent accept that it helps combat the rise in the levels of the greenhouse gas emissions. The surveyed agents suggest improvements of a basic level of service based on a basic level of service: in the last mile and travel time (13.2%), trip frequency and capacity (25%), and network expansion (52.5%) to increase accessibility. In general, public satisfaction is very high (through a score of 44.1% excellent, 53.4% good), thus showing that Bradenton significantly participates to the achievement of sustainable urban transport among the interviewed population (see Fig. 1, 2, 3).

Nevertheless, Pune Metro seems to be gaining acceptance lately. Bombay bridge on September 2024 had metro carrying more than 4.6 million passengers in September along with revenue of ₹70.6 million. This number of daily passengers brought a reliance on the metro system by commuters to an all time high. The second most number generating line has turned in to be PCMC to Swargate route next to the Vanaz to Ramwadi route.

This analysis has provided an interesting insight of the Aqua and Purple line of the metro, overall. Since there is a similar number of stations, the Aqua line is longer and stations are farther from each other than they are with the Expo line. The passenger may not be able to access a station easily or easily complete their first and last mile of travel as this will reduce the accessibility of the station and increase the first and last mile travel time. It has been demonstrated that a metro system with a higher usage density makes the costs more economical as the costs get pulled down on account of the stations not being spaced out too much (Lindsey et al., 2010) (Refer Fig. 4).

Such a construction on the Aqua line (₹1904.95 Cr) with higher and more variable construction costs can indicate inefficiency in cost management or construction methods whereas the cost for the shorter purple line seems like a manifestation of better cost efficiency relative to the cost on red line. This is line with the study that Sonmez and Ontepeli (2022) present of the importance of an accurate predesign cost estimation in urban railway projects in terms of improving financial planning and control.

Surprisingly low and consistent length and station count standard deviations for all but the closest pair of segments, indicate that all are uniform and can be exploited for improved operational predictability. Even then, the costs per kilometer of the Aqua line are lower than the purple line and hence the latter is not cost effective in this case as well. In this way, all this implies effective project management and strict cost constraining. (Love et al., 2017) states that Future proofing and sustaining of light rail projects commercially is contingent upon the ability to understand and control cost performance of light rail transit projects. This analysis proves that metro construction projects require a proper and well-designed plan; and are required to effectively manage costs in order to sustain the economic aspect of such projects. From Pune Metro lines to illustrate that construction cost has a very strong positive linear correlation ($r \approx 1.027$) with line length and so one needs to bear the rise in expense in case if there is a conflict point in time with respect to the planned metro lines.

Total costs are higher for longer metro lines, but per kilometer costs are lower because of scale economies, except in the unusual case (for a case where an unusually high cost occurs) of New York's East Side Access. The cost per route kilometer of urban rail in different projects varies widely (Flyvbjerg et al., 2008), which can be influenced by there are more or less underground or above ground constructions, or the distance between stations (Table- 2).

3.1 Pune Metro Extensions:

Phase 1 of Pune Metro, now in full operation since 6th March 2024 has 16.59 kilometers of Purple Line (PCMC to Swargate) and 14.66 kilometers of Aqua Line (Vanaz to Ramwadi) that eases the public transportation and decongestion. To enhance last mile connectivity, they plan to add four new extensions i.e., Nigdi, Katraj, Chandni Chowk, and Wagholi. During Phase 2, the proposal is for seven more new corridors pending central approval. Vanaz–Chandni Chowk (1.2 km), Ramwadi–Wagholi (11.63 km), Khadakwasla–Kharadi via Swargate, Hadapsar (25.66 km) etc. are the key routes. These expansions are intended to widen the stretch of metro coverage and eventually motivate people to prefer public travelling in Pune. (Pune Metro Rail Project). (Refer Fig. 5)

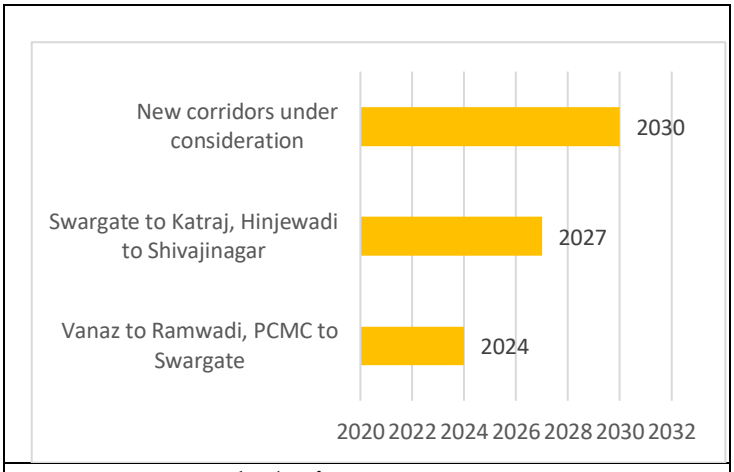

Fig. 5: Future Outlook of Pune Metro

3.2 Modified Matrix for Pune Metro Project

Table 3: Simple Modified Matrix for Pune Metro

Action Factors	Construction Phase	Operation Phase	Environmental Impact Severity	Mitigation Priority Level	Duration of Impact	Regulatory Compliance Need	Public Health Risk
Air Quality	M	M	H	H	Continuous	Yes	M
Surface water	M	L	M	M	Long term	Yes	L
Groundwater (Aquifer Levels, Contamination)	L	L	M	M	Long term	Yes	L
Flora & Fauna (Urban Green Cover & Biodiversity)	M	L	H	H	Long term	Yes	L
Solid Waste Generation	M	M	H	H	Long term	Yes	L
Noise Pollution	M	M	H	H	Continuous	Yes	M
Traffic & congestion	L	L	M	M	Continuous	Yes	L
Carbon Emission	M	L	H	H	Longterm	Yes	L
Public Health & Well being	M	M	H	H	Continuous	Yes	M
Economics Benefits	M	H	H	H	Long term	yes	L

Note: M = Medium, L = Low, H = High.

There are distinct challenges as well as advantages of the Pune Metro. Air quality, noise and waste generation (e.g. dust, v noise barriers and efficient waste disposal) is controlled in the construction. Proper tree plantation and drainage of channels meaningful protect on the water resources as well as green cover. After it comes into function, it reduces carbon emissions, cuts traffic, propels the economy, improves public health and so on for a 'sustainable city'. (Pune Metro Rail Corporation Limited); Public Environmental and Social Data Sheet). (Table 3)

Table 4: Urban Transport and Environmental Considerations for Pune Metro

Factors	Current Scenario	Future Projection	Requirement
Traffic Congestion	H	VH	Efficient Public Transport
Pollution Levels	M	H	Low-Emission Transport
Need for Sustainable Transportation	Urgent	Critical	Metro Expansion & Green Mobility
AQI (Air Quality Index) Requirements	M	P	Strict Air Quality Regulations

Note: VH = Very High, H = High, M = Medium, P = Poor

However, in the present form the urban transportation scenario is full of serious traffic congestion, little amount of pollution emission and growing inclination towards sustainable public transport. Without implementing efficient public transport systems such as metro networks, congestion is likely to aggravate, and pollution may turn out to rise. Due to the continuing urban expansion, there is a most critical need for low emission transportation to reduce environmental hazards. Also, to try and stop more decline in air quality stricter air quality regulations need to be implemented. To tackle these issues, especially increase its urban extended by constructing metro infrastructure and a greener mobility policy, will be imperative, to reduce congestion, solve pollution issue and create a new sustainable urban transport system for the next future. (Maharashtra Pollution Control Board, 2021) (Table 4)

3.3 Metro System Highlights: Pune, Delhi, Hyderabad, Bangalore

Table 5: Comparative Analysis of Metro Systems in Pune, Delhi, Hyderabad and Bangalore

Parameter	Pune	Delhi	Hyderabad	Bangalore
Total Network Length	33.2 km (Phase 1), expanding to 82 km	393 km, expanding beyond 500 km	69.2 km, expanding to 200 km	42.3 km (Phase 1), expanding to 114 km
Sustainability Approach	IGBC Platinum-certified, solar-powered stations	First metro with carbon credits, large-scale solar adoption	Solar-powered stations, green building practices	Solar-powered stations, electric buses
Energy Consumption	~80-90 kWh/km	~80-90 kWh/km	~70-80 kWh/km	~75-85 kWh/km
Energy Efficiency	65% energy from solar, aiming for net-zero	Regenerative braking saves 30% energy, solar-powered stations	26 MW solar power generation, regenerative braking system	Regenerative braking, solar-powered stations
Carbon Emission Reduction	Expected reduction of 1 lakh tonnes CO_2 per year	Reduces 57,000 tonnes CO_2 per day	Expected reduction of 1 lakh tonnes CO_2 per year	Expected to reduce 1 lakh tonnes CO_2 per year

Ridership Capacity	2-3 lakh daily (initial), target 7-8 lakh	50+ lakh daily commuters	10-15 lakh daily commuters	15-20 lakh daily commuters
Smart Infrastructure	Automated fare collection, real-time tracking	Smart cards, AI-based crowd management	Smart fare collection, real-time tracking	Smart cards, AI-based crowd management
Economic Impact	Improves connectivity, real estate growth	Contributes ₹1,500 crore annually	Contributes ₹800 crore annually	Contributes ₹3,000 crore annually
Cost of Construction	₹12,000 crore (Phase 1); ₹226 crore/km	₹70,000 crore, higher cost per km	₹14,000 crore, ₹200 crore/km	₹14,800 crore, ₹260 crore/km
Modal Shift Impact	Expected reduction in private vehicle use by 15-20%	Reduced private vehicle use by 30-40%	Expected reduction in private vehicle use by 15-20%	Reduced private vehicle use by 15-20%
Future Expansion	Plans to expand to 82 km in Phase 2 & 3	Expanding beyond 500 km	Expanding to 200 km, Phase 3 and 4 under development	Expanding to 114 km in Phase 2, further expansion planned

Pune, Delhi, Bangalore, and Hyderabad metro systems, to quote a few are enabling sustainable transport by easing traffic and emission. Pune is rapidly growing and Delhi Metro, the largest, is growing beyond 500 km. Solar power and regenerative braking are some of the green features that improve the efficiency of cities. Pune aims to check 1 lakh tonnes annually, whereas Delhi Metro prevents 57,000 tonnes of CO_2 daily. Pune aims 15–20% cut in private vehicle use while Delhi can manage up to 40%. Pune Metro is emerging with smart tech and global inspiration and is a model of ecofriendly urban mobility. (Basavaraja & Puttaiah, 2018; Rajesh et al., 2019; Shaikh & Deulkar, 2015) (Table 5).

Table 6: Comparison of Metro System Strength and Scale in Pune, Delhi, Hyderabad, and Bangalore

Parameter	**Pune**	**Delhi**	**Hyderabad**	**Bangalore**	**Impact Severity**	**Long term Benefits**	**Challenges**
Network Length	M	H	M	M	M	Increased Connectivity	Renewable Energy Integration
Sustainability	M	H	M	H	M	Lower Emissions, Eco-Friendly Transit	Renewable Energy Integration
Energy Efficiency	M	H	M	H	M	Reduced Operational Costs	High Initial Investment
Carbon Reduction	M	H	M	H	M	Improved Air Quality	Ensuring Consistent Reduction
Ridership	M	H	M	H	H	Less Traffic Congestion	Behavioural Shift to Public Transport
Smart Infrastructure	M	H	M	H	M	Enhanced Urban Planning	Integration With Existing Infrastructure

Economic Impact	M	H	M	H	H	Boosts Real Estate and Businesses	High Maintenance Costs
Construction Cost	M	H	M	M	H	Long-Term Economic Growth	Funding and Cost Overruns
Traffic Reduction	M	H	M	M	H	Smoother Urban Mobility	First-Mile, Last-Mile Connectivity
Future Expansion	M	H	H	H	H	Scalability and Accessibility	Land Acquisition Issues

Here, M = Medium and H = High,

The comparative assessment of metro systems in Pune, Delhi, Hyderabad and Bangalore is given in the table with its scale and strengths classified with an M (medium) or H (high) in some other parameters. In terms of sustainability, ridership, energy efficiency and economic impact, Delhi and Bangalore perform well and are acknowledged as established metro networks. Although being young, Pune and Hyderabad have moderate strengths with potentials of expansion, still. According to future expansion plans, there are important ways that it could be improved, for instance enhancing urban mobility and making the city more sustainable. Pune Metro Rail Project, Maharashtra Metro Rail Coporation Limited)(Chounde & Darade, 2008; Saminathan ; Subrahmanyan et al.) (Table 6)

Table 7: Comparison of Pune Metro with Other Urban Transport Modes

Parameter	Pune metro	Buses	Auto- rickshaws	Private Vehicles
Carbon emissions	L	M	H	VH
Energy Efficiency	H	M	L	L
Traffic Congestion Impact	L	M	H	VH
Speed & Travel Time	Fast	M	Slow	Varies
Affordability	Moderate	L	H	H
Sustainability Rating	H	M	L	VL

Note: VH = Very High, H = High, M = Medium, VL= very Low, L= Low

Instead of buses, auto rickshaw and private vehicles, the Pune Metro is a more sustainable and efficient mode of commute. It relieves the congestion and carbon emissions at the same time without sacrificing the affordability of daily commuter (Misal et al.; Sen et al., 2023). (Table7)

Table 8: Pune Metro's Sustainability Initiatives and Green Certifications

Initiative	Description	Certification	Significance
Solar Power Integration	Metro stations and depots use solar energy	IGBC Platinum Rating (Indian Green Building Council, 2023)	Highlights the metro's leadership in sustainability and energy-efficient practices.
Energy-efficient lighting	LED-based lighting across stations	ISO 50001 Certification (International Organization for Standardization, 2018)	Improve efficiency, reduce costs, and minimize environmental impact.

Water Recycling & Conservation	Rainwater harvesting and wastewater treatment	Green Building Certified (Pune Metro Rail Corporation Ltd., 2017)	Efficient water management and sustainable infrastructure practices.
Reduced Carbon Footprint	Lower emissions due to electric trains	UNFCCC Recognition (United Nations Framework Convention on Climate Change, 2024)	Reducing carbon emissions and supporting climate action goals.
Urban Green Cover Enhancement	Plantation drives along metro corridors	Local Government Approval TNN. (2021, July 20). Times of India	City's commitment to enhancing air quality, biodiversity, and overall urban sustainability.

Multiple sustainability measures are implemented by Pune Metro such as renewable energy use, water conservation, reduced emission of carbon, multiple green certifications such as LEED Gold certification for metro stations and LEEDv4 Gold for Akurdi Depot and administrative building (Maha Metro Rail Corporation Limited Pune Metro Rail Project) (Table 8).

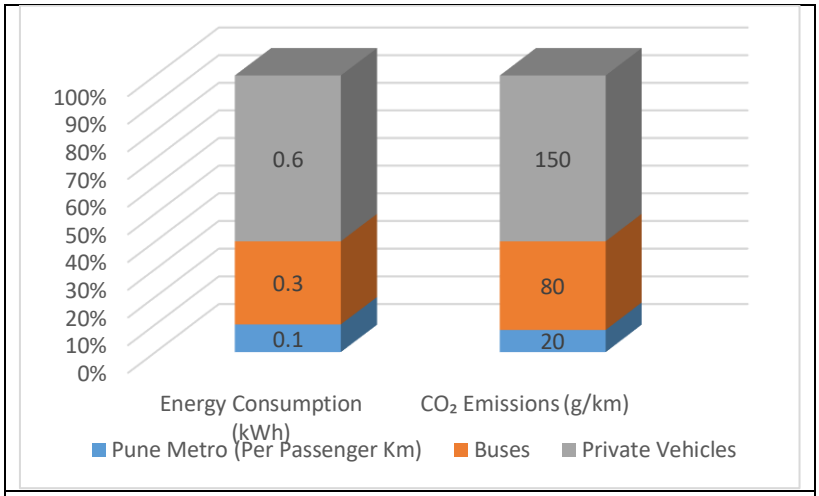

Fig. 6: Energy Utilization and Carbon Footprint Analysis

As for as energy consumption and carbon emissions are concerned, (Refer Fig. 6) the Pune Metro system is also much less than those of traditional public and private transport systems, towards a cleaner urban environment.

3.4 Sustainable Energy Transition:

A sustainable metro infrastructure strategy includes design that minimizes environmental impact, enhance sustainability, passenger experience, and resilience (Bagdadee et al., 2025; Dominković et al., 2018) green buildings, solar power, efficient station layout and design. This results in the enhanced transit experience, the reduced congestion and improved safety (Deng et al., 2023). Evaporative cooling fosters system resilience, enabling metro systems to withstand various environmental challenges. This method gives operations reliability, decreasing service interrupt, energy efficiency and treating water conservation for passenger development systems (see Fig. 7 and 8).

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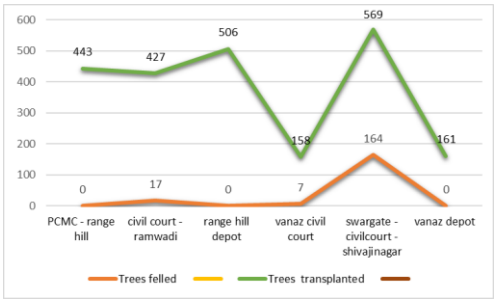

Fig. 7: Greenery Expansion in Lieu of Metro Station Construction

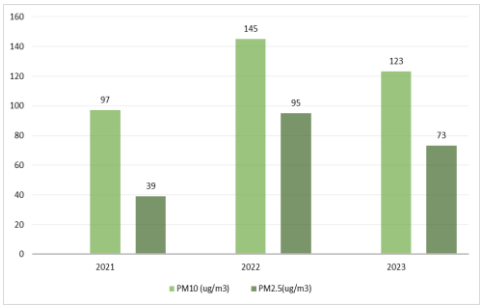

Fig. 8: Reduction in Pollutants

Table 9: Projected Solar Power Generation and Estimated Cost Savings

Station/Depot	Installed Solar Capacity (kWp)	Daily Energy Generation (kWh/day)	Annual Energy Generation (kWh/year)	Estimated Annual Savings (₹)
Range Hill Depot	4,300	4,300	1,569,500	₹6.53 crore
Shivaji Nagar Depot	2,000	2,000	730,000	₹3.06 crore
Total	**6,300**	**6,300**	**2,299,500**	**₹9.59 crore**

Table 9 presents the solar power generation and cost savings for Range Hill and Shivaji Nagar depots of Pune Metro. By utilizing solar energy, these depots reduce dependence on conventional electricity, leading to significant cost savings. The Range Hill Depot contributes a large share of the savings, while Shivaji Nagar Depot, though smaller, still plays an important role. Together, these depots are projected to save ₹9.59 crore annually, demonstrating the financial and environmental benefits of integrating renewable energy in the metro's operations. (Hindustan Times, 2023; Pune Mirror, 2023; Pune Metro, 2023)

3.5 Implemented Sustainability Policies

Various sustainability initiatives have been suggested by Pune metro in solving the environmental and social challenges. The displacement, resettlement, and compensation of the affected communities is planned as per the Resettlement Policy Framework, so that the affected communities can get adequate compensation, rehabilitation and rehabilitation, and livelihood support in the least disrupted manner. Mane et al. (2019). Thus, the project is in tune with the Contract Labour Act, thereby offering comparatively fair regional employment and social security to the contract workers. It has cheap and convenient urban travel supported by its eco friendly fare system of contact less smart cards. This then underlines Pune Metro's commitment to socially responsible practices for socially building an environmentally sustainable and an equitable transit system (Obeng & Ugboro, 2008).

3.6 Future Developmental Aspects

In order to improve both energy and efficiency, the metro rail systems throughout the world are using innovative technologies. Rooftop photovoltaic (PV) systems integrated in metro in Beijing minimize energy consumption and carbon emission by 26.1–47.8% and cost reduction with PV-battery (PVB) by the same margin (Guan et al., 2024). At that scale, metro for goods (M4G) model helps decrease emissions in low emission zones with cargo bike based last mile deliveries (Villa & Monzón, 2021). The other implementation is in Beijing (Chai et al., 2023) for intermodal train scheduling optimization that joins

metro and commuter rail networks. Building information modeling (BIM), machine learning, and simulations are things which have improved evacuation efficiency by shortening the evacuation time by 15.3% and reducing over-density rates by 39.3% (Guo et al., 2023).

Thus, passenger flow predictions are improved through the split attention relational graph convolution network (SARGCN) in Shenzhen and Hangzhou (Zeng & Tang, 2023). Changchun shows that prefabricated technologies in metro station construction solve the labor shortage problem and its environmental issues. For Shenzhen metro ridership, the results of Multiple Geographic Weight Regression (MGWR) model provide better insights into urban planning (Kim and Nicholls, 2016). Finally, automatic train operation (ATO) systems control train speed and station dwell times in order to achieve consistent headways and energy saving.

Table 10: Expected Environmental Improvements Attributed to Pune Metro (2024–2030)

Year	CO_2 Emission Reduction (tons/year)	Reduction in Vehicular Emissions (%)	Fuel Savings (liters/year)	Estimated Air Quality Improvement (%)
2024	18,000	5%	750,000	4%
2025	30,000	10%	1,250,000	6%
2030	75,000	20%	3,500,000	15%
2035	100,000	30%	5,000,000	20%

Table 10 outlines the anticipated environmental benefits of Pune Metro from 2024 to 2035. As the network of the metro broadens and attracts more people using it, significant carbon emission reductions will take place with 100,000 tons annually by 2035. It also is projected to save up to 5 million litres annually in fuel consumption. Furthermore, the metro could also lead to improving air quality levels up to 20% for the city, demonstrating the metro's ability in controlling pollution and pursing sustainable urban mobility. (Public Environmental and Social Data Sheet; Maharashtra Metro Rail Corporation Limited [MMRCL], ESIA-ESMP Report)

3.7 Areas for Improvement

Cost overruns and delays of the metro projects are derived from the global infrastructure reports and case studies due to geological uncertainties, changing design requirements, and procurement inefficiencies (Chai et al., 2023). Other environmental and social problems related to Metro are pollution, habitat loss, too much energy usage, displacement, traffic, and the like. After launch, there is a need for efficient handling of problems such as maintenance and service disruption. Financial sustainability thus necessitates having a well-planned approach of fares, ridership—and revenue above all. The ESIA-ESMP Report states this (ESIA-ESMP Report, Maharashtra Metro Rail Corporation Limited [MMRCL]).

4. CONCLUSION

As the study shows that using the metro is rather affordable and convenient, the level of its usage is of a moderate level. However, apart from cleanliness and fare prices, the call for change in last mile connectivity, service frequency and network coverage will be in order. Moreover, with the help of a metro system it is possible to minimize traffic congestion and air pollution which is the important element of urban transport to sustainable or long-term use. While the efficiency of the Purple Line is superior to that of Aqua Line, cost differential implies prudence to improve financial prudence. The effect of construction is low except for noise and air quality which can be done away with ecofriendly measures. Correlation with the line length and the construction costs is strong, therefore budget management is a critical issue. Higher ridership and greater congestion relieve on the network expansion; however, it should be carried out based on adequate monitoring of the service sustainability and cost efficiency to attain long term advantages.

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Conflict of interest
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Ethics statement
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