

A Comprehensive Review and Analysis on Contributions of Electric Three-Wheelers for Sustainable Traffic Operations

¹Subhada Nayak*, ²Mahabir Panda, ³Prasanta Kumar Bhuyan

¹Ph.D. Scholar, National Institute of Technology, Rourkela-769008, India

²Professor, National Institute of Technology, Rourkela-769008, India

³Professor, National Institute of Technology, Rourkela-769008, India

E-mail Id: 519ce1004@nitrrkl.ac.in, subhadanayak@gmail.com

Abstract:

Electric three-wheelers (E3Ws) are redefining urban transportation by addressing sustainability, operational efficiency, and cost-effectiveness. Transportation contributes nearly 24% of global CO₂ emissions, and E3Ws offer a cleaner alternative with zero tailpipe emissions and lifecycle greenhouse gas (GHG) reductions of 40–60% when powered by renewable energy. Technological advancements, including lithium-ion batteries with energy densities exceeding 300 Wh/kg and solar integration, have significantly improved range and performance. Cost analyses reveal E3Ws operate at 50% of the cost-per-kilometre compared to internal combustion engine (ICE) vehicles, with drivers reporting income increases of up to 50%. However, adoption barriers remain. Urban areas face a 70% shortfall in charging infrastructure, while high initial investment costs deter rural deployments. Despite these challenges, policy incentives such as subsidies in India and Bangladesh are accelerating adoption. Integration into public transport networks has enhanced last-mile connectivity, reducing transit times by 20–30%. Future opportunities include rural deployment for agricultural logistics and leveraging AI and IoT for smarter fleet management and safety. Recycling batteries could further cut costs by 15–20%. This review highlights E3Ws' advancements, challenges, and transformative potential in achieving sustainable transportation goals through innovation and policy support.

1. Introduction

Transportation remains one of the largest contributors to Global Greenhouse Gas (GHG) emissions, accounting for approximately 24% of energy-related CO₂ emissions worldwide. Among the various modes of transportation, road vehicles constitute the majority of these emissions, driven by the heavy reliance on fossil fuels. As urbanization accelerates globally, there is an urgent need to transition to sustainable transport solutions that mitigate environmental impacts, improve economic viability, and support equitable access to mobility. Electric vehicles (EVs) have emerged as a key component in the strategy to decarbonize transportation. Within this domain, electric three-wheelers (E3Ws) play a critical role due to their unique positioning as affordable, compact, and versatile vehicles. Primarily used in developing and emerging economies for passenger and goods transport, E3Ws have demonstrated significant potential in reducing urban air pollution and operating costs compared to conventional internal combustion engine (ICE) vehicles. E3Ws are particularly well-suited for last-mile connectivity, addressing the gap between public transportation hubs and final destinations. In densely populated urban centres like Delhi, Dhaka, and Jakarta, E3Ws are a common sight, offering affordable and efficient mobility solutions. According to a 2023 report by Bloomberg NEF, the global market for electric three-wheelers is expected to grow at a compound annual growth rate (CAGR) of 8.5% between 2023 and 2030, driven by government incentives and advancements in battery technology. A key factor in the adoption of E3Ws is their cost-effectiveness.

Studies indicate that E3Ws operate at nearly half the cost-per-kilometre of ICE vehicles, primarily due to lower fuel and maintenance expenses. For instance, drivers in Pakistan reported monthly income increases of up to 50% after transitioning to E3Ws (Khan et al., 2022). Figure 1 below illustrates the cost comparison between E3Ws and ICE three-wheelers across different regions. The upfront cost of electric three-wheelers is generally higher than that of ICE variants. For instance, in India, E3Ws can start around ₹1.3 lakh, with models from manufacturers like Mahindra and Piaggio priced around ₹1.7 lakh or higher. Traditional petrol or diesel three-wheelers typically have lower initial costs, making them more accessible to buyers without subsidies (Mombeuil and Diunugala, 2024). Electric vehicles benefit from lower fuel costs, as electricity is generally cheaper than petrol or diesel. For example, running an electric three-wheeler for three years can cost approximately ₹36,000, compared to ₹3.6 lakh for a petrol vehicle over the same period, assuming daily usage of 70–80 km. The environmental benefits of E3Ws extend beyond zero tailpipe emissions. Lifecycle assessments (LCA) reveal that when powered by renewable energy sources, E3Ws reduce lifecycle

GHG emissions by 40–60% compared to ICE vehicles. This reduction is particularly significant in regions where coal-based electricity grids are transitioning to renewable energy.

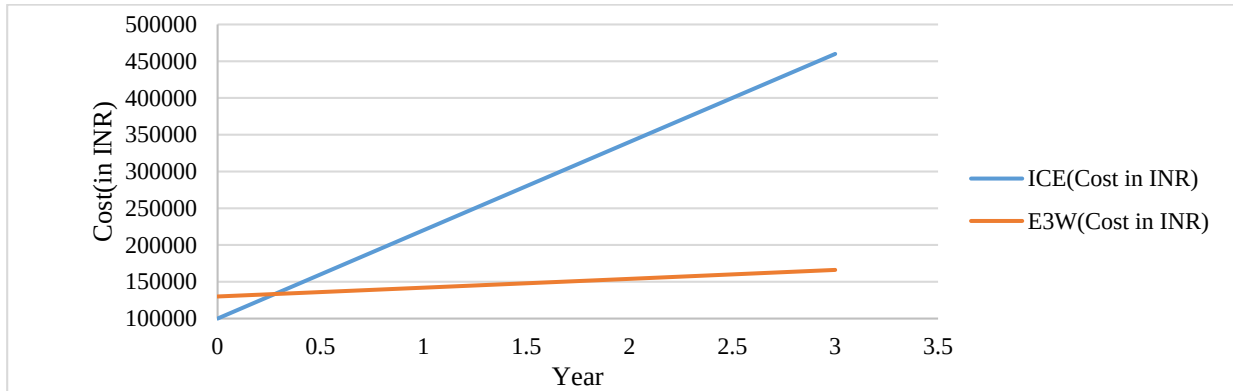


Figure 1: Cumulative cost comparison graph between E3Ws and ICE three-wheelers Globally

Moreover, the adoption of E3Ws can contribute to improved urban air quality by mitigating pollutants such as particulate matter (PM_{2.5}) and nitrogen oxides (NO_x). Solar-assisted designs are also gaining traction, particularly in regions with abundant sunlight. For example, pilot projects in India have demonstrated the feasibility of integrating solar panels into E3Ws, reducing dependency on grid electricity and further lowering operating costs (Mulhall et al., 2010). Despite their advantages, E3Ws face significant barriers to widespread adoption. Inadequate charging infrastructure is one of the most pressing challenges, with urban areas often experiencing a 70% shortfall in charging facilities relative to demand. High upfront costs, driven by battery expenses, also deter adoption, particularly among low-income populations (Ayeter et al., 2023). Public perception remains another hurdle. Concerns regarding vehicle range, battery durability, and performance reliability continue to influence consumer decisions. Addressing these issues through targeted awareness campaigns and incentives can play a crucial role in overcoming these barriers (Ravi et al., 2024). E3Ws are increasingly being integrated into public transportation systems as feeder vehicles, connecting commuters to larger transit hubs. In Delhi, for example, the integration of E3Ws into metro networks has reduced transit times by 20–30%, enhancing commuter satisfaction and reducing traffic congestion.

Objective of the Study: This study aims to provide a comprehensive review and analysis of electric three-wheelers (E3Ws) as a critical component of sustainable urban transportation. The primary objective is to evaluate the technological advancements, economic implications, environmental impacts, and policy frameworks associated with E3Ws. By synthesizing data from recent studies, lifecycle cost analyses, and regional case studies, the background study highlights the transformative potential of E3Ws in addressing global transportation challenges. This analysis, provides policymakers, researchers, and industry stakeholders with actionable insights to accelerate the adoption of E3Ws and achieve sustainable mobility goals.

2. Technological Advancements

Battery and Motor Technologies: E3Ws predominantly utilize lithium-ion batteries due to their high energy density and efficiency. Advances in solid-state batteries and battery management systems (BMS) have further improved vehicle range and safety (Sindha et al., 2018). Motors such as permanent magnet synchronous motors (PMSMs) are gaining popularity for their superior efficiency and lower maintenance. Battery and motor technologies are pivotal to the performance, efficiency, and adoption of electric vehicles (EVs), including electric three-wheelers (E3Ws). Modern E3Ws predominantly use lithium-ion batteries due to their high energy density, longevity, and fast-charging capabilities. Emerging technologies such as solid-state batteries are gaining attention for their improved safety and higher energy capacity, with some prototypes achieving energy densities exceeding 400 Wh/kg, compared to 150–250 Wh/kg in conventional lithium-ion batteries. On the motor side, brushless DC (BLDC) motors are the industry standard, offering advantages like higher efficiency (up to 90%), lower maintenance, and smoother operation. Advances in permanent magnet synchronous motors (PMSMs) are further improving torque density and reducing energy losses. Studies have shown that combining energy recovery systems, such as regenerative braking, with optimized power electronics can increase overall vehicle

efficiency by 15–30%. These technological strides are crucial for extending range, reducing costs, and accelerating the transition to electric mobility.

Renewable Energy Integration: Permanent magnet synchronous motors (PMSMs), widely used in E3Ws, deliver high efficiency and lower maintenance requirements compared to traditional motors. Solar-assisted systems have been piloted in various models to reduce reliance on grid electricity, as evidenced in studies on solar-powered E3Ws. Figure 2 presents a lifecycle emissions comparison between E3Ws and ICE vehicles, highlighting the substantial environmental savings achievable with renewable energy integration. Advancements in battery and motor technologies have been pivotal in enhancing the performance and adoption of E3Ws. Lithium-ion batteries, with energy densities exceeding 300 Wh/kg, offer improved range and efficiency. Solid-state batteries, though still in development, promise further advancements in energy density, safety, and lifecycle costs. ICE vehicles emit the highest amount of CO₂, increasing rapidly over time. E3W with Grid Electricity emits significantly less CO₂ but still accumulates emissions. And E3W with Renewable Energy achieves the lowest emissions, demonstrating substantial environmental savings.

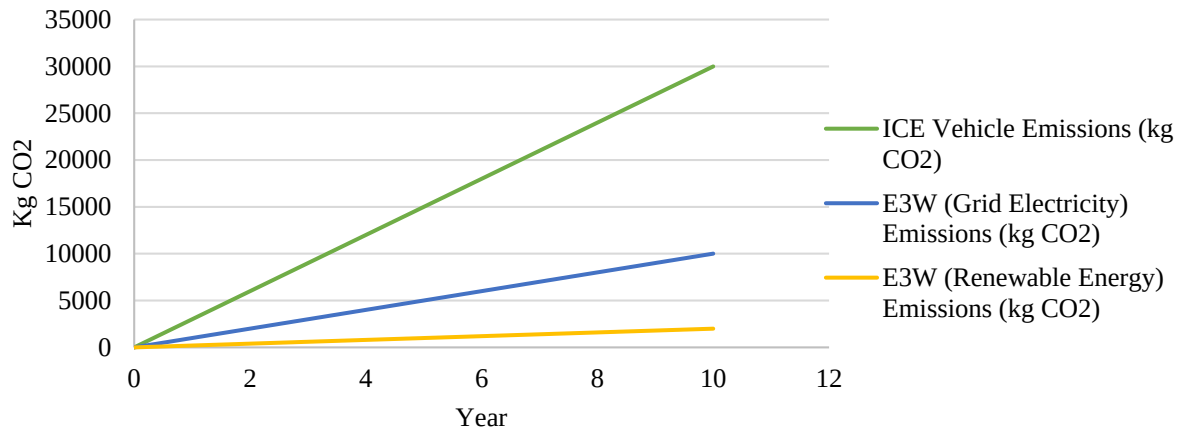


Figure 2: Lifecycle Emission Comparison between E3Ws and ICE with Renewable integration

Automation and Safety Features: Both electric three-wheelers (E3Ws) and internal combustion engine (ICE) three-wheelers are evolving with automation and safety features to enhance efficiency and passenger safety. Table 1 shows the Automation Features Comparison of E3Ws and ICE Three-Wheelers.

Table 1: Automation Features Comparison of E3Ws and ICE Three-Wheelers

Automation Features	ICE 3Ws	E3Ws
Auto-Start/Stop System	Some models have manual stop/start	Yes, prevents idle energy wastage
Adaptive Driving Modes	Fixed engine performance	Yes, Eco/Sport modes for efficiency
Cruise Control	Not common	Available in some premium models
Automatic Battery Management	N/A	Yes, manages charging & discharging
IoT Integration	Rarely available	Yes, supports real-time tracking, remote diagnostics

Electric three-wheelers (E3Ws) are integrating smart automation features to enhance efficiency, safety, and user experience. Unlike traditional internal combustion engine (ICE) three-wheelers, E3Ws come equipped with smart telematics, enabling fleet tracking and remote diagnostics through IoT integration. They also feature regenerative braking, which helps recover energy and improves battery efficiency. Additionally, adaptive driving modes allow users to switch between Eco and Sport modes for optimized performance. Motorized three wheelers are commonly used for public and freight transport in urban and sub urban cities, has High share in urban transportation system, known for Last mile connectivity, also for its being Affordable and its Compact and flexible structure. (Nayak et al., 2025). Another key advantage is the auto-start/stop system, which reduces idle energy wastage, a feature rarely found in ICE three-wheelers (Neaimeh et al., 2013). Advanced automatic battery management systems help regulate charging and discharging, improving battery lifespan. Some premium E3W models even offer cruise control, enhancing ride comfort. Overall, E3Ws provide superior automation, making them a more sustainable and efficient mobility solution.

The safety features of E3Ws and ICE three-wheelers show a clear technological advantage for electric vehicles in terms of driver and passenger protection. Anti-lock Braking Systems (ABS) and Electronic Stability Control (ESC), which enhance braking efficiency and vehicle stability, are available in some high-end E3Ws but are rarely found in ICE three-wheelers. Additionally, crash-resistant body structures in E3Ws, often made from fibre-reinforced materials, provide better shock absorption than the metal frames of ICE vehicles, which are more prone to deformation upon impact. And Table 2 gives some insights towards Safety Features Comparison of E3Ws and ICE Three-Wheelers.

Table 2: Safety Features Comparison of E3Ws and ICE Three-Wheelers

Safety Features	ICE 3Ws	E3Ws
Seat Belts for Driver/Passengers	Available in modern models	Standard in some markets
Anti-lock Braking System (ABS)	Rarely available	Some premium models
Crash-Resistant Body Structure	Mostly metal frames, higher impact risk	Fiber-reinforced, better shock absorption
Electronic Stability Control (ESC)	Not available	Available in high-end models
Side Impact Protection	Basic protection	Some E3Ws have reinforced doors
Reversing Sensors & Cameras	Rare in ICE models	Common in newer E3Ws
Fire Safety System	No fire suppression mechanism	Battery thermal management for overheating prevention

One major fire safety advantage of E3Ws is the battery thermal management system, which helps prevent overheating and reduces the risk of fire—an issue more common in fuel-powered vehicles due to flammable petrol or diesel. Furthermore, reversing sensors and cameras, which improve visibility and prevent accidents in crowded areas, are commonly integrated into newer E3Ws but are rarely seen in ICE three-wheelers. From a safety perspective, E3Ws are clearly superior, integrating modern intelligent monitoring systems and passenger protection enhancements. These advancements, coupled with regenerative braking for better skid prevention, position E3Ws as a safer alternative to traditional ICE models in urban and last-mile transportation. Developments

in stability control mechanisms and active tilt technology enhance vehicle safety and comfort, making E3Ws more appealing to consumers (Indhumathi et al., 2023).

3. Environmental Impact and Life Cycle Cost Analysis

Environmental Impact: E3Ws significantly reduce tailpipe emissions, contributing to improved urban air quality. Lifecycle assessments (LCA) indicate that E3Ws have a smaller carbon footprint compared to ICE three-wheelers, especially when powered by renewable energy sources (Mosleuzzaman et al., 2024). However, challenges in battery disposal and recycling need to be addressed to maximize their environmental benefits. The shift from internal combustion engine (ICE) three-wheelers to electric three-wheelers (E3Ws) presents a significant opportunity for reducing environmental damage. E3Ws have a lower carbon footprint, producing zero tailpipe emissions, unlike ICE vehicles, which release CO₂, nitrogen oxides (NO_x), and particulate matter (PM) that contribute to air pollution and climate change (Zahoor et al., 2023). ICE three-wheelers, running on petrol or diesel, emit over 3,000 kg of CO₂ annually per vehicle, whereas E3Ws powered by grid electricity produce only about 1,000 kg CO₂ per year. When charged with renewable energy, E3Ws can reduce emissions to just 200 kg CO₂ per year, achieving over 90% lower lifecycle emissions compared to ICE models.

E3Ws do not release toxic exhaust gases, reducing urban air pollution, which is a major health concern in many cities. Additionally, ICE engines contribute to noise pollution, whereas E3Ws operate almost silently, improving overall urban liveability. E3Ws require less energy for operation compared to fuel-based counterparts. Moreover, advancements in battery recycling and renewable energy integration further enhance their sustainability (Dalkic-Melek et al., 2024). Transitioning to E3Ws significantly reduces carbon emissions, improves air quality, and lowers noise pollution, making them a sustainable choice for the future of urban mobility (Vaidehi et al., 2020). Figure 3 provides an overview of the distribution of charging infrastructure in urban and rural settings, illustrating the disparity in accessibility.

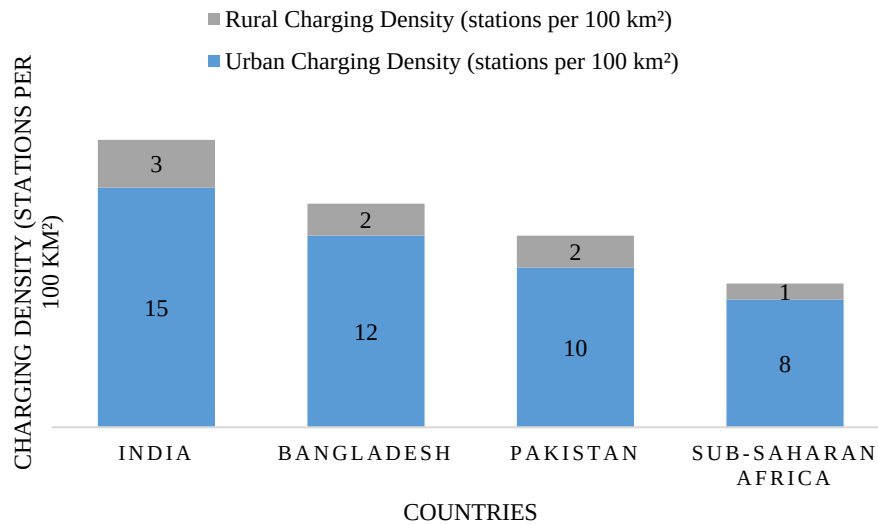


Figure 3: Distribution of charging infrastructure in urban and rural settings

Urban areas enjoy significantly better access to charging infrastructure due to higher population densities and government focus on urban EV deployment. Rural areas experience an 80–90% shortfall in infrastructure, limiting E3W deployment and adoption (Deb et al., 2018). This gap is further exacerbated by insufficient grid infrastructure, especially in remote regions where electricity availability is inconsistent. The Factors Driving Urban-Rural Disparity are various, one is Cost of Installation (Wang et al., 2019). Charging stations in rural areas require additional investment due to weaker grid infrastructure and longer distances for electricity supply. Second, Demand Concentration: Urban centers have higher E3W adoption rates, leading to a focus on urban

charging networks. And third, Policy Neglect: Incentives and subsidies for charging infrastructure are often targeted at cities, leaving rural areas underserved.

Life Cycle Cost Analysis: E3Ws demonstrate lower operating costs than ICE counterparts due to reduced fuel and maintenance expenses. Studies in Pakistan reveal that drivers’ monthly earnings can increase by 50% with E3Ws (Alaee et al., 2023). Government incentives, such as subsidies and tax benefits, have been pivotal in boosting E3W adoption in countries like India and Bangladesh. Nonetheless, inconsistent policies and lack of infrastructure remain significant barriers. Table 3 shows Lifecycle Cost Analysis of Electric Three-Wheelers vs. Internal Combustion Engine (ICE) Three-Wheelers in different regions. Drivers in rural areas face higher operating costs due to limited charging options, leading to reliance on diesel-powered vehicles (Majumdar et al., 2022). Rural residents and businesses are discouraged from transitioning to E3Ws due to a lack of confidence in charging availability. The limited adoption of E3Ws in rural areas prolongs reliance on polluting alternatives, undermining decarbonization goals. Addressing the disparity in charging infrastructure requires innovative and targeted solutions. Mobile or modular charging units can be deployed in rural areas to bridge immediate gaps (Nayal et al., 2024) and address infrastructure shortfalls.

Table 3: Lifecycle Cost Analysis of Electric Three-Wheelers vs. Internal Combustion Engine (ICE) Three-Wheelers Globally.

Cost Component	E3Ws (USD)	ICE Three-Wheelers (USD)	Savings (%)
Purchase Cost	3,000	2,500	-20% (Higher)
Fuel/Electricity Cost (per km)	0.02	0.10	80% Savings
Maintenance Cost (per year)	200	500	60% Savings
Battery Replacement Cost	800 (every 5 years)	-	N/A
Total Lifecycle Cost (10 years)	7000	1000	~36% Savings

Public-private partnerships should be fostered to co-invest in rural charging networks, leveraging resources from both sectors for maximum impact. Integrating renewable energy sources, such as solar and wind-powered charging stations, can reduce dependency on the grid and ensure sustainable operation in remote locations. Additionally, targeted subsidies should be extended to prioritize underserved rural regions, incentivizing infrastructure development and accelerating electric three-wheeler adoption.

4. Conclusion

Electric three-wheelers represent a transformative solution for sustainable urban and peri-urban transportation. While significant advancements have been made in technology and policy support, challenges such as infrastructure deficits and public perception must be addressed. Future research should focus on improving battery technologies, enhancing renewable energy integration, and formulating comprehensive policy frameworks to realize the full potential of E3Ws. The findings of this analysis highlight the following key insights:

1. E3Ws significantly reduce lifecycle greenhouse gas (GHG) emissions by 40–60% compared to internal combustion engine (ICE) vehicles, particularly when powered by renewable energy sources. Their adoption can also improve urban air quality by minimizing pollutants such as PM2.5 and NOx.
2. With operational costs nearly 50% lower than ICE vehicles, E3Ws offer substantial economic benefits to drivers, particularly in developing regions.
3. Innovations in lithium-ion batteries, solar-assisted systems, and efficient motors like permanent magnet synchronous motors (PMSMs) have enhanced the performance and reliability of E3Ws. These advancements have made E3Ws increasingly competitive in urban and peri-urban transportation.

4. Government initiatives supporting EV manufacturing, battery recycling, and charging infrastructure have been instrumental in fostering E3W adoption. However, the urban-rural disparity in charging station density remains a significant barrier, with rural areas experiencing a 70–90% shortfall.
5. Harmonized global policies aligned with the Paris Agreement and UN Sustainable Development Goals (SDGs) can accelerate standardization and adoption, while targeted local policies can address specific regional challenges.

In conclusion, electric three-wheelers are poised to play a pivotal role in achieving global sustainable transportation goals. By addressing existing barriers and leveraging technological, economic, and policy-driven opportunities, E3Ws can transform urban and rural mobility, contributing significantly to decarbonization and sustainable development efforts. Table 4 gives some Key Statistics on E3Ws.

Table 4: Key Statistics on E3Ws

Features	Value
Average GHG Reduction	40–60%
Energy Density (Li-ion)	>300 Wh/kg
Charging Infrastructure Gap	~70% in urban areas
Operating Cost Reduction	~50% compared to ICE
Projected Market Growth	8.5% CAGR (2023–2030)

The future of E3Ws lies in their ability to address mobility challenges in underserved regions. Rural deployment offers significant opportunities for agricultural logistics and last-mile delivery services. Additionally, advancements in artificial intelligence (AI) and the Internet of Things (IoT) can optimize fleet management, energy consumption, and safety features. Battery recycling initiatives also hold promise, with potential cost reductions of 15–20% achievable through improved recycling processes. Harmonized global policies supporting EV manufacturing, recycling, and infrastructure development will be crucial in realizing the full potential of E3Ws.