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Assessment of Electric Two-Wheelers: A Narrative Review of Technological Trends, Market Growth, and Policy Drivers Associated with Environmental Concerns

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ABSTRACT

Electric two-wheelers (E2Ws) are key components in decarbonizing urban transportation. Their sustainability implications across different economic contexts remain uneven and are insufficiently synthesized. This review evaluates the sustainability of E2Ws across different economic contexts by synthesizing technological, environmental, market, and policy evidence. Databases such as Scopus, Web of Science, ScienceDirect, and IEEE Xplore were searched for peer-reviewed articles published between January 2015 and September 2025. A structured narrative review approach was applied, and data were synthesized across the technological, environmental, market, and policy dimensions. Studies were categorized according to economic context, including advanced economies (Europe and North America), large emerging economies (China and India), and rapidly motorizing emerging economies (e.g., Vietnam and Southeast Asia). The synthesized evidence focused on battery technologies, regenerative braking systems, charging models, and life cycle sustainability under different electricity mixes. The evidence synthesis found that while E2Ws consistently reduce operational greenhouse gas emissions. Overall sustainability outcomes are strongly influenced by the impacts of battery manufacturing, recycling infrastructure availability, and policy coherence. These findings provide transferable, evidence-based insights to support policymakers and industry stakeholders in accelerating sustainable E2W deployment across both mature and emerging markets.

1. INTRODUCTION

The rapid urbanization of the 21st century has intensified the global demand for sustainable, efficient, and cost-effective transportation modes. In this context, electric two-wheelers (E2Ws) have emerged as a critical component of the global mobility transition, particularly in densely populated countries where two-wheelers form the backbone of daily transportation (Hiep et al. 2023). With over 1.2 billion motor vehicles in use worldwide and projections indicating a rise to two billion by 2035, the decarbonization of personal transport is increasingly urgent, particularly in the face of rising greenhouse gas emissions, energy insecurity, and deteriorating air quality (Raza et al. 2025). Two-wheelers dominate the vehicle fleets of many developing economies. In India alone, over 187 million two-wheelers are in operation, accounting for more than 70% of the country's total registered vehicles (Jindel et al. 2022). Their affordability, maneuverability, and fuel efficiency render them indispensable for short- and medium-distance commuting. However, the heavy dependence on internal combustion engine (ICE)-based two-wheelers has exacerbated fossil fuel consumption and environmental pollution (Liu et al. 2024). Globally, the transport sector is responsible for nearly 24% of the direct CO_2 emissions from fuel combustion (Solaymani 2019). Personal mobility accounts for a significant share of CO_2 emissions. E2W are powered primarily by lithium-ion

(Li-ion) battery systems (Nayak et al. 2023). They offer a promising alternative with the potential to reduce emissions and noise pollution, contingent on the electricity generation mix and usage patterns.

The technological evolution of E2Ws has been largely attributed to improvements in battery chemistry, regenerative braking, and compact motor design. Innovations in battery swapping and fast charging infrastructure have further enhanced their usability (Ahmad et al. 2020). These developments, along with government incentives and environmental directives, have spurred market growth in key regions of the globe, such as China, India, the European Union, and North America. For instance, China's aggressive policy push and domestic manufacturing ecosystem have resulted in over 300 million E2Ws on its roads (Zuev et al. 2019). This growth illustrates a scale-driven adoption model that has proven effective under specific regulatory, manufacturing and infrastructure conditions. Lifecycle assessments (LCA) indicate that while E2Ws significantly reduce tailpipe emissions, their sustainability advantage is moderated by upstream emissions from electricity generation and battery manufacturing (Ahmadzadeh et al. 2025). Additionally, the lack of robust end-of-life recycling mechanisms for Li-ion batteries poses a growing environmental concern that must be addressed.

Despite the rapid global growth of E2Ws, sustainability assessments remain fragmented across regions, technologies, and policy environments, with most existing studies confined to single-country analyses or isolated themes. Such fragmentation limits the transferability of insights across economies at different stages of their development. This narrative review addresses this gap by critically assessing E2W sustainability using a comparative economy-based framework and synthesizing evidence across four key dimensions: technological advancement, environmental performance, economic viability, and policy intervention. Countries are classified into advanced economies, large emerging economies, and rapidly motorizing emerging economies to enable cross-economy comparisons and policy learning. Special emphasis is placed on major E2W markets such as India, China, and Vietnam as representative emerging economies with high two-wheeler dependency, where affordability, policy design, and grid carbon intensity critically shape adoption outcomes (Hiep et al. 2023, Kim et al. 2025). By integrating technological, environmental, market, and policy perspectives within this comparative framework, the review aims to provide actionable insights for policymakers, manufacturers, and researchers seeking to accelerate a scalable, inclusive, and sustainable transition toward electric two-wheeler mobility.

2. REVIEW METHODOLOGY

The literature was retrieved from Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar, covering publications from January 2015 to September 2025. Search strings included combinations of "electric two-wheelers," "electric motorcycles," "battery technology," "lifecycle assessment," "policy incentives," and "market adoption." Studies were included if they addressed at least one of the following dimensions: technology, environmental performance, market dynamics, and policy frameworks. Grey literature was excluded, except where official policy documents were necessary for contextual understanding. Rather than statistical aggregation, thematic synthesis representing thematic relevance, geographic diversity, and policy significance was conducted to provide a cross-regional comparison.

3. TECHNOLOGICAL DEVELOPMENTS IN E2WS

Technological advancements in two-wheelers have led to the E2W revolution. The development of lead-acid-powered two-wheelers to high-performance Li-ion-based vehicles represents a significant leap in energy efficiency. Core technological components, such as battery innovations, motor configurations, and charging technologies, play a significant role in enhancing the performance and sustainability of E2Ws. The advanced E2W is an architecture with a robust user interface, integrated with IoT, telematics, and advanced battery packs with a regenerative braking system (Fig. 1).

3.1. Battery Innovations

The industry has largely transitioned from valve-regulated lead-acid and nickel-metal hydride batteries to Li-ion chemistries because of their higher energy densities, which range from 150–250 $Wh.kg^{-1}$ (Kumar et al. 2023). They have a longer cycle life, ranging from 1,000 to 2,000 cycles, and superior charge/discharge efficiency. Among Li-ion variants, lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) are the most widely adopted for two-wheelers (Walvekar et al. 2022). LFP batteries are characterized by strong thermal and chemical stability and operate in the temperature range of −20°C to 60°C. This temperature range makes them suitable for high-ambient-temperature regions such as India and Southeast Asia (Zhao et al. 2024). In contrast, NMC batteries provide higher energy densities (180–250 $Wh\ kg^{-1}$) and operate optimally within −10°C to 50°C temperature range. At the materials level, LFP cathodes employ stable olivine crystal structures with reported particle sizes in the 100–300 nm range, whereas NMC cathodes utilize layered oxide structures of ~200–500 nm that enhance

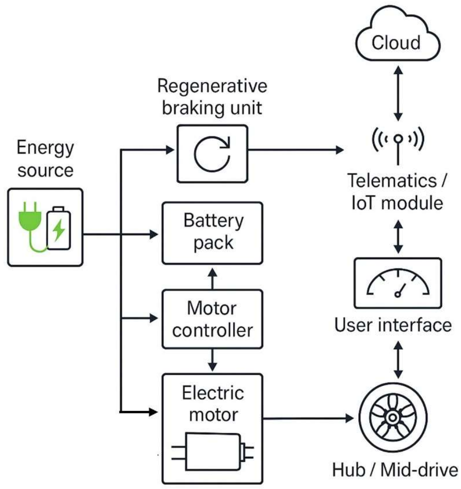

Fig. 1: System architecture of electric two-wheelers.

lithium diffusion but increase sensitivity to thermal and structural stress (Padhi et al. 1997, Xu et al. 2012)

Solid innovations have provided alternatives, such as solid-state batteries, which replace liquid electrolytes with solid electrolytes. They offer higher energy densities, which may exceed 400 $Wh.kg^{-1}$ (Xiao et al. 2020). Sodium-ion (Na-ion) batteries are also gaining attention as low-cost, resource-abundant options. They offer moderate energy densities (100–160 $Wh.kg^{-1}$) and improved thermal stability (Voß et al. 2025). From a life cycle perspective, battery manufacturing accounts for a substantial share of total E2W greenhouse gas emissions, contributing approximately 30–45% of cradle-to-gate emissions, depending on the chemistry and energy source (Ellingsen et al. 2016).

Although commercial deployment is still limited by high production costs and material challenges, companies such as Toyota and CATL have reported significant breakthroughs that could reach the E2W market within the next five years. Another key development is the modular and swappable battery designs. Battery swapping technologies can reduce downtime and permit smaller and lighter battery packs in fleet and shared mobility applications (Vallera et al. 2021). This architecture is beneficial for shared mobility and commercial fleet applications, where uptime is critical. Likewise, advancements in battery management systems (BMS) have significantly improved real-time monitoring and charge balancing. Modern BMS units use AI and cloud-based telematics to optimize the charging behavior, predict faults, and extend the battery lifespan (Nyamathulla & Dhanamjayulu 2024). Thermal management remains a critical focus in high-temperature areas. Cooling solutions, such as phase-change materials, air ducts, and liquid-cooled enclosures, are being developed to maintain optimal operating temperatures (Zonouzi et al. 2024). Innovations in recyclability, cobalt-free chemistries, and green synthesis routes drive improvements in battery lifecycle sustainability. Startups and research institutions are investing in closed-loop recycling techniques that use hydrometallurgy and direct cathode regeneration. A comparative summary of evolving battery technologies used in E2Ws is presented in Table 1.

3.2. Charging Technologies

Charging infrastructure is a critical enabler of widespread electric E2W adoption in the country. E2Ws primarily rely on three charging modalities: slow charging, fast charging, and battery swapping. Each offers distinct benefits and use-case suitability (Al-Saadi et al. 2021). Slow charging is based on Level 1 or Level 2 AC systems. These systems use 230V single-phase AC outlets with onboard chargers rated between 250 W and 1.5 kW (Gnann et al. 2019). It takes approximately 4 to 6 h for a full charge, although the overall charging time also depends on the battery capacity. Slow charging maintains battery longevity owing to lower thermal stress and minimal overvoltage risks. However, the extended charging time can be a limitation for fleet-based applications or high utilization scenarios.

Fast charging uses DC charging protocols such as CHAdeMO or CCS2. These systems deliver power in the range of 3–22 kW for two-wheelers (Tu et al. 2019). Battery chemistries, such as lithium-titanate in conjunction with thermal management systems, have enabled E2Ws to safely achieve an 80% state-of-charge in under 30 min (Hussain et al. 2024). Nonetheless, fast charging can accelerate battery degradation if not properly managed by the BMS, thus requiring trade-offs between speed, cost, and battery health. Battery swapping is an emerging solution

Table 1: Comparative summary of battery technologies used in electric two-wheelers.

Battery Type	Chemistry	Energy Density [Wh.kg^{-1}]	Cycle Life (cycles)	Safety	Advantages	Limitations	Typical Application Stage
Lead-Acid	$PbSO_4$	30–50	300–500	Low (acid leakage, gas release)	Low cost, easy recycling	Heavy, short lifespan, slow charging	Legacy models (China, India - low speed)
Nickel Metal Hydride	NiMH	60–80	500–800	Moderate	Better than lead-acid, moderate cost	Memory effect, lower energy density	Early transition models
Lithium Cobalt Oxide	$LiCoO_2$	150–200	500–1000	Low to moderate (thermal instability)	High energy density	Poor thermal stability, expensive cobalt content	Limited two-wheeler use (mainly consumer electronics)
Lithium Iron Phosphate	$LiFePO_4$	90–160	2000–4000	High (excellent thermal stability)	Long cycle life, safer, wide temperature tolerance	Lower energy density	Dominant for E2Ws in India, China
Lithium Nickel Manganese Cobalt	$Li(NiMnCo)O_2$	150–250	1500–3000	Moderate (improved BMS needed)	High energy density, good power output	Complex thermal management	Premium E2Ws, motorcycles
Solid-State	Solid electrolyte (various chemistries)	300–400+	3000–5000+	Very high	High energy density, very safe, fast charging	Expensive, limited commercialization	R&D phase, emerging
Sodium-Ion	Na-based compounds	100–160	2000+	High (chemically stable)	Low cost, resource abundance	Lower energy density, early stage	Experimental, potentially low-cost future alternative

with demonstrated viability in selected urban logistics, ride-sharing, and commercial fleet contexts, subject to standardization and infrastructure density (Ahmad et al. 2020, Vallera et al. 2021). In this approach, depleted battery packs are replaced with fully charged units at designated swapping stations, reducing the "charging" time to less than five minutes. Battery-as-a-service (BaaS) models decouple battery ownership from vehicles, thereby reducing upfront costs and addressing range anxiety. Companies such as Gogoro, NIO, and Ola Electric have deployed modular and interoperable battery platforms to promote standardization and network scalability (Boti et al. 2024). The integration of smart charging systems is gaining momentum. These systems use Internet of Things (IoT) platforms and communication protocols, such as the Open Charge Point Protocol, to enable load balancing, dynamic pricing, and grid-friendly demand response. Vehicle-to-grid (V2G) capabilities, though nascent in two-wheelers, hold potential for grid stabilization during peak load conditions

3.3. Electric Motor and Powertrain Systems

Electric motors are the core propulsion components of E2Ws. Modern E2Ws predominantly employ brushless DC (BLDC) motors and permanent-magnet synchronous motors (PMSMs) (Prabhu et al. 2023). BLDC motors provide simplified control, whereas PMSMs provide superior efficiency at higher speeds. An improved design of the electric motor is prudent for efficient deployment. For example, hub motors dominate the low-cost segment because of their space efficiency and reduced transmission losses (Madichetty et al. 2021). However, they often exhibit lower heat dissipation and are limited in terms of torque output. In contrast, mid-drive motors are attached to a gear system (Choudhary et al. 2023). This integration allows for better torque multiplication and load distribution. Motor controllers play a pivotal role in regulating the torque, speed, and efficiency by precisely modulating the current and voltage. Field-oriented control and direct torque control perform dynamic responses under varying loads and terrain conditions. Inverters utilizing SiC or gallium nitride power devices have also been introduced to increase the switching frequency and reduce thermal losses (Suthar et al. 2025). Integrated motor-controller units reduce the component count and wiring complexity, thereby improving reliability and reducing manufacturing costs. Moreover, intelligent thermal management systems employing active air or liquid cooling are being incorporated to mitigate heat buildup during high-demand operations, particularly in tropical environments.

The performance of E2W powertrains is often evaluated based on metrics such as torque density (Nm.kg^{-1}), power-to-weight ratio, efficiency curves across speed-load profiles, and thermal stability (Kumaresan & Rammohan 2024). Innovations in rare-earth magnet technology, winding topologies, and core material selection have continued to improve these metrics. Recent advances in axial flux motor designs are also attracting attention due to their flat geometry, high torque output, and suitability for compact vehicular platforms (Gadiyar et al. 2023).

3.4. Regenerative Braking and Energy Recovery

Regenerative braking is a mechanism by which the kinetic energy of a vehicle is converted back into electrical energy and stored in the battery (Yang et al. 2024). This is achieved by operating an electric motor as a generator during deceleration. The harvested energy is rerouted through a bidirectional inverter and managed by the BMS to safely recharge the battery (Wager et al. 2018). In E2W, regenerative braking can contribute approximately 10–20% of the overall energy recovery under urban stop-and-go driving conditions. The degree of energy recovery depends on factors such as vehicle speed, mass, terrain, braking intensity, and the regenerative braking algorithm implemented by the control unit of the vehicle. This recovery typically corresponds to approximately 5–15 $Wh.km^{-1}$ of reclaimed energy, depending on the vehicle mass, average speed of 20–40 km h^{-1}, braking intensity, and control strategy implemented by the motor controller and battery management system. Higher recovery efficiencies have been reported in dense urban traffic and delivery-use cycles, whereas lower gains have been observed under steady-speed or highway-like conditions, where braking opportunities are limited. Modern E2Ws use variable levels of regenerative braking, either preset or user-adjustable, to balance the braking smoothness with the energy recovery performance. Although regenerative braking adds a layer of complexity to the drivetrain, the benefits in energy efficiency are substantial.

3.5. IoT Integration, BMS and Telematics

The integration of smart technologies, such as GPS navigation, remote diagnostics, and ride behavior analytics, into E2Ws is playing a growing role in enhancing safety, efficiency, and user experience. These features are enabled by IoT platforms and embedded telematics. IoT integration helps E2Ws build cloud platforms and infrastructure systems. As these smart technologies are embedded with sensors and microcontrollers, they continuously monitor vehicle parameters such as the battery state of charge, motor temperature, and fault codes (Nayak et al. 2023). This information is transmitted to cloud servers via cellular or low-power, wide-area networks. Thus, vehicle health, geofencing, and OTA software updates were ensured. Similarly, the BMS regulates the charging and discharging processes to ensure optimal battery performance (Thangavel et al. 2023). The BMS models also support estimation models for the state of health, state of energy, and remaining useful life, which are essential for managing battery degradation and planning maintenance or replacements.

Telematics further extends the capabilities of E2Ws by employing cloud analytics (Kirushanth & Kabaso 2020). This allows improvements in functionalities, such as routing optimization, energy consumption monitoring, and scheduling downtime for charging or maintenance. In addition, the aggregation of telematics data across users helps in understanding traffic management at the macro level. In the emerging frontier, AI-powered edge computing on E2W controllers has been tested for low-latency decision-making without reliance on constant cloud connectivity (Ming 2023).

Synthesis across technological dimensions indicates a pronounced regional differentiation in E2W development pathways. Advanced economies prioritize high-performance battery chemistries, fast-charging compatibility, and digitally integrated powertrains with mature infrastructure and a higher consumer willingness to pay. In contrast, large emerging economies, such as China and India, emphasize cost optimization and scalable manufacturing to support mass adoption. Rapidly motorizing economies, such as Vietnam and parts of Southeast Asia, predominantly adopt entry-level E2W technologies that balance affordability and basic connectivity. These comparisons indicate that technological sustainability in E2Ws is not solely determined by component performance but also by the alignment between battery design, charging strategy, digital integration, and the economic and policy context in which deployment occurs.

4. ENVIRONMENTAL PERFORMANCE AND LIFECYCLE SUSTAINABILITY

The technological configuration of E2Ws outlines their environmental and life-cycle sustainability outcomes. E2Ws are widely promoted as sustainable alternatives to ICE vehicles. However, the environmental benefits of E2Ws must be assessed from raw material extraction to end-of-life disposal (Fig. 2). This section evaluates the environmental footprint of E2Ws, focusing on greenhouse gas (GHG) emissions, air quality, noise pollution, and battery disposal challenges.

4.1. Lifecycle Emissions and Carbon Footprint

Compared to ICE two-wheelers, E2Ws produce zero tailpipe emissions (García-Afonso & González-Díaz 2023). According to LCA studies, battery E2Ws can reduce GHG emissions by 50% to 70% per kilometre travelled, depending

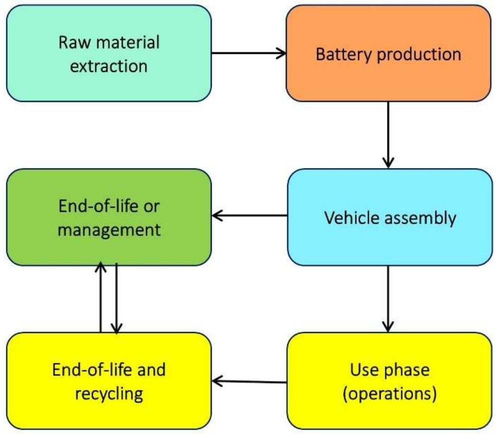

Fig. 2: Life cycle assessment of electric two-wheelers.

on the source of electricity used for charging (Ahmadzadeh et al. 2025). In regions powered by renewable energy (e.g., hydro, solar, or wind), the emission reduction is even more pronounced. However, in coal-dependent countries such as India and China, the upstream emissions from electricity generation partially offset the tailpipe benefits. The manufacturing phase, particularly of Li-ion batteries, is energy-intensive and contributes a considerable share of overall emissions. Despite this, the operational phase of E2Ws can offset the initial carbon debt over time through lower energy consumption and higher efficiency, with compensation periods varying according to electricity grid intensity, vehicle utilization, and battery chemistry.

Beyond carbon emissions, E2Ws contribute meaningfully to improved air and acoustic quality (Münder & Carbon 2022). By eliminating combustion-based exhaust, E2Ws significantly reduce the release of fine particulate matter. These particulate matters, such as PM2.5 and PM10, nitrogen oxides, and other hazardous pollutants, are major contributors to respiratory illnesses and cardiovascular disorders (Henning 2024). This is important in urban centers of low- and middle-income countries, where obsolete emission standards prevail. Furthermore, the quiet operation of electric motors mitigates urban noise pollution. While beneficial, this near-silent performance has also raised pedestrian safety concerns, leading some jurisdictions to mandate minimum noise levels for electric vehicles to alert passersby, particularly the visually impaired (Pardo-Ferreira et al. 2020).

4.2. Battery Disposal and Recycling Concerns

The end-of-life management of batteries is a significant environmental concern. Li-ion batteries contain toxic and rare metals such as cobalt, nickel, and lithium, which pose ecological risks if not recycled properly (Piątek et al. 2021). The inadequate recycling infrastructure in many countries has led to improper disposal practices. For instance, landfilling and incineration can result in groundwater contamination and the generation of hazardous waste. Efforts are underway to establish closed-loop recycling systems and second-life applications for used EV batteries. In India, policy frameworks under the Battery Waste Management Rules (2025), released by the Ministry of Environment, Forest, and Climate Change, India, aim to promote extended producer responsibility and safe collection, disassembly, and material recovery (Central Pollution Control Board 2025). Technologies such as hydrometallurgical and pyrometallurgical recycling are being developed to extract critical minerals efficiently and safely (Sethurajan et al. 2019).

4.3. Sustainability Trade-Offs and Regional Disparities

The sustainability profile of E2Ws is highly dependent on the context. In countries with greener electricity grids, strong recycling systems, and robust policy support, E2Ws offer substantial and long-term benefits. In contrast, in regions lacking renewable energy infrastructure and battery recycling facilities, the full environmental potential of E2Ws is unrealized. Furthermore, the global reliance on resource-intensive battery materials raises ethical and ecological questions related to mining practices and supply chain sustainability, particularly in resource-rich but economically vulnerable regions, such as the Democratic Republic of the Congo (for cobalt) (Feng et al. 2023).

4.4. Raw Materials and Resource Extraction

The production of lithium-ion (Li-ion) batteries requires raw materials such as lithium, cobalt, nickel, manganese, and graphite. These minerals are primarily sourced from geologically concentrated regions, such as lithium from South America's "Lithium Triangle," cobalt from the

Democratic Republic of Congo, and nickel from Indonesia and the Philippines. Mining operations in these areas raise concerns regarding ecological degradation (Piatek et al. 2021). Extraction processes are energy- and water-intensive. This tedious processing contributes to a notable upstream carbon footprint even before manufacturing begins. The lack of stringent environmental regulations in many mineral-rich countries exacerbates the sustainability dilemma. While efforts are underway to encourage responsible sourcing initiatives, government initiatives have also been implemented to encourage researchers and manufacturers to explore next-generation battery chemistries, such as solid-state batteries or Na-ion alternatives.

4.5. Waste Conservation Strategies

Significant waste is generated through metal processing, component molding, and battery cell fabrication during manufacturing. As end waste has significant environmental implications, manufacturers are gradually adopting lean manufacturing practices and zero-waste production targets. At the post-consumer stage, the focus shifts to waste conservation through reuse, repurposing, and recycling. One promising approach that is gaining prominence is the repurposing of used EV batteries for stationary energy storage (Sethurajan et al. 2019). This extends the utility of batteries before they enter recycling channels and reduces the pressure on raw material extraction. Eco-design principles are gaining traction, encouraging modular vehicle architectures that facilitate easy component recovery. Regulatory bodies mandate manufacturers to establish take-back schemes and eco-labeling for tracking. These strategies support a shift from a linear “take-make-dispose” model to a closed-loop, resource-efficient E2W ecosystem.

Cross-economy synthesis of environmental performance reveals that life cycle sustainability outcomes vary significantly by regional context. In advanced economies, E2Ws achieve faster carbon payback periods and greater net emission reductions. In large emerging economies, operational emission benefits are partially offset by grid carbon intensity and battery manufacturing emissions, shifting the sustainability emphasis toward battery longevity and recycling efficiency. Rapidly motorizing economies exhibit the highest marginal mitigation potential owing to heavy two-wheeler reliance; however, environmental gains remain constrained by limited recycling infrastructure and fossil-dominated power systems. These inferences highlight that the environmental advantages of E2Ws are contingent on systemic factors that extend beyond vehicle technology alone.

5. MARKET DYNAMICS AND ADOPTION TRENDS

Although environmental performance determines sustainability potential, market dynamics ultimately govern the scale and pace of E2W adoption. The global E2W market has witnessed a significant surge in recent years (Fig. 3). This surge was induced by increasing environmental awareness, regulatory support, and advances in battery and motor technologies. Although traditional ICE two-wheelers still dominate global sales, E2Ws are rapidly gaining market share. This section explores market trends, adoption patterns, regional comparisons, and consumer behavior that shape the evolving E2W landscape.

The E2W market was valued at approximately USD 15.5 billion in 2017, with forecasts projecting growth to USD 30 billion by the end of 2025, at a compound annual growth rate of over 7.5% (Nayak et al. 2023). The market surge is due to rising fuel prices, urban air quality mandates, and favorable government incentives. Asia-Pacific dominates the E2W market, with China alone accounting for over 300 million E2Ws in operation (He et al. 2022, Li et al. 2018). This

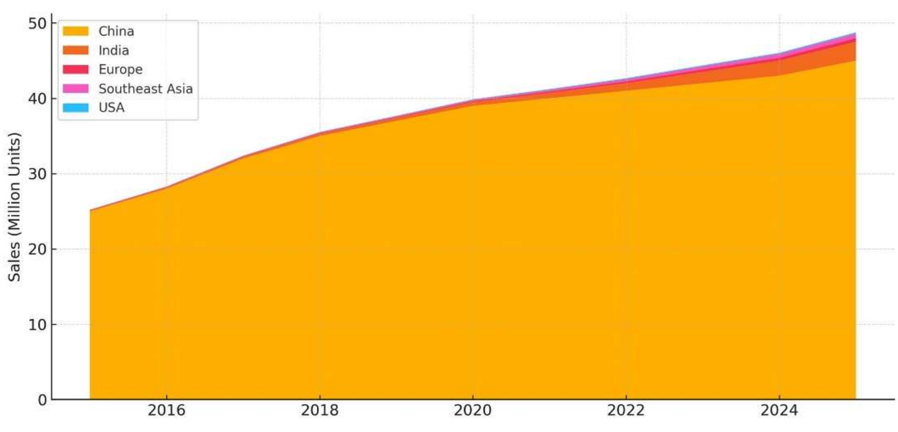

Fig. 3: Global electric two-wheeler sales (2016-2024).

is possible because of the supported regulatory mandates, domestic battery production, and aggressive urban transport policies (Wu et al. 2021). India is emerging as a pivotal region for E2W growth, owing to its status as the world's largest two-wheeler market by volume (Chaturvedi et al. 2022). With over 187 million two-wheelers in circulation and a high dependence on ICE scooters and motorcycles, India presents both challenges and opportunities for electric mobility. The implementation of national programs such as FAME-I and FAME-II, coupled with state-level incentives and tax rebates, has catalyzed the growth of domestic players, such as Ather Energy, Ola Electric, Hero Electric, and TVS (Singh et al. 2022). In contrast, adoption in Europe and North America is relatively moderate but accelerating owing to climate commitments, fuel economy regulations, and urban low-emission zones (Knez et al. 2019). Countries such as the Netherlands, Germany, and France have seen an increased uptake of electric mopeds and shared micro-mobility solutions (Razmjoo et al. 2022). In the United States, although adoption remains niche, innovative startups and rideshare platforms are expanding the E2W footprint, particularly in cities with sustainability mandates (Jenn et al. 2018).

5.1. Regional Adoption Patterns

The adoption of E2Ws varies significantly across different regions. In China, the E2W market is the most mature and expansive. With over 300 million E2Ws in operation, China accounts for more than 80% of the global E2W sales (Ou et al. 2021). This dominance is attributed to early policy interventions, extensive subsidies, and the rapid deployment of charging and battery-swapping infrastructure. The success of leading manufacturers such as Yadea, Aima, and Niu Technologies has further strengthened China's position as a global hub for both domestic consumption and export of E2Ws. In India, the E2W market has shown promising growth, despite infrastructural and regulatory challenges. India's two-wheeler dominance in the global ICE market is now translating into a shift towards electrification, driven by start-ups such as Ather Energy and Ola Electric and established players such as Hero Electric and TVS (Gupta & Anand et al. 2025). Localized production mandates and state-level subsidies have further accelerated market penetration, particularly in metropolitan regions and among last-mile delivery operators. European countries, particularly the Netherlands, France, Germany, and Spain, are witnessing a steady rise in E2W adoption as part of broader climate action strategies and sustainable mobility plans (Razmjoo et al. 2022). Growth is primarily concentrated in urban areas, where strict emissions regulations, congestion charges, and dedicated bike lanes create a conducive environment for electric mobility. Unlike Asia, in Europe, E2W is frequently positioned as a lifestyle or eco-conscious choice. Several governments provide purchase incentives and tax rebates, whereas shared mobility companies such as Lime and Tier have integrated E2Ws into their micro-mobility fleets (Lime 2025). In the United States, E2W adoption remains relatively niche but is growing steadily, especially in coastal urban centers such as San Francisco, New York, and Los Angeles (Onat et al. 2018). Regulatory support, such as grants for electric vehicle infrastructure, is uneven across states but is improving. The market is primarily led by high-end manufacturers such as Zero Motorcycles and new entrants offering affordable urban commuting options. The Southeast Asian market, comprising countries such as Vietnam, Thailand, and Indonesia, shows high latent potential owing to the dominant role of two-wheelers in daily transportation (Kim et al. 2025). However, the uptake of E2Ws is currently hampered by cost sensitivity, limited charging infrastructure, and a lack of localized policy incentives. Nevertheless, increasing investments from regional automotive firms and government-backed pilot projects are beginning to lay the groundwork for broader adoption of hydrogen vehicles.

5.2. Consumer Behavior and Market Segmentation

Consumer behavior is the adoption of E2Ws. Several factors influence the decision to adopt E2Ws. Environmental awareness, operational convenience, and government incentives are the prime deciding factors. In developing markets such as India, Southeast Asia, and parts of Africa, cost sensitivity remains the dominant factor in shaping consumer behavior (Eccarius et al. 2020). Consumers in these regions prioritize the total cost of ownership, factoring in both the initial purchase price and long-term fuel savings. However, range anxiety, limited public charging infrastructure, concerns about battery degradation, and uncertainties surrounding resale value continue to pose psychological barriers. Conversely, in developed markets, environmental concerns increasingly motivate consumers to adopt E2Ws. Here, a segment of environmentally conscious early adopters drives demand, often prioritizing zero-emission credentials, quiet operation, and integration with broader smart mobility ecosystems (Ashok et al. 2024).

The E2W market can be broadly segmented into three principal categories: low-speed, mid-range, and high-performance (Jaiswal et al. 2022). Low-speed electric scooters operating at 25–45 $km.h^{-1}$ are widely adopted for short-distance urban commutes and require minimal licensing and registration in many jurisdictions. This segment is particularly dominant in China. Mid-range commuter E2Ws, operating in the 50–70 $km.h^{-1}$ speed range, represent the largest market segment in countries such as India. These vehicles cater to mainstream consumers seeking alternatives to ICE motorcycles. High-performance electric motorcycles serve a niche yet rapidly growing segment, primarily in developed economies. These models can exceed 100 km.h^{-1}, with ranges surpassing 150 km. They are appealing to users seeking advanced technology, superior acceleration, and recreational value. In parallel, subscription-based ownership, battery leasing, and BaaS are gaining traction among individuals who find personal vehicle ownership impractical or cost-prohibitive. These models help mitigate concerns regarding battery replacement costs and depreciation, further lowering the barriers to entry for prospective E2W users.

Market adoption patterns differ markedly across different economic contexts. China's large-scale manufacturing ecosystem provides rapid diffusion through price compression and infrastructure availability, whereas India's market growth remains highly policy-driven and uneven across states. Emerging economies exhibit high latent demand due to two-wheeler dependence; however, adoption is constrained by affordability, financing access, and charging availability. These findings indicate that market growth is not solely technology-driven but is shaped by institutional and economic conditions.

6. POLICY LANDSCAPE AND INCENTIVE MECHANISMS

Given the observed disparities in market adoption across regions, policy frameworks play a critical role in shaping the deployment trajectories. Government policies, financial incentives, and regulatory frameworks influence the adoption of E2Ws. Given the socioeconomic and infrastructural disparities across countries, policy frameworks vary in scale and scope. This section evaluates policy approaches across economies through three thematic lenses: implementation burden, localizability feasibility, and financial sustainability.

6.1. Fiscal Incentives and Subsidies

Fiscal incentives aim to offset the high upfront costs of E2Ws, which remain a major barrier to adoption. In India, the FAME-I (2015) and FAME-II (2019–ongoing) schemes have stimulated demand through purchase subsidies linked to battery capacity and localization requirements (Saha et al. 2024). Under FAME-II, subsidies of ₹10,000 per kWh are contingent upon 50% component localization, whereas the GST on electric vehicles has been reduced to 5% compared with 28% for ICE two-wheelers (Salman et al. 2018). However, such incentives impose fiscal burdens and raise questions regarding their long-term affordability once subsidies are withdrawn.

Historically, China has provided substantial purchase subsidies, reaching up to 60,000 yuan, coupled with extensive public investment in charging and battery-swapping infrastructure (Zhao et al. 2024). The gradual phase-out of these subsidies reflects concerns over fiscal sustainability, with policy emphasis shifting toward research, development, and domestic battery manufacturing. European countries, such as France, Germany, and Italy, offer targeted purchase incentives and tax deductions, often supplemented by non-monetary benefits, such as parking exemptions (Sheldon & Dua 2019). In the United States, federal tax credits of up to USD 2,500 are complemented by state-level programs and infrastructure funding under the Bipartisan Infrastructure Law (Muehlegger et al. 2022). Across regions, evidence suggests that subsidies accelerate early adoption but yield diminishing returns without parallel infrastructure and market maturation.

6.2. Non-Fiscal Incentives and Urban Policies

Non-fiscal policies enhance the usability and regulatory acceptance of E2Ws but differ in administrative complexity. License exemptions for low-speed E2Ws reduce entry barriers for new users, whereas low-emission and EV-restricted zones in cities discourage ICE use and indirectly promote electrification (Patil & Majumdar 2021). Fleet electrification mandates for delivery and ridesharing services, such as India's 30% electrification target by 2030 (Chaturvedi et al. 2022), demonstrate strong regulatory intent but impose substantial coordination and enforcement burdens, particularly in fragmented governance systems. Therefore, implementation effectiveness is contingent on institutional capacity and urban planning integration, rather than policy ambition alone.

6.3. Localization and Manufacturing Policies

Localization policies seek to reduce import dependence and strengthen domestic supply chains in the country. India's Production Linked Incentive scheme for advanced chemistry cells allocates ₹18,100 crores to stimulate domestic battery manufacturing (Kumar & Shrimali 2020), supported by phased manufacturing programs targeting motors, controllers, and power electronics. China's vertically integrated manufacturing ecosystem, supported by sustained policy backing and market access for firms such as CATL and BYD, has achieved rapid cost reductions and scale advantages (Liu et al. 2019, Li et al. 2022). Comparative evidence indicates that localization success depends on pre-existing industrial capacity and supplier ecosystems; in their absence, localization mandates risk, increasing costs, and delaying the deployment.

6.4. Comparative Effectiveness of Policies

Policy effectiveness varies widely across economies owing to differences in governance structures. China's centralized policymaking has provided rapid scaling and industrial dominance through early ICE restrictions and coordinated manufacturing support (Ou et al. 2021, Zhao et al. 2024). In contrast, India's ambitious but fragmented policy landscape has produced heterogeneous outcomes across states despite national-level incentives (Knez et al. 2019, Gupta & Anand 2025). European approaches have been effective in dense urban contexts but remain limited in scale, while rapidly motorizing economies continue to face gaps in developing stable incentive frameworks. Overall, the evidence suggests that durable E2W adoption emerges not from isolated incentives but from a coherent alignment between fiscal capacity, administrative feasibility, and industrial readiness.

7. KEY CHALLENGES, EMERGING OPPORTUNITIES, AND FUTURE RESEARCH DIRECTIONS

In direct response to the problem (the sustainability of E2W remains fragmented and context-dependent across economies) identified in this review, this section synthesizes the key challenges, emerging opportunities, and future outlook shaping large-scale E2W adoption. Numerous challenges hinder the widespread and sustainable adoption of E2Ws. These challenges span technological, economic, infrastructural, and behavioral dimensions of the industry. A comprehensive understanding of these obstacles is essential for the effective and equitable scaling up of electric mobility solutions (Tarei et al. 2021). Although the global E2W market has demonstrated significant growth, several technical, economic, and institutional barriers continue to constrain the sector's full potential. The high upfront cost of E2Ws remains a persistent obstacle. Although the total cost of ownership of E2Ws is often favorable over the vehicle's lifespan owing to lower fuel and maintenance costs, the initial purchase price is elevated largely owing to the high cost of Li-ion batteries. The cost accounts for approximately 30–40% of the vehicle cost (Patil et al. 2022). Although government subsidies have partially mitigated this burden, many consumers remain price-sensitive.

Charging infrastructure gaps represent another major limitation (Palani et al. 2023). Public charging stations remain concentrated primarily in urban centers, whereas rural and semi-urban regions continue to suffer from inadequate grid access and unreliable electricity supply. Although battery-swapping models offer a promising alternative, the absence of standardized battery formats across manufacturers limits widespread interoperability and scalability. Battery safety and thermal management are also critical concerns (Misar & Thombre 2024). Li-ion battery packs are highly sensitive to environmental conditions, such as temperature, humidity, and overcharging. In hot and humid climates, improper battery management has led to several well-publicized fire incidents that undermine consumer confidence. Range anxiety and battery degradation remain psychological and technical challenges, respectively. Although the E2W range has improved with advances in energy density, many consumers continue to perceive range limitations as a significant risk. Regulatory fragmentation and policy uncertainty hinder consistent growth. Financing barriers further complicate adoption by individual and institutional consumers. Many traditional lenders are reluctant to finance E2Ws because of their relatively untested resale markets and perceived technological risks.

Several emerging trends and untapped opportunities have the potential to accelerate E2W adoption and reshape the global mobility landscape in the next decade. The localization of battery manufacturing and supply chains is emerging. Many countries, such as India, are investing heavily in the domestic production of advanced battery chemistries, supported by government-backed incentive schemes, such as the production-linked incentive program. As battery technologies mature, research into alternative chemistries, such as Na-ion batteries and cobalt-free lithium iron phosphate formulations, is increasing (Chu et al. 2021). Developing circular economy frameworks is another opportunity that can enable battery repurposing in the automotive industry. Technologies such as hydrometallurgical recycling are being actively developed to maximize the recovery rates of critical minerals. The integration of E2Ws with renewable energy systems and smart grids is another area of significant potential (Ismail et al. 2023). The deployment of solar-powered charging stations with net metering and dynamic pricing models can reduce the carbon intensity of charging operations in the long run. Facilities with V2G capabilities could allow E2Ws to serve as distributed storage assets (Shah & Payami 2023). Urbanization and smart city development are also creating new markets for multimodal transport systems, where E2Ws complement mass transit networks as first- and last-mile solutions.

8. LIMITATIONS

This study had certain limitations that should be acknowledged. The analysis used secondary literature and offers qualitative interpretation rather than a quantitative meta-analysis, which may introduce selection or interpretive bias. In addition, heterogeneity across studies in lifecycle assessment boundaries, grid emission factors, and technology performance metrics limits direct numerical comparability. While substantial literature is available for major markets, empirical evidence from rapidly motorizing economies remains comparatively limited, which may affect the depth of contextual interpretation in these regions. Ongoing advancements in battery chemistry, charging infrastructure, and regulatory frameworks may outpace the temporal coverage of the reviewed literature, meaning that some conclusions reflect current trends rather than long-term, stabilized outcomes.

9. CONCLUSIONS

E2Ws represent a transformative step toward sustainable, affordable, and inclusive mobility. As nations strive to meet climate targets, the electrification of two-wheelers provides a practical and scalable solution. Despite technological advancements and increasing policy support, the widespread adoption of E2Ws faces several challenges. However, ongoing innovations are progressively addressing these issues. Emerging business models enhance convenience and reduce cost barriers. To capitalize on these opportunities, coordinated efforts are required across the policy, industry, and research domains. Localized manufacturing, circular economy practices, renewable energy integration, and data-driven policymaking must be prioritized to accelerate E2W deployment. As cities continue to evolve toward cleaner and smarter mobility systems, E2Ws are poised to play a pivotal role in shaping urban transport.

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