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Review

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 for decarbonizing urban transport. Their sustainability implications across different economic contexts remain uneven and insufficiently synthesized. This review evaluates the sustainability of E2Ws across different economic contexts by synthesizing technological, environmental, market, and policy evidences. 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 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 battery manufacturing impacts, 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.

Key Words	Battery technology, Electric two-wheelers, Lifecycle assessment, Policy incentives, Sustainable mobility
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1. INTRODUCTION

The rapid urbanization of the 21st century has intensified the global demand for sustainable, efficient, and cost-effective modes of transportation. In this context, electric two-wheelers (E2Ws) have emerged as a critical component of the global mobility transition, especially 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 fleet in many developing economies. In India alone, there are over 187 million two-wheelers in operation, accounting for more than 70% of the country's total registered vehicles (Jindel et al. 2022). Their affordability, maneuverability, and fuel efficiency make them indispensable for short- and medium-distance commuting. However, the heavy dependence on internal combustion engine (ICE)-based two-wheelers exacerbates fossil fuel consumption and environmental pollution (Lie et al. 2024). Globally, the transport sector is responsible for nearly 24% of direct CO_2 emissions from fuel combustion (Solaymani 2019). The personal mobility accounting for a significant share in 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 electricity generation mix and usage patterns.

The technological evolution of E2Ws has been largely because of improvements in battery chemistries, regenerative braking, and compact motor designs. Innovations in battery swapping and fast-charging infrastructure have further enhanced their usability (Ahmad et al. 2023). 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.

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 thematic dimensions. Such fragmentation limits the transferability of insights across economies at different stages of development. This narrative review addresses this gap by critically assessing E2W sustainability through a comparative, economy-based framework, 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 comparison and policy learning. Special emphasis is placed on major E2W markets such as India and China, alongside Vietnam as a representative emerging economy 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

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, or 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 cross-regional comparison.

3 TECHNOLOGICAL DEVELOPMENTS IN E2WS

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

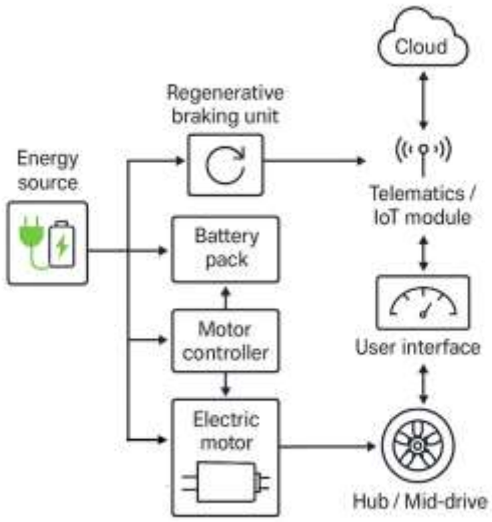

Fig. 1. System architecture of electric two-wheelers.

3.1 Battery Innovations

The industry has largely transitioned from valve-regulated lead-acid and nickel-metal hydride batteries to Li-ion chemistries due to their higher energy densities that range from 150–250 Wh/kg (Kumar et al. 2023). They have longer cycle life, ranging from 1,000–2,000 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, operating in a temperature range of −20 °C to 60 °C. This temperature range make 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. 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 lithium diffusion but increase sensitivity to thermal and structural stress (Padhi et al. 1997; Xu et al. 2012)

Solid innovations have provided alternatives like solid-state batteries, which replace the liquid electrolyte with a solid electrolyte. They offer the higher energy densities which may be greater than 400 Wh/kg (Xiao et al. 2020). Sodium-ion (Na-ion) batteries are also gaining attention as a low-cost, resource-abundant option. The offer moderate energy densities (100–160 Wh kg^{-1}) and improved thermal stability (Voß et al. 2025). From a lifecycle 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 chemistry and energy source (Ellingsen et al. 2016).

Although commercial deployment is still limited by high production costs and material challenges, companies like 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 design. Battery swapping technologies can reduce downtime and permit smaller, lighter battery packs in fleet and shared-mobility applications (Vallera et al. 2021). This architecture is beneficial in shared mobility and commercial fleet applications where uptime is critical. Likewise, advancements in battery management systems (BMS) have significantly improved the real-time monitoring and charge balancing. Modern BMS units use AI and cloud-based telematics to optimize charging behavior, predict faults, and extend battery lifespan (Nyamathulla & Dhanamjayulu 2024). Thermal management remains a critical focus in high-temperature regions. 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). Improvements in battery lifecycle sustainability are being driven by innovations in recyclability, cobalt-free chemistries, and green synthesis routes. Startups and research institutions are investing in closed-loop recycling techniques using 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. E2Ws primarily rely on three charging modalities: slow charging, fast charging, and battery swapping, each offer distinct benefits and use-case suitability (Al-Saadi et al. 2021). The 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 250W and 1.5kW (Gnann et al. 2019). It takes approximately 4 to 6 hours for a full charge, though overall charging time depends on battery capacity too. Slow charging maintains battery longevity due 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 use DC charging protocols such as CHAdeMO or CCS2. These systems deliver power in the range of 3 kW to 22 kW for two-wheelers (Tu et al. 2019). Battery chemistries such as lithium-titanate in conjugation with thermal management systems have enabled E2Ws to safely achieve 80% state-of-charge in under 30 minutes (Hussain et al. 2024). Nonetheless, fast charging can accelerate battery degradation if not properly managed by BMS, thus requiring trade-offs between speed, cost, and battery health. Battery swapping is an emerging solution 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 "charging" time to less than five minutes. Battery-as-a-service (BaaS) models decouple battery ownership from the vehicle, thereby reducing upfront costs and addressing range anxiety. Companies such as Gogoro, NIO, and Ola Electric are deploying modular and interoperable battery platforms to promote standardization and network scalability (Boti et al. 2024). The integration of smart charging systems is also gaining momentum. These systems use Internet of Things (IoT) platforms and communication protocols such as 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 component 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 while PMSMs provide superior efficiency at higher speeds. An improved design in electric motor is prudent in efficiency deployment. For example, hub motors dominate the low-cost segment due to their space efficiency and reduced transmission losses (Madichetty et al. 2021). However, they often show lower heat dissipation and are limited in torque output. On the other hand, mid-drive motors are attached with a gear system (Choudhary et al. 2023). This integration allows better torque multiplication and load distribution. Motor controllers play a pivotal role in regulating torque, speed, and efficiency through precise modulation of current and voltage. Field-oriented control and direct torque control perform dynamic response under varying load and terrain conditions. Inverters utilizing silicon carbide or gallium nitride power devices are also being introduced to increase switching frequency and reduce thermal losses (Suthat et al. 2025). Integrated motor-controller units reduce 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), 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 continue 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).

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

Battery Type	Chemistry	Energy Density (Wh/kg)	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, potential low-cost future alternative

3.4 Regenerative Braking and Energy Recovery

Regenerative braking is a mechanism by which the kinetic energy of the vehicle is converted back into electrical energy and stored in the battery (Yang et al. 2024). This is achieved by operating the electric motor as a generator during deceleration. The harvested energy is re-routed 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 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. This recovery typically corresponds to about 5–15 Wh km^{-1} of reclaimed energy, depending on 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 are reported in dense urban traffic and delivery-use cycles, while lower gains are 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 braking smoothness with 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 like 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 units. IoT integration helps E2Ws to build cloud platforms and infrastructure systems. As these smart technologies are embedded with sensors and microcontrollers, they continuously monitor vehicle parameters such as 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 are ensured. Likewise, BMS regulates the charging and discharging processes to ensure optimal battery performance (Thangavel et al. 2023). The BMS models also support estimation models for 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 schedule downtime for charging or maintenance. In addition, the aggregation of telematics data across users helps in macro-level understandings for traffic management. In the emerging frontier, the AI-powered edge computing on E2W controllers, are tested for low-latency decision-making without reliance on constant cloud connectivity (Ming 2023).

Synthesis across technological dimensions indicates 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 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, for instance, Vietnam and parts of Southeast Asia, predominantly adopt entry-level E2W technologies that balance affordability and basic connectivity. These comparisons point that technological sustainability in E2Ws is not solely determined by component performance, but by 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 lifecycle sustainability outcomes. E2Ws are widely promoted as a sustainable alternative to ICE vehicles. However, the environmental benefits of E2Ws must be assessed from raw material extraction to end-of-life disposal (Figure 2). This section evaluates the environmental footprint of E2Ws, focusing on greenhouse gas (GHG) emissions, air quality, noise pollution, and battery disposal challenges.

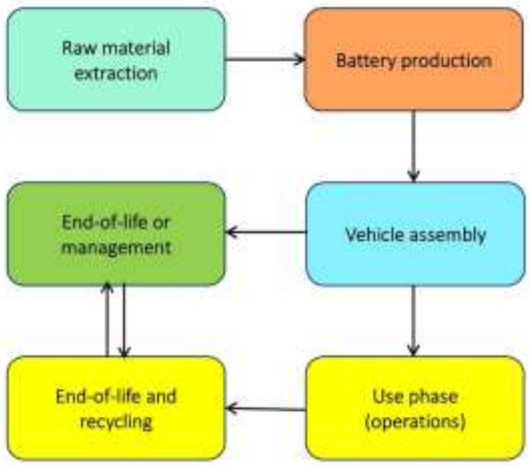

Fig. 2. Life cycle assessment of electric two wheelers.

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 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 remains a significant environmental concern. Li-ion batteries contain toxic and rare metals such as cobalt, nickel, and lithium, which pose ecological risks if not properly recycled (Piątek et al. 2021). Inadequate recycling infrastructure in many countries has led to improper disposal practices. For instance, landfilling and incineration can result in groundwater contamination and hazardous waste generation. 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 context-dependent. In countries with greener electricity grids, strong recycling systems, and robust policy support, E2Ws offer substantial long-term benefits. In contrast, in regions lacking renewable energy infrastructure and battery recycling facilities, the full environmental potential of E2Ws remains 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 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 e.g., 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 about ecological degradation (Piatek et al. 2021). The extraction processes are energy- and water-intensive. The tedious processing contributes to a notable upstream carbon footprint even before manufacturing begins. A lack of stringent environmental regulations in many mineral-rich countries exacerbates the sustainability dilemma. While as efforts are underway to encourage responsible sourcing initiatives, the government initiatives are also put in place 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 the manufacturing phase. As the end waste has significant environment 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 earning prominence is repurposing used EV batteries for stationary energy storage purposes (Sethurajan et al. 2019). This extends the utility of batteries before they enter recycling channels and reduces pressure on raw material extraction. Eco-design principles are gaining traction, encouraging modular vehicle architecture that facilitates easy component recovery. Regulatory bodies mandates manufacturers to establish take-back schemes and eco-labelling 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 lifecycle 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 sustainability emphasis toward battery longevity and recycling efficiency. Rapidly motorizing economies exhibit the highest marginal mitigation potential due to heavy two-wheeler reliance, but 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 extending beyond vehicle technology alone.

5 MARKET DYNAMICS AND ADOPTION TRENDS

While 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 (Figure 3). This surge is induced by increasing environmental awareness, regulatory support, and advances in battery and motor technologies. While 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.

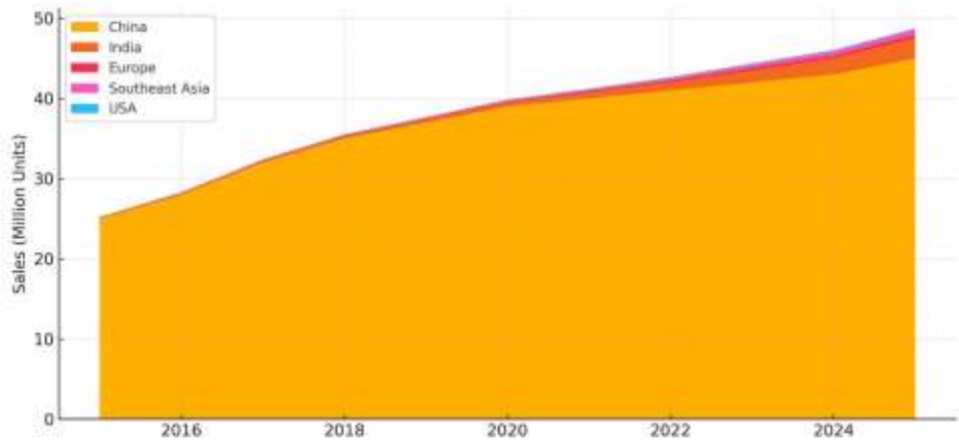

Fig. 3. Global electric two-wheeler sales (2016-2024).

The E2W market was valued at approximately USD 15.5 billion in 2017, with forecasts projecting growth to USD 30 billion by 2025 end, at a compound annual growth rate of over 7.5% (Nayak et al. 2023). The market surge is because of 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 is possible because of 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 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 a challenge and an opportunity 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 like 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 due to climate commitments, fuel economy regulations, and urban low-emission zones (Knez et al. 2019). Countries such as the Netherlands, Germany, and France are seeing increased uptake of electric mopeds and shared micro-mobility solutions (Razmjoo et al. 2019). In the United States, although adoption remains niche, innovative startups and ride-share platforms are expanding the E2W footprint, particularly in cities with sustainability mandates (enn et al. 2018).

5.1 Regional Adoption Patterns

The adoption of E2Ws varies significantly across regions. In China, the E2W market is by far the most mature and expansive. With over 300 million E2Ws in operation, China accounts for more than 80% of global

E2W sales (Ou et al. 2021). This dominance is attributed to early policy interventions, extensive subsidies, and 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 the 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 like Ather Energy, 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, especially 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). The 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 are frequently positioned as lifestyle or eco-conscious choices. Several governments provide purchase incentives and tax rebates, while shared mobility companies like 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 improving. The market is primarily led by high-end manufacturers like Zero Motorcycles and new entrants offering affordable urban commuting options. The Southeast Asian market, comprising countries like Vietnam, Thailand, and Indonesia, shows high latent potential due 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.

5.2 Consumer Behavior and Market Segmentation

Consumer behavior is determinantal in the adoption of E2Ws. The decision to adopt E2Ws is influenced by multiple factors. Environmental awareness, operational convenience, and government incentives are prime deciding factors. In developing markets such as India, Southeast Asia, and parts of Africa, cost sensitivity remains the dominant factor shaping consumer behavior (Eccarius et al. 2020). Consumers in these regions prioritize 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 act as psychological barriers. Conversely, in developed markets environmental concerns increasingly motivate consumers to adopt E2Ws. Here, a segment of environmentally conscious early adopters is driving 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 commuter, and high-performance (Jaiswal et al. 2022). Low-speed electric scooters operating under 25–45 km/h, 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 speed range and represent the largest market segment in countries like India. These vehicles cater to mainstream consumers seeking an alternative to ICE motorcycles. High-performance electric motorcycles serve a more niche yet rapidly growing segment, primarily in developed economies. These models are capable of exceeding 100 km/h with ranges surpassing 150 km. They are emerging appealing in users who seek 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 as impractical or cost-prohibitive. These models help to mitigate concerns over battery replacement costs and depreciation, further lowering barriers to entry for prospective E2W users.

Market adoption patterns differ markedly across 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, but adoption is constrained by affordability, financing access, and charging availability. These findings indicate that market growth is not solely technology-driven but 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 deployment trajectories. Government policies, financial incentives, and regulatory frameworks influence the adoption of E2Ws. Given the socio-economic 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, localization feasibility, and financial sustainability.

6.1 Fiscal Incentives and Subsidies

Fiscal Fiscal incentives aim to offset the high upfront cost of E2Ws, which remains a major adoption barrier. 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, while 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 long-term affordability once subsidies are withdrawn.

China historically 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 like 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 usability and regulatory acceptance of E2Ws but differ in administrative complexity. License exemptions for low-speed E2Ws reduce entry barriers for new users, while low-emission and EV-restricted zones in cities discourage ICE use and indirectly promote electrification (Patil & Majumdar, 2021). Fleet electrification mandates for delivery and ride-sharing 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. Implementation effectiveness is therefore 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. India's Production Linked Incentive scheme for advanced chemistry cells allocates ₹18,100 crore 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 deployment.

6.4 Comparative Effectiveness of Policies

Policy effectiveness varies widely across economies due to differences in governance structure. China's centralized policymaking 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 stable incentive frameworks. Overall, evidence suggests that durable E2W adoption emerges not from isolated incentives, but from 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 (sustainability of E2W remain 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 sustainable adoption of E2Ws. These challenges span technological, economic, infrastructural, and behavioral dimensions. A comprehensive understanding of these obstacles is essential to scale up electric mobility solutions effectively and equitably (Tarei et al. 2021). While 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 is a persistent obstacle. Although the total cost of ownership of E2Ws is often favorable over the vehicle's lifespan due to lower fuel and maintenance costs, the initial purchase price is elevated largely due to the high cost of Li-ion batteries. The cost accounts for approximately 30–40% of vehicle costs (Patil et al. 2022). While 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, while 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 continues to limit widespread interoperability and scalability. Battery safety and thermal management also present 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, undermining consumer confidence. Range anxiety and battery degradation remain psychological and technical challenges. While 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 also hinder consistent growth. Financing barriers further complicate adoption for both individual and institutional consumers. Many traditional lenders are reluctant to finance E2Ws due to 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 over the next decade. Localization of battery manufacturing and supply chains are emerging. Many countries, for instance India, is (are) investing heavily in domestic production of advanced battery chemistries, supported by government-backed incentive schemes such as the production linked incentive program. As battery technologies mature, there is also increasing research into alternative chemistries such as Na-ion batteries and cobalt-free lithium iron phosphate formulations (Chu et al. 2021). Developing circular economy frameworks is another opportunity that can enable battery repurposing. Technologies like hydrometallurgical recycling are being actively developed to maximize recovery rates of critical minerals. The integration of E2Ws with renewable energy systems and smart grids provides 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 like 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 multi-modal transport systems, where E2Ws complement mass transit networks as first- and last-mile solutions.

8 LIMITATIONS

This study has certain limitations that should be acknowledged. The analysis used secondary literature and offers qualitative interpretation rather than 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 for 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 CONCLUSION

E2Ws represent a transformative step toward achieving sustainable, affordable, and inclusive mobility. As nations strive to meet climate targets the electrification of two-wheelers provide a practical and scalable solution. Despite technological advancements and increasing policy support, the widespread adoption of E2Ws faces challenges. However, ongoing innovations are progressively addressing these limitations. Emerging business models are enhancing convenience and reducing cost barriers. To capitalize on these opportunities, coordinated efforts are required across 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 the future of urban transport.

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