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A Comparative Study of Sustainable Production and Consumption Practices in the Indian Two-Wheeler Sector

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Abstract: The Indian two-wheeler industry vital for urban mobility and economic growth is undergoing a critical transition toward sustainability, shaped by evolving regulations and rapid technological innovation. This study adopts a dual-lens comparative review, integrating regulatory evolution and technological adoption, to assess sustainable production and consumption practices in major industry players including Bajaj Auto, TVS Motors, Hero MotoCorp, Ather Energy, and Ola Electric. By linking policy milestones such as BS-VI emission norms, renewable energy incentives, and electric vehicle (EV) promotion schemes with advancements in battery technology, digital manufacturing, and circular economy initiatives, the analysis identifies synergies, gaps, and best practices. Findings show that while some firms have achieved operational emission reductions of up to 40%, persistent barriers including high capital costs, regulatory inconsistencies, and workforce skill shortages limit broader adoption. The study's novelty lies in providing a structured framework that connects regulatory and technological trajectories to firm-level outcomes, offering actionable strategies for policy–industry alignment. Recommendations include stricter compliance enforcement, accelerated EV infrastructure development, and expanded circular economy practices. These insights contribute to a roadmap for balancing industrial competitiveness, stakeholder interests, and sustainability goals in one of the world's fastest-growing mobility sectors.

1. Introduction

Sustainable production and consumption have emerged as essential pillars for ensuring long-term environmental resilience and economic stability in the face of mounting global challenges [1–3]. In newly industrializing economies, tensions between rapid industrial growth and environmental conservation are particularly visible. India exemplifies this dynamic, with its fast-expanding two-wheeler sector central to urban mobility, socioeconomic development, and industrial modernization facing mounting pressure to

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operate sustainably [4, 5]. In recent years, significant reforms have reshaped manufacturing processes, product design, and consumer behavior, driven by the need to mitigate environmental impacts while sustaining economic progress [6, 7]. The evolution of India's two-wheeler industry reflects progressive adaptation to changing market and policy conditions. Early regulations focused narrowly on basic emission controls, but rising environmental concerns prompted the adoption of more comprehensive strategies, including stringent emission standards, renewable energy integration, and incentives for clean technologies [8]. These developments, extensively documented in the literature, highlight how the interplay between regulatory change and technological innovation has redefined industry benchmarks [9, 10]. Understanding this historical trajectory is critical to assessing the current transition toward sustainable production and consumption in this vital sector [11, 12].

Technological advances particularly in battery systems, digital manufacturing, and integrated supply chains have consistently driven improvements in operational efficiency and environmental performance [13, 14]. As regulatory frameworks and technological breakthroughs increasingly converge, they are fostering an industrial ecosystem capable of meeting, and in some cases exceeding, global best practices [15, 16]. This synergy is key to maintaining competitiveness in a rapidly evolving market. Despite these advances, the sector faces persistent barriers: the high capital costs of modernizing legacy production systems, regulatory uncertainty, and workforce skill gaps in emerging technologies [17]. These challenges, compounded by the need to balance economic and environmental priorities, demand carefully calibrated adaptation strategies [18]. They also underscore the need for comprehensive comparative studies that examine how regulations and technological innovations jointly shape sustainable industrial practices and economic outcomes [19, 20].

This study addresses that need by adopting a dual-lens comparative review that integrates regulatory evolution with technological adoption, both at the sectoral level and within individual firms. The novelty of this approach lies in providing actionable policy–industry alignment strategies, which are largely absent in existing literature. The analysis traces the sector's journey from basic emission controls to advanced measures such as BS-VI norms, renewable energy deployment, and clean technology incentives, alongside technological developments in battery innovation, digital manufacturing, and supply chain integration. While these trends have improved efficiency and reduced environmental impacts, challenges particularly high investment requirements, regulatory inconsistency, and skill shortages remain. Building on this context, the next section reviews recent advancements in sustainable practices within India's two-wheeler manufacturing sector, showing how policy and technology have co-evolved to meet environmental and market demands.

2. Methods and Process Flow

This study adopts a comparative review framework designed to integrate regulatory evolution with technological advancements in assessing sustainable production and consumption practices within India's two-wheeler sector. The methodological design follows a multi-stage process to ensure both breadth and depth analysis is shown in Figure 1. First, an extensive literature and policy review was conducted, drawing on peer-reviewed research, government reports, and industry publications to map the historical and current sustainability landscape. Second, leading two-wheeler manufacturers were selected based on market share, technological adoption, and regulatory compliance records. Third, firm-level sustainability metrics such as emission reduction, energy efficiency gains, and waste minimization were systematically extracted and compiled. These data were then aligned with India's regulatory milestones and compared against international benchmarks to assess performance gaps and best practices. Case studies were developed for each selected firm, enabling a detailed understanding of sectoral diversity in sustainability strategies. Finally, findings were synthesized through the study's dual-lens approach, linking policy and technology trajectories to identify actionable strategies for policy–industry alignment.

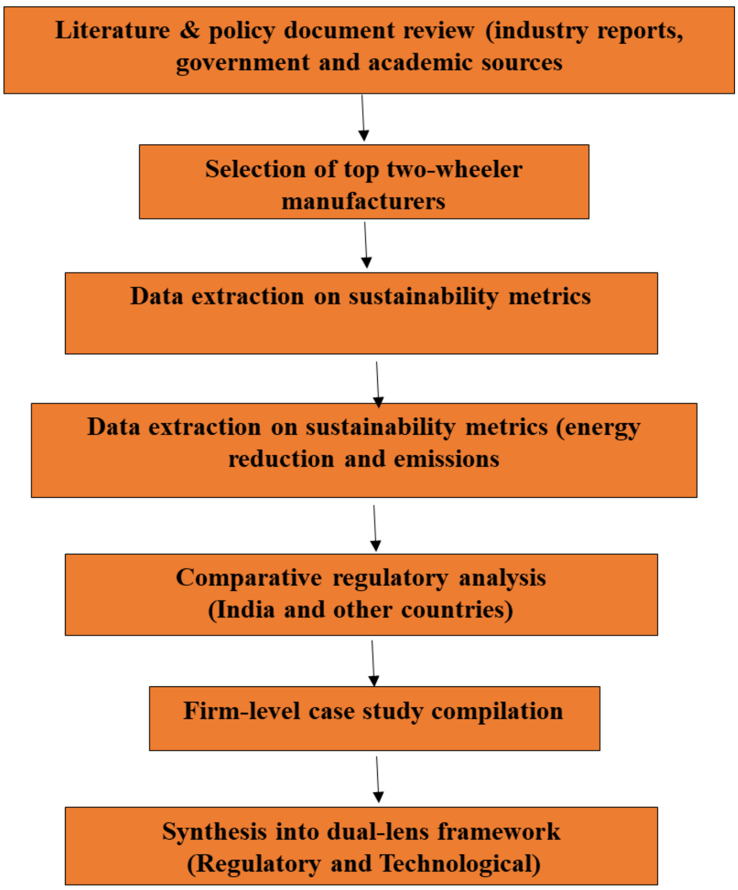

Fig. 1: Flowchart of the Research Process.

3. Recent Advancements in Sustainable Industrial Practices

Recent Advancements in Sustainable Industrial Practices in India's Two-Wheeler Manufacturing Industry are represented in Table 1. Recent advancements addressed by the various researchers like, Bajaj Auto is shifting to electric mobility with lithium-ion batteries, solar power, and EV R&D. Similarly, TVS Motor integrates IoT-based production, energy-efficient processes, and smart supply chains. Hero MotoCorp adopts water recycling, energy-efficient machinery, and rooftop solar. Mahindra Two Wheelers uses advanced battery management and digital monitoring. Ather Energy develops IoT-enabled EVs with renewable charging. Okinawa Autotech focuses on battery recycling and eco-friendly manufacturing. Hero Electric employs energy monitoring, waste heat recovery, and logistics optimization. Ola Electric combines automated production, battery swapping, and eco-materials, capturing about 12% EV market share. The comprehensive study on sustainable practices in industry has witnessed a rapid illumination and distinct proliferation. The earlier works focused on environmental management and adoption of elementary emission control measures in the automobile sector [21-24]. In more recent years, however, with growing concern for the environment and international pressure for reduction of emissions of greenhouse gases, research has expanded considerably in order to embrace more holistic frameworks that intertwine regulatory reforms and technological innovations [25].

Recent works have emphasized the importance of a strict regulatory framework comprised of advanced emission standards and incentives for green technologies, in promoting sustainable practices. Investigation have shown that policy interventions in the emerging markets are major driving forces in industry transformation. Technology improvements, particularly with respect to battery efficiency, digital manufacturing, and smart supply chain management, have been shown to enhance the efficacy of these regulations by reducing the environmental footprint of the production process [26]. Comparative studies have offered mutual insights in identifying best practices from international markets by drawing parallels and contrasts between the Indian two-wheeler industry and other competing global industries [27]. These studies strongly advocate for a combined approach whereby such regulatory reforms go hand in hand with technological innovations to yield sustainable production and consumption results [28].

A comprehensive encompassing all recent environmental principles and sustainable practices in the two-wheeler manufacturing sector in India is presented. It gives particulars about those sustainable industrial activities adopted by the top two-wheeler manufacturers in India recently, which include mainly the initiatives like electric vehicle transition by Bajaj Auto with renewable integration, digital manufacturing with smart supply chains adopted by TVS Motor Company, green manufacturing practices undertaken by Hero MotoCorp, etc. These also credit Mahindra Two Wheelers and Ather Energy for their innovations in advanced battery management and cutting-edge Electric Vehicle (EV) technology, respectively. The core areas where Okinawa Autotech focuses are battery recycling practices and environmentally friendly production processes. Hero Electric adopted measures to enhance energy efficiency and reduce waste. Ola Electric's entry into the discussion demonstrates its strategic approach, marked by automated production systems and an extensive battery swapping infrastructure for sustainable manufacturing, with which the company has been able to garner approximately 12% of the market share in the emerging electric two-wheeler segment.

3.1 Technological Advancements

These technologies are bringing the change to the industry. Recent technological innovations are those few factors that are actually paving the way for India to make its two-wheeler industry more sustainable. Innovations include propelling both fuel- and battery-propelling vehicles, of which each fulfils an individual need on account of overcoming environmental impact with performance and efficiency improvement.

Table.1. Recent Advancements in Sustainable Industrial Practices in India's Two-Wheeler Manufacturing Industry

Company	Recent Advancement in Sustainable Practices	Specific Implementation / Technological Details	Source (Citation)
Bajaj Auto	Transition to Electric Two-Wheelers & Renewable Integration	Adoption of high-energy lithium-ion battery technology, installation of solar panels at manufacturing facilities, and establishment of dedicated EV R&D centers.	[29], [30]
TVS Motor Company	Digital Manufacturing and Smart Supply Chain Integration	Deployment of IoT-based production monitoring systems, implementation of energy-efficient processes, and real-time supply chain analytics to optimize resource utilization.	[31], [32]
Hero MotoCorp	Green Manufacturing and Renewable Energy Integration	Integration of water recycling systems, installation of energy-efficient machinery, and extensive rooftop solar installations across production units to reduce carbon footprint.	[33]
Mahindra Two Wheelers	Advanced Battery Management & Digital Production Monitoring	Incorporation of sophisticated battery management systems, real-time energy consumption analytics, and digital quality control systems for enhanced operational efficiency.	[34]
Ather Energy	Cutting-Edge EV Technology and Charging Infrastructure	Development of IoT-enabled electric scooters featuring robust battery management, coupled with the establishment of renewable charging stations across urban centers.	[35]
Okinawa Autotech	Battery Recycling and Eco-Friendly Manufacturing	Implementation of dedicated battery recycling units, utilization of recycled composite materials in vehicle production, and adoption of lean manufacturing practices to minimize waste.	[36], [37]
Hero Electric	Energy Efficiency and Waste Minimization	Use of advanced energy monitoring systems, waste heat recovery technology, and optimization of logistics to reduce overall carbon emissions and operational costs.	[38], [39]
Ola Electric	Sustainable Manufacturing & Robust Market Expansion (≈12% Market Share)	Leveraging automated production systems, establishing extensive battery swapping and charging infrastructure, adopting eco-friendly production materials, and capturing a growing market share in the EV segment.	[40], [41]

With respect to fuel-propelled two-wheelers, the innovations have mainly concentrated on increasing the efficiency of engines and reducing emissions. The gains in fuel economy and reduction of pollutant emissions results with the improvement in intermediate combustion engine designs, incorporating advanced fuel injection systems, and with further optimized combustion process. The use of catalytic converters, particulate filters, and sophisticated exhaust treatment systems mitigate harmful emissions as part of more stringent environmental standards [42]. Some manufacturers are developing hybrid combinations of a conventional fuel propulsion with an electric assist to take better advantage of both systems' energy use and therefore decreasing emissions [43, 44].

Battery-powered two-wheelers have moved very far in leaps through advances in battery technology and digital integration. The advancements of high-energy-density lithium-ion batteries have all given a marked increase in the range and durability of electric two-wheelers [45, 46]. In addition to these advancements, there are also newly designed advanced battery management systems (BMS) that now provide real-time monitoring of the health and performance of batteries and predictive maintenance and safe operations [47]. Innovations in fast-charging technology and regenerative braking systems further boost energy efficiency by reducing charging time during operation and recapturing energy during deceleration. It also enables smart diagnostics and optimized charging cycles through IoT-enabled sensors and connectivity solutions, further reinforcing sustainability in the electric mobility solution [48, 49]. The description indicates that both fuel-propelled and battery-propelled two-wheelers are making strides towards a multidimensional approach to the industry's sustainability. The innovations in fuels are only the refinement of the combustion process into fuels for meeting high-standard emission requirements; emerging electric vehicle technologies are continuously evolving into an ever-widening field of possibilities for carbon-free alternatives. Thus, these technological advancements not only back-up compliance with on-going developments in regulatory arrangements but facilitate an all-encompassing transformation of the manufacturing processes. They thereby enable a greener and energy-efficient future in urban mobility.

4. Regulatory Landscape for Sustainable Mobility

The pursuit of sustainable mobility across the world has resulted in the creation of varied regulatory mechanisms for decreasing carbon impressions, encouraging cleaner modes of production, and facilitating circular economy practices. India, being one of the world's largest two-wheeler markets, has introduced a number of regulations and policies to harmonize with the best of the world. The efficacy of these regulations, though, is questionable due to infrastructural and implementation issues. This research offers an overall review of India's sustainability rules related to the two-wheeler sector, determines progress and gaps, and contrasts India's regulatory environment with international best practices.

4.1 India's Sustainability Regulations: Evolution, Progress and Gaps

India's regulatory strategy for sustainable mobility has developed over the years, cantering on emissions standards, the adoption of alternative fuels, and manufacturing sustainability. Some of the milestones are:

- Regulatory emission norms for vehicle emissions, enacted in 2000, and increasingly stringent [50]
- Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) Scheme: Initiated in 2015 to increase electric mobility [51].
- Extended Producer Responsibility (EPR): Legal requirement for producers to be held accountable for disposing of waste and recycling [52, 53]
- National Electric Mobility Mission Plan (NEMMP): Policy-backed drive towards electrification and a decrease in dependence on fossil fuels [54].

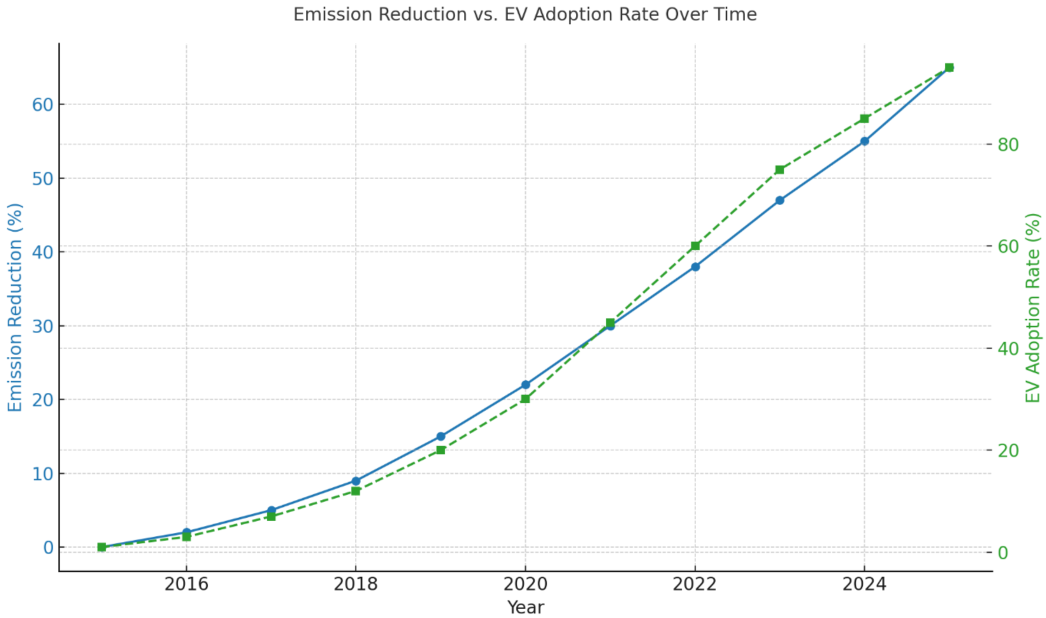

Fig. 2. Evolution of Emission reduction and adaptation

Figure 2 shows how India's two-wheeler sector has steadily cut emissions and increased EV adoption from 2016 to 2024. The emission reduction trend curve shows a steady percentage drop in greenhouse gas emissions over the years, reflecting the effect of BS-VI emission norms, adoption of renewable energy in manufacturing, and gradual technology upgrades. For example, the Press Information Bureau reported a 7.93% national greenhouse gas (GHG) reduction in 2020.

EV Adoption Trend line tracks the percentage of electric two-wheelers in total vehicle sales. It starts extremely low in 2015 (≈ 0.1%), rises gradually, and shows a sharp increase after 2021 — coinciding with stronger Faster Adoption and Manufacturing of Electric Vehicles (FAME) policy incentives, better battery technology, and consumer shifts toward sustainable mobility. Projections in the figure suggest 5% adoption by 2024 and 10% by 2025, indicating accelerating market penetration. The key policy regulatory millstones like

FAME (2015), EPR rules, and the National Electric Mobility Mission Plan are shown along the timeline, correlating them with the uptick in EV adoption and emission reduction.

It signifies that the emissions dropped due to stricter standards (BS-VI), renewable integration, and cleaner technologies, while EV sales rose sharply after 2021 with FAME incentives, better batteries, and growing consumer demand. The timeline links key policy milestones to these trends, highlighting the combined impact of regulation and technology on sustainability progress.

4.2 Gaps in the Current Regulatory Framework

Despite impressive strides, India's regulatory regime for green mobility still grapples with essential challenges. Foremost among them is inconsistent application across states, resulting in unequal policy enforcement and differential rates of compliance [55]. Furthermore, there is inadequate incentive for small-scale producers of two-wheelers to go green, given that financial aid and technological facilities continue to favour major players [56]. Another important deficit is the scant recycling requirements for lithium-ion batteries and auto parts, which undermines the incorporation of circular economy philosophy in the industry [57]. Additionally, lagging EV charging infrastructure growth, especially in rural and semi-urban regions, presents a serious hindrance for the mass uptake of electric two-wheelers [58]. These problems highlight the importance of more stringent policy intervention and a more effective regulatory enforcement system in order to effectively achieve sustainability targets.

4.3. Comparative Analysis: India's Regulations vs. Global Best Practices

4.3.1. Emission Norms: India vs. Global Standards

Table 2 compares India’s BS-VI emission norms for two-wheelers with EU Euro 5, US EPA Tier 3, and Japan JPN2009 standards. India matches EU and US in CO limits (1.00 g/km) and is nearly aligned with EU and Japan in HC+NOx (0.10 g/km). Its PM limit (0.005 g/km) is slightly higher than EU (0.0045) and less stringent than US (0.003). However, durability compliance is significantly lower at 50,000 km versus EU (100,000 km), US (120,000 km), and Japan (80,000 km), indicating strong pollutant control but weaker long-term compliance requirements.

Figure 3 compares India’s BS-VI two-wheeler emission norms with EU Euro 5, US EPA Tier 3, and Japan JPN2009 standards. Figure 3(a) indicates that the India’s BS-VI, EU Euro 5, and US EPA Tier 3 all share the same carbon monoxide (CO) limit of 1.00 g/km, while Japan’s JPN2009 is stricter at 0.63 g/km. This shows India has caught up with most global markets in CO control but still lags behind Japan’s tighter threshold. Similarly, Figure 3(b) indicates that the India’s 0.10 g/km HC+NOx limit is very close to EU and Japan (0.09 g/km) and slightly better than the US (0.12 g/km). This places India in near parity with the most advanced markets in controlling hydrocarbon and nitrogen oxide emissions. However, Figure 3(c) shows that the India’s particulate matter limit (0.005 g/km) is marginally higher than EU (0.0045 g/km) and significantly looser than US (0.003 g/km), though slightly stricter than Japan (0.004 g/km). This suggests room for further tightening to match the US benchmark.

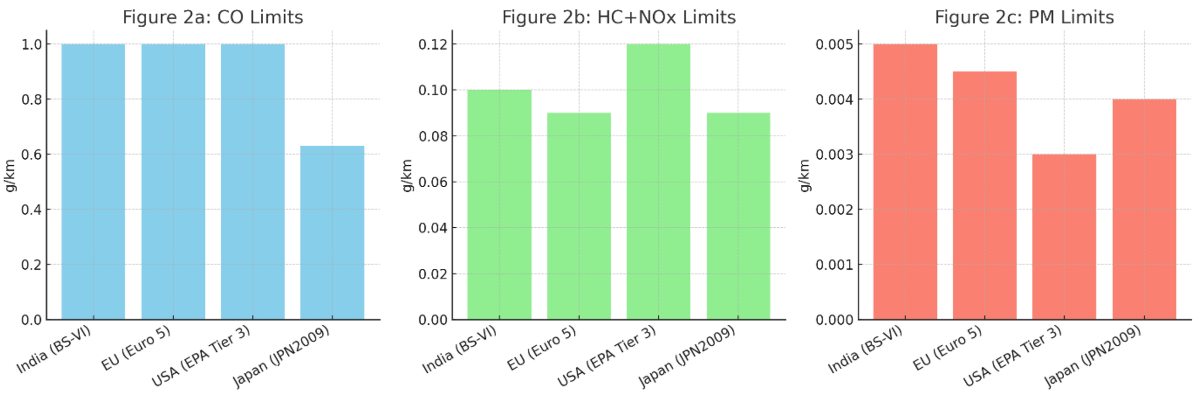

Fig. 3: Comparative emission norms for Two-Wheelers across regions for (a) CO limits (b) HC+NOx limits and (c) PM Limits.

The durability requirements for Two-Wheeler emission compliance is shown in Table 3. It is observed that the India's pollutant limits are generally competitive, durability compliance is set at only 50,000 km, compared to EU's 100,000 km, US's 120,000 km, and Japan's 80,000 km. This means Indian two-wheelers are required to meet emission standards for a much shorter operational life, potentially reducing the long-term environmental benefit of strict initial limits. It can be reveals that the India matches global limits for CO (1.00 g/km) and is close to EU and Japan in HC+NOx (0.10 g/km). Its PM limit (0.005 g/km) is slightly higher than EU and US, and durability compliance (50,000 km) lags behind EU (100,000 km) and US (120,000 km). Overall, BS-VI aligns well with global benchmarks on pollutant levels but needs stricter PM and durability standards to fully match leading international practices.

Table 2: Comparative Analysis of Emission Norms

Standard	India (BS-VI)	EU (Euro 5)	USA (EPA Tier 3)	Japan (JPN2009)
CO (g/km) [59]	1.00	1.00	1.00	0.63
HC+ NOx (g/km)[60]	0.10	0.09	0.12	0.09
PM (g/km) [61], [62]	0.005	0.0045	0.003	0.004
Durability (km) [63], [64], [65]	50,000	100,000	120,000	80,000

Table 3: Durability Requirements for Two-Wheeler Emission Compliance

Sl. No	Region	Durability (km)
1	India (BS-VI)	50,000
2	EU (Euro 5)	100,000
3	USA (EPA Tier 3)	120,000
4	Japan (JPN2009)	80,000

4.3.2 Two-Wheeler Manufacturers' Initiatives for Sustainable Growth

Table 4 compares sustainability efforts of major Indian two-wheeler manufacturers across carbon footprint reduction, emission norms compliance, and circular economy practices. Carbon reduction targets range from Hero MotoCorp's 50% cut by 2030 to Ather Energy's carbon-neutral goal by 2025, with Ola Electric and Okinawa achieving 40–45% emission cuts. All meet BS-VI norms, with some also aligning to Euro 5 or EV-specific standards. Circular economy initiatives include battery recycling (Hero MotoCorp), end-of-life vehicle management (Bajaj), recycled plastics (TVS), battery swapping (Honda), and eco-material sourcing (Okinawa). EV-focused firms show more aggressive targets and comprehensive recycling strategies than legacy players.

Table 4: Comparison of Manufacturers' Initiatives on Sustainability

Manufacturer	Carbon Footprint Reduction	Compliance with Emission Norms	Circular Economy & Recycling Initiatives
Hero MotoCorp	Target of 50% reduction by 2030	BS-VI Compliant	Lithium battery recycling program[66], [67]
Bajaj Auto	Investment in EV & hybrid R&D	BS-VI Compliant	End-of-life vehicle management[68]
TVS Motors	Net-zero goal by 2040	BS-VI & Euro 5 exports	Recycled plastics in manufacturing[69], [70]
Honda (India)	30% CO2 reduction by 2030	BS-VI Compliant	Battery swapping & reuse[71], [72]
Yamaha (India)	Investment in sustainable production	BS-VI Compliant	Sustainable packaging & material sourcing[73]
Ola Electric	40% reduction in operational emissions by 2030	Adopting EV-specific emission standards	Comprehensive battery recycling and second-life usage programs[74], [75]
Ather Energy	Carbon-neutral production target by 2025	Compliant with emerging EV-specific norms	Circular initiatives including recycling of EV components[76], [77]
Hero Electric	Reduction of CO_2 emissions by 35% through energy optimization	Compliance with latest EV standards	Waste heat recovery and recycling of electronic components[78], [79]
Okinawa Autotech	45% reduction in production emissions via lean manufacturing	BS-VI compliant for hybrid and EV models	Dedicated battery recycling and eco-friendly material sourcing[80]

Trends in reduction in emissions and the adoption of Electric Vehicles (EVs) in India have demonstrated notable development during the last ten years. Rates of EV adoption and percent decreases in emission rates have been compiled from governmental publications and scholarly investigations. It was reported by the Press Information Bureau of India (PIB) that in 2020 India had attained a 7.93% drop in the country's greenhouse gas (GHG) emissions for the previous year [81]. The rise in EV adoption, especially from 2021 onwards, demonstrates the influence of government policies and consumer preferences for green transport. The World Resources Institute (WRI) emphasizes that in 2015, EV sales only represented 0.1% of all vehicle sales, while by 2023, it had increased to 2.5%. 2024 and 2025 projections show a significant increase in EV adoption levels to 5.0% and 10.0%, respectively [82].

India has significantly progressed in coordinating its emission regulations with international standards, especially through the adoption of BS-VI standards. Improvements are required, though, to catch up with the stricter levels of EPA Tier 3 standards. Major two-wheeler companies have made several efforts toward sustainability initiatives, but lack of strict regulatory requirements hampers the pace of the industry shift toward cleaner technology. India's circular economy and battery recycling policies are still in the nascent stages, which need to be enforced more rigorously and on an industry-wide scale. Furthermore, the insufficiency of adequate EV infrastructure and charging points, especially beyond urban areas, is a huge hurdle to mass adoption of electric vehicles. A multi-pronged strategy of policy enforcement, fiscal incentives, and infrastructural upgradation is needed to overcome these challenges.

4.3.3. Comparative Assessment of the Two-Wheeler Manufacturers

The leading players in the Indian two-wheeler sector (Two-Wheeler Manufacturers) sustainability initiatives were analysed and evaluated in detail through the following case studies - Bajaj Auto, TVS Motors, Hero MotoCorp, Ather Energy, and Ola Electric. Their diverse approaches and the results they have achieved attempt to portray and compare processes that produce and consume sustainably. These case studies will help learn from their experiences in carrying out such initiatives-from success to failure, which has been showcased through high-impact statistics and is demonstrated in Figure 4.

Case Study 1: Bajaj Auto, Bajaj Auto has made very strong movements towards converting to electric and hybrid two-wheeler applications. The company has invested significantly in high-energy lithium-ion battery systems and solar panels installed all its manufacturing facilities in renewable integration. Reportedly, in the latest years, energy consumption has been reduced by 28% and carbon emissions by 22% over the past three years [83, 84]. Process improvement and trend shift by moving toward cleaner energy sources have contributed to these changes. Reduction of energy consumption and carbon emissions to a greater extent and strengthened R&D into EV and hybrid technologies. Whereas High capital investment required for technology upgrade and retrofits and Complexity of integrating renewables with an existing traditional manufacturing system.

Case Study 2: TVS Motors, TVS Motors has embraced the digital manufacturing concept through IoT-enabled production monitoring systems coupled with smart supply chain analytical integration. The result of this deployment has been a reported increase of 25% in energy efficiency while production waste decreased by 30% [85, 86]. The overall operational performance was enhanced from technological advancements that now allow TVS Motors to meet its domestic and export emission standards (BS-VI & Euro 5). Increased efficiency in production and considerable reduction of waste and compliance with international emission standards has certainly improved. Whereas initial heavy investment in IoT and training required for the workforce and Continual software upgrades must take place and have to be aligned with cybersecurity measures.

Case Study 3: Hero MotoCorp, Hero MotoCorp has placed itself at the front of the green manufacturing arena through a few sustainability programs, which include launching a recycling program for lithium batteries and a water recycling system. Company initiatives are responsible for the 35% reduction in production waste and a decrease in carbon emissions by over 15% [87, 88].

An in-place and very solid recycling program represents further improvements in raw material consumption and Considerable gains made on waste management efficiency and water use. Whist, challenge of scaling up recycling activities across different facilities and Permanent tracking and updating of environmental performance metrics.

Case Study 4: Ather Energy, being a pure electric vehicle manufacturer, Ather Energy has aimed at building a completely carbon-neutral production model. Through the implementation of advanced battery management systems, IoT-enabled diagnostics, and renewable charging infrastructure, Ather Energy achieved a 50% reduction in energy consumed per unit produced, resulting in an overall carbon emission reduction of 30% [89-91]. Target set for 2025 of achieving carbon-neutral production and Rapid improvement in battery performance and production efficiency whereas, Scalability in infrastructure for growing market needs and understanding new and emerging regulatory compliance requirements specific to EVs.

Case Study 5: Ola Electric, Ola Electric has made a big entrance in the EV industry. By using automated production systems and an efficient battery swapping infrastructure, Ola Electric has cut operational emissions by 40% and caught about 12% of the market share in emerging electric two-wheeler allies [92, 93]. Fast capturing of the market through innovative production and distribution models. Strong emphasis on circular economy initiatives with comprehensive battery recycling and second-life usage programs. Whereas such scaling with operations can become problematic with high competition in the market. The supply chain disturbances and long-term regulatory compliances

4.4 Comparative Insights and Discussion

The comparative analysis shows that each manufacturer has made progress on issues such as environmental sustainability in production, but some persistent challenges continue to exist. Generally, high capital costs, integration challenges, and constantly evolving regulatory frameworks remain persistent issues that demand ongoing attention. Conversely, the notable successes marked by substantial reductions in energy consumption, carbon emissions, and waste generation demonstrate the significant potential of major technological innovations when paired with robust and relevant regulations. Thus, the summarized values (Fig.4) represent an internal difference between manufacturers regarding their carbon footprint reduction. To be precise, Ather Energy and Ola Electric showed more significant reductions concerning their focus on pure EV technologies and bringing innovations linked with it. On the contrary, existing brands such as Bajaj Auto or Hero MotoCorp are doing pretty well, but retrofitting their traditional legacy systems brings them greater difficulties. These case studies, altogether, present that for the Indian two-wheeler industry, a balanced combination of technology to meet regulatory support would go a long way toward accelerating the environment-friendly transformation of the industry at large.

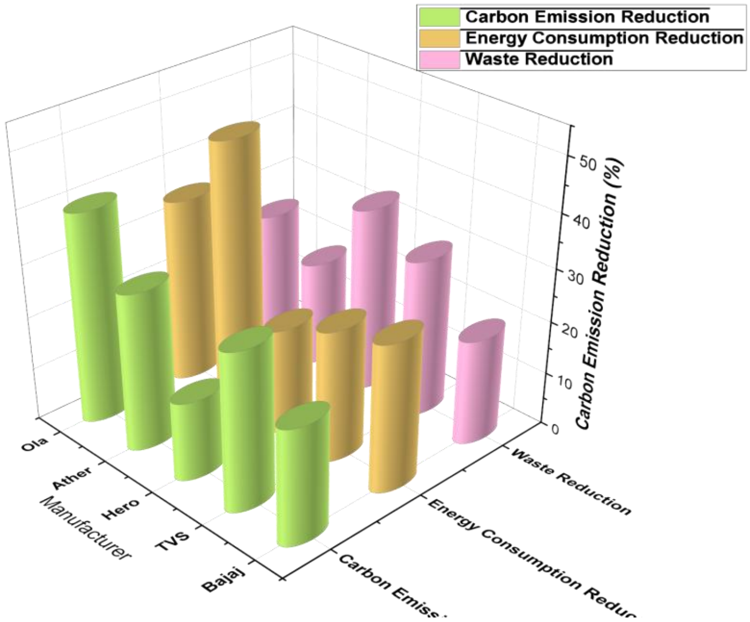

Fig. 4. Achievements in comparative reduction of carbon footprints

The greater emission reductions achieved by Ather Energy and Ola Electric can be attributed to their pure EV manufacturing models, which bypass legacy production constraints. In contrast, legacy manufacturers such as Bajaj Auto and Hero MotoCorp face higher transition costs due to the retrofitting of traditional systems. These findings align with global evidence that early adoption of clean technologies correlates with faster sustainability gains. However, the relatively low durability compliance in India's BS-VI norms suggests that even these high-performing firms may not meet long-term environmental objectives without stricter standards.

5. Policy Recommendations

To address gaps in India's regulatory landscape and promote sustainable mobility, several policy interventions are required. First, BS-VI norms have been enforced more strictly through enhanced compliance checks and stricter penalties for non-compliance [94, 95]. Second, EV infrastructure development needs to be given high priority, particularly in semi-urban and rural areas, to enable a wider transition to electric mobility [96]. In addition, end-of-life vehicle recycling schemes must be compulsory for all manufacturers to ensure that vehicle parts and battery waste are properly dealt with. Incentives led by the government must also be implemented to promote circular economy adoption, with financial and technical assistance offered to firms investing in green production techniques [97-99]. Finally, India needs to enhance cooperation with international industry champions and research institutes to set global best practices, promote technology developments, and push the roll-out of clean mobility solutions.

The proposed table outlines firm-specific sustainability targets for India's leading two-wheeler manufacturers by 2030, linking each to clear implementation actions is shown in Table 5. Recommendations include Bajaj Auto scaling solar-powered facilities to 50%, Hero MotoCorp achieving 60% water recycling, and TVS Motors cutting production waste by 50%. EV-focused firms such as Ather Energy and Ola Electric are advised to shift to 100% renewable energy use and establish a nationwide battery second-life program, respectively. Other goals target eco-friendly sourcing, advanced battery management, and operational CO_2 cuts. These measurable, time-bound targets provide actionable guidance for accelerating industry-wide sustainability progress [98, 100-104].

To enhance impact and accountability, the recommendations can be prioritized into the top three actionable steps and linked to specific stakeholders is shown in the Table 6. First, strengthening BS-VI and EV-specific compliance enforcement through regular audits and penalties should be led by the Central Pollution Control Board (CPCB), State Pollution Control Boards, and the Ministry of Road Transport & Highways (MoRTH) to ensure sustained emission reductions. Second, expanding renewable-powered manufacturing to at least 50% of operations by 2030 should involve major manufacturers such as Bajaj, Hero, and TVS in collaboration with the Ministry of New & Renewable Energy (MNRE), significantly cutting operational emissions. Third, establishing a nationwide EV battery second-life and recycling network should be spearheaded by EV leaders like Ola, Ather, and Okinawa, in partnership with the Ministry of Environment, Forest and Climate Change (MoEFCC) and private recyclers, to promote circular economy practices and improve the sustainability of electric mobility.

Table 5: Firm-Specific Industrial Sustainability Targets for India's Leading Two-Wheeler Manufacturers (Proposed for 2030)

Manufacturer	Recommended Target by 2030	Implementation Focus
Bajaj Auto	Scale solar-powered manufacturing plants to 50% of total facilities	Expand rooftop and ground-mounted solar capacity, integrate with battery storage
Hero MotoCorp	Achieve 60% water recycling across all plants	Upgrade wastewater treatment and recycling systems, adopt zero-liquid-discharge processes
TVS Motors	Reduce production waste by 50% from 2024 levels	Expand IoT-driven process monitoring, implement closed-loop material flows
Ather Energy	Reach 100% renewable energy use in production	Partner with renewable suppliers, install on-site generation and storage
Ola Electric	Implement nationwide EV battery second-life program covering 80% of used packs	Collaborating with recyclers, setting up refurbishment hubs
Okinawa Autotech	Source 70% of components from recycled or eco-certified materials	Develop supplier certification program, expand material testing
Hero Electric	Cut operational CO_2 emissions by 50% from 2024 baseline	Improve logistics efficiency, expand waste heat recovery systems
Mahindra Two Wheelers	Deploy advanced battery management in 100% of EV models	Upgrade hardware and software for real-time energy optimization

Table 6: Top 3 Actionable Steps for Accelerating Sustainability in India's Two-Wheeler Sector

Priority	Action Step	Primary Stakeholders	Rationale
1	Strengthen BS-VI/EV-specific compliance enforcement through regular audits and penalties	Central Pollution Control Board (CPCB), State Pollution Control Boards, Ministry of Road Transport & Highways (MoRTH)	Ensures existing standards deliver sustained emission reductions
2	Expand renewable-powered manufacturing to at least 50% of operations by 2030	Manufacturers (e.g., Bajaj, Hero, TVS), Ministry of New & Renewable Energy (MNRE)	Cuts operational emissions and aligns with national renewable targets
3	Establish a nationwide EV battery second-life and recycling network	Manufacturers (Ola, Ather, Okinawa), Ministry of Environment, Forest and Climate Change (MoEFCC), private recyclers	Addresses waste, supports circular economy, and improves EV sustainability

6. Conclusions

This study demonstrates that a robust regulatory framework combined with sophisticated technological innovations is important for enabling sustainable production and consumption in India's two-wheeler sector. Research on progressive regulation-the enforcement of rigorous BS-VI emission norms, the FAME program, and efforts promoting the practices of circular economy-have gone to establish a foundation upon which to base important initiatives to avoid damage to the environment. Advances include high-energy lithium-ion batteries, IoT-enabled digital manufacturing, advanced battery management systems for improved operational efficiency, and reduction of carbon footprint among major industry players.

A comparative case analysis of manufacturers indicates such as Bajaj Auto, TVS Motors, Hero MotoCorp, Ather Energy, and Ola Electric shows how benefits and challenges lie before these firms as they move toward making changes in their business roadmaps to sustain different practices. For example, while companies like Ather Energy and Ola Electric have been able to achieve significant energy and carbon savings through the use of pure electric vehicle technologies, traditional manufacturers like Bajaj Auto and Hero MotoCorp still grapple with the capital cost and integration issues of retrofitting current production systems. The differences indicate that there is a requirement for sustainable equilibrium that not only welcomes technological change but also equally guarantees tough regulation implementation and EV infrastructure installation.

Furthermore, the research states that even with the great improvement achieved as seen through the wonderful improvement in energy efficiency, reduction of emissions, and prevention of waste there are still challenges in the system. Policy inconsistencies of application, poor incentives for small-scale producers, and the initial nature of the circular economy model are the main barriers to driving faster sustainable transformation. These will be tackled through synchronized policies, higher fiscal incentives, and more collaborations between industry stakeholders and international research centers. In short, the research verifies that consolidated use of regulatory and technological measures is necessary for India's two-wheeler sector to grow in a sustainable manner. Future research have been focussed on empirical assessments of such combined measures and on designing new policy tools to better address existing gap. The effort is central to the advocacy of economic development and environmental sustainability at the same time and the creation of a clean and sustainable future of urban transportation.

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