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CLOSING THE PRODUCTIVITY GAP IN ELECTRIC VEHICLE MANUFACTURING: CHALLENGES AND SOLUTIONS

Md Rabbe Khan [1]
[1]Master of Industrial Engineering, College of Engineering, Lamar University, Texas, USA
Correspondent Email: mkhan46@lamar.edu

Md Tahmidul Islam [2]

[2]Master of Engineering Management, College of Engineering, Lamar University, Texas, USA
Email: tahmid.info@gmail.com

Kazi Saiful Islam [3]

[3]Master of Industrial Engineering, College of Engineering, Lamar University, Texas, USA
Email: kislam4@lamar.edu

Amjad Hossain [4]
[4]Master of Industrial Engineering, College of Engineering, Lamar University, Texas, USA
Email: ahossain9@lamar.edu

Keywords

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ABSTRACT

This study provides a systematic review of the challenges and solutions in electric vehicle (EV) manufacturing, addressing key areas such as technological advancements, workforce readiness, supply chain optimization, sustainability practices, and lean manufacturing principles. A total of 86 peer-reviewed articles published between 2015 and 2023 were analyzed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure rigor and transparency. The findings reveal that technological innovations, including automation, artificial intelligence (AI), and digital twin technologies, significantly improve production efficiency and resource optimization, though their adoption remains hindered by high implementation costs and infrastructural incompatibilities. Workforce challenges, including skill mismatches and labor shortages, were identified as critical barriers, particularly in emerging economies where education and training initiatives remain insufficient. Supply chain inefficiencies, driven by raw material dependency and geopolitical risks, continue to disrupt production, despite the potential of predictive analytics and digitalization to enhance resilience. Sustainability practices, such as circular economy strategies and energy-efficient manufacturing processes, were found to reduce environmental impacts and operational costs, though scalability remains a challenge. Finally, lean manufacturing principles emerged as effective solutions for improving productivity and reducing waste, though their success depends on organizational commitment and workforce adaptability.

1 INTRODUCTION

The electric vehicle (EV) industry is emerging as a cornerstone in achieving sustainable transportation and reducing greenhouse gas emissions, aligning with global climate goals outlined in agreements like the Paris Accord (International Energy Agency [IEA], 2021). Over the past decade, EV adoption has surged due to advancements in battery technology, favorable policies, and consumer demand for cleaner energy solutions (Abdelhamid et al., 2014). However, this growth has highlighted significant productivity gaps in EV manufacturing, which stem from inefficiencies in supply chains, technological integration, and human

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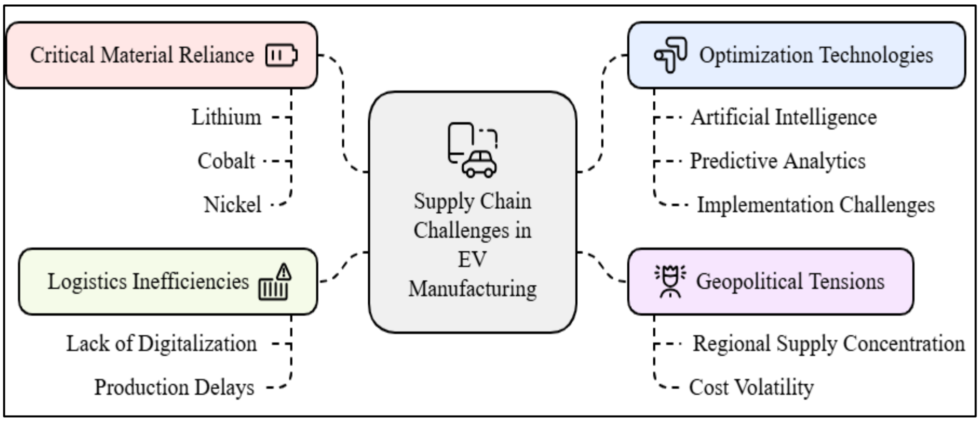
capital limitations (Dijk et al., 2013). Addressing these challenges is critical, as productivity improvements are essential for reducing costs, scaling production, and meeting increasing market demand (Thackeray et al., 2012). This paper seeks to identify the core barriers contributing to these gaps and examine potential solutions, particularly through technological innovations and strategic workforce development.

One of the most prominent challenges in EV manufacturing lies within supply chain disruptions and resource constraints. The reliance on critical materials, such as lithium, cobalt, and nickel for batteries, has created bottlenecks in production (Thackeray et al., 2012). For example, a study by Diekmann et al. (2016) emphasizes that geopolitical tensions and the concentration of raw material supply in a few regions increase costs and volatility in the supply chain. Furthermore, inefficient logistics and a lack of digitalization exacerbate delays, hindering the ability to scale production efficiently (Qiao et al., 2017). Adopting supply chain optimization technologies, such as artificial intelligence (AI) and predictive analytics, has shown promise in reducing lead times and improving resource utilization (Wang et al., 2023). However, widespread adoption remains limited due to high implementation costs and resistance to change among traditional manufacturers (Keshavarzmohammadian et al., 2018).

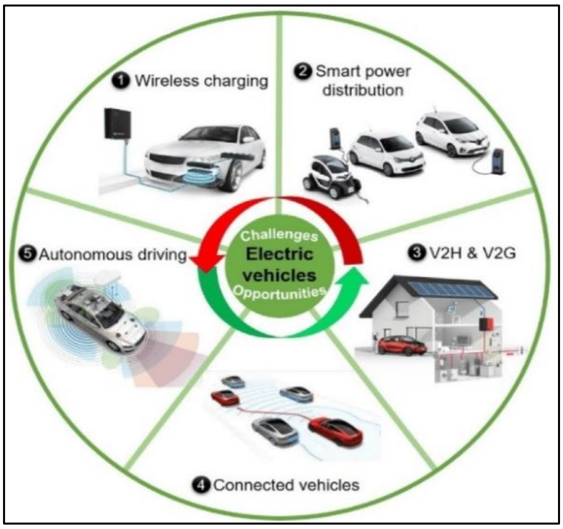
Technological integration represents another critical factor contributing to productivity challenges in EV manufacturing. While automation, robotics, and digital twin technologies can significantly streamline production processes, the integration of these systems often requires significant investments and expertise (Zeng et al., 2019). Research by Shi et al. (2019) highlights that manufacturing plants that utilize advanced technologies like the Internet of Things (IoT) and AI-driven systems achieve higher productivity and quality consistency. Conversely, older production facilities often face compatibility issues when retrofitting these technologies, leading to inefficiencies and production downtimes (Mwambeleko & Kulworawanichpong, 2017). This technological divide underscores the need for EV manufacturers to strategically invest in modernized infrastructure while balancing cost constraints (Goodenough & Braga, 2018). Moreover, labor force challenges also exacerbate the productivity gap in EV manufacturing. The shift toward electric vehicles requires a highly skilled workforce adept at handling advanced technologies, such as battery assembly, software integration, and automation processes (Larcher & Tarascon, 2014). However, studies indicate a persistent skills gap, particularly in regions transitioning from internal combustion engine manufacturing to EV production (Hannan et al., 2018). For instance, empirical findings by Lu et al. (2013) reveal that insufficient workforce training programs and inadequate collaboration between educational institutions and manufacturers limit the industry's capacity to bridge this skill mismatch. Addressing this issue requires a dual approach: implementing workforce upskilling initiatives and fostering partnerships between governments, industry players, and academic institutions (Lipu et al., 2018). Furthermore, achieving optimal productivity in EV manufacturing necessitates a focus on cost efficiency and scalability while maintaining sustainability goals. Research by Hannan et al. (2017) underscores the importance of reducing operational costs through lean manufacturing techniques and circular economy principles. Sustainable practices, such as recycling battery

Figure 1: Challenges in Electric Vehicle (EV) Manufacturing



components and adopting energy-efficient manufacturing processes, can significantly reduce waste and enhance productivity (Yang et al., 2018). However, balancing cost-effectiveness with environmental responsibility poses a significant challenge for manufacturers seeking competitive advantages in global markets (Islam et al., 2024; Islam et al., 2024). Strategic planning and the adoption of AI-driven solutions, such as predictive maintenance and real-time data analytics, can facilitate this balance (Kim et al., 2018). The primary objective of this study is to investigate the underlying challenges contributing to the productivity gap in electric vehicle (EV) manufacturing and to propose viable solutions for overcoming these barriers. This research aims to identify key factors such as supply chain inefficiencies, technological integration issues, and workforce skill mismatches that impede the productivity of EV production. By analyzing current industry practices and emerging trends, the study explores the role of advanced manufacturing technologies, including automation, artificial intelligence (AI), and Internet of Things (IoT) systems, in enhancing operational efficiency. Additionally, the research emphasizes the importance of workforce development initiatives, such as upskilling and reskilling programs, to bridge the labor skill gap required for modern EV manufacturing. Through a comprehensive review of existing literature and case studies, this study seeks to provide strategic recommendations for policymakers, manufacturers, and industry stakeholders to address these challenges and close the productivity gap, ensuring a sustainable and competitive future for EV manufacturing.

Figure 2: Five new trends in Evs



2 LITERATURE REVIEW

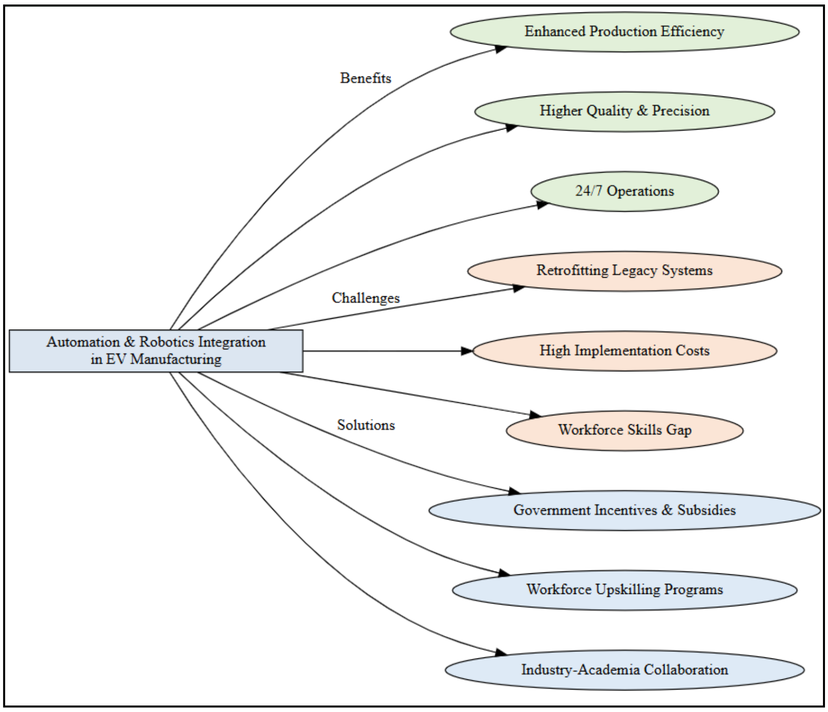
The rapid expansion of electric vehicle (EV) manufacturing has brought significant opportunities for sustainable transportation, yet the sector faces several productivity challenges that hinder its growth potential. Understanding these challenges requires a thorough examination of existing studies on supply chain inefficiencies, technological advancements, labor force preparedness, and cost management within the EV industry. Prior research highlights the importance of integrating advanced technologies, optimizing supply chains, and upskilling the workforce to address the productivity gap. However, there remains a lack of cohesive analysis that synthesizes these diverse factors to propose comprehensive solutions. This literature review critically analyzes studies related to EV manufacturing, emphasizing key themes such as technological innovation, workforce transformation, and sustainability practices.

2.1 Automation and Robotics Integration

Automation and robotics have significantly transformed modern manufacturing processes, particularly in the electric vehicle (EV) industry, by enhancing production efficiency and reducing operational costs (Bock, 2016). Cai et al. (2019) emphasized that automation technologies streamline repetitive tasks, improve precision, and minimize human error, resulting in faster production cycles and higher output quality. Similarly, Kasperzyk et al. (2017) found that the integration of robotics for assembling EV components, such as battery modules and powertrains, reduces variability and increases production consistency. The study further highlighted that robotics-driven workflows enable manufacturers to meet rising market demands while maintaining stringent quality control. Furthermore, Haas et al. (1995) argue that automation significantly enhances productivity by leveraging interconnected robotic systems that operate 24/7, outperforming manual processes. These advancements align with Industry 4.0 frameworks, where robotic solutions combined with AI and IoT technologies foster efficient resource utilization and improved throughput (Bock, 2006; Faisal et al., 2024; Faisal et al., 2024). Despite the substantial benefits of automation, retrofitting legacy systems in existing manufacturing facilities poses a major challenge for many EV producers. According to Cai et al. (2019), traditional production lines lack the digital infrastructure necessary to integrate modern robotics and automation technologies seamlessly. Kasperzyk et al. (2017) further noted that older plants often experience compatibility issues, leading to production downtime and high implementation costs during technology upgrades (Hasan & Islam, 2024; Islam, 2024). This issue is particularly pronounced in emerging markets, where limited financial resources and outdated machinery impede the adoption of advanced manufacturing technologies (Haas et al., 1995). Cao et al. (1997) underscored the need for phased automation strategies to minimize disruptions while gradually modernizing production capabilities. Additionally, studies by Cai et al. (2019) highlighted that resistance to change among stakeholders further complicates retrofitting processes, delaying the full potential of robotics integration.

The cost implications of adopting robotics and automation remain a significant barrier, especially for small- and medium-sized enterprises (SMEs) engaged in EV manufacturing. Research by Bock (2006) revealed that while automation promises long-term cost savings, the upfront investment in robotics, infrastructure upgrades, and skilled labor can be prohibitively expensive. For example, the capital required to deploy robotic arms and sensor-driven technologies in EV battery assembly plants can take years to generate a return on investment (Cao et al., 1997; Faisal, 2023). Similarly, Kasperzyk et al., (2017) found that smaller manufacturers struggle to justify these investments due to fluctuating demand and narrow profit margins. Studies such as those by Haas et al. (1995)and Bock (2006) suggest that government incentives, subsidies, and collaborative financing models could facilitate automation adoption while easing financial pressures. In addition to cost and retrofitting challenges, effective automation adoption necessitates a skilled workforce capable of operating, maintaining, and optimizing robotic systems. Research by Cai et al. (2019) and Kasperzyk et al. (2017)identified a persistent skills gap in the EV manufacturing sector, particularly concerning expertise in robotics programming, predictive maintenance, and human-robot collaboration. Training programs tailored to Industry 4.0 technologies are essential to address these challenges (Bock, 2016; Helal, 2024; Islam & Helal, 2018). For instance, initiatives that promote workforce upskilling in automation-related fields have shown success in reducing downtime and enhancing overall production efficiency (Cao et al., 1997). However, Kasperzyk et al. (2017) argued that systemic gaps in education and industry-academia collaboration remain obstacles to developing a future-ready workforce. By fostering partnerships between

Figure 3: Automation and Robotics in EV Manufacturing – Benefits, Challenges, and Solutions



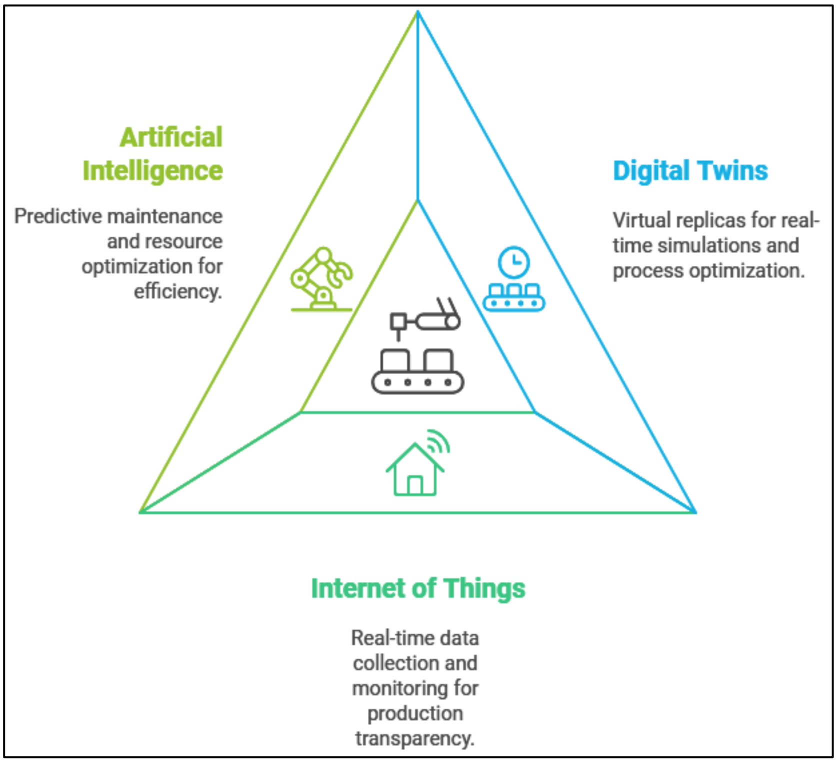
manufacturers, academicinstitutions, and governments, the EV industry can accelerate the adoption of robotics while ensuring sustained productivity growth.

2.2 Advanced Manufacturing Technologies

Advanced manufacturing technologies, including digital twins, the Internet of Things (IoT), and artificial intelligence (AI) (Faisal et al., 2024; Mintoo et al., 2024), have revolutionized the electric vehicle (EV) industry by enhancing production efficiency, quality, and scalability emphasized that digital twin technology allows manufacturers to create virtual replicas of production processes, enabling real-time simulations and performance optimization (Martinez et al., 2013). By replicating EV assembly lines virtually, manufacturers can identify bottlenecks, improve workflow efficiency, and minimize downtime (Lim et al., 2012; Islam et al., 2024; Mintoo, 2024). Similarly, IoT devices integrated with sensors provide real-time data collection and monitoring, enhancing transparency across production systems (Mintoo, 2024; Rahman et al., 2024; Turner et al., 2021). A study by Martinez et al. (2013) found that AI-driven systems, when combined with IoT, facilitate predictive maintenance, reducing unplanned stoppages and ensuring uninterrupted production cycles. These technologies collectively improve operational agility, aligning EV production with the dynamic demands of the market. Moreover, digital twins and IoT technologies play a vital role in addressing quality control issues in EV manufacturing. Research by Boje et al. (2020) highlighted that digital twins enable real-time detection of defects during battery module assembly, significantly reducing rework and waste. By integrating IoT sensors, manufacturers can monitor critical parameters, such as temperature and pressure, to ensure consistent product quality (Min et al., 2019; Nandi et al., 2024). Furthermore, AI algorithms enhance defect detection accuracy by analyzing vast datasets to identify anomalies beyond human capabilities (Lee et al., 2021). Studies by Khajavi et al. (2019) and Tao et al. (2019) demonstrated that these technologies significantly lower manufacturing errors and improve yield rates in EV production facilities. However, Qi and Tao (2018) noted that successful implementation requires substantial infrastructure investments and training, which can be prohibitive for smaller manufacturers.

The integration of artificial intelligence (AI) in EV production enables smarter decision-making and resource optimization. According to Lee et al. (2021), AI algorithms analyze production data to predict equipment failures, optimize assembly line schedules, and reduce energy consumption. This predictive

Figure 4: Advanced Manufacturing in EVs

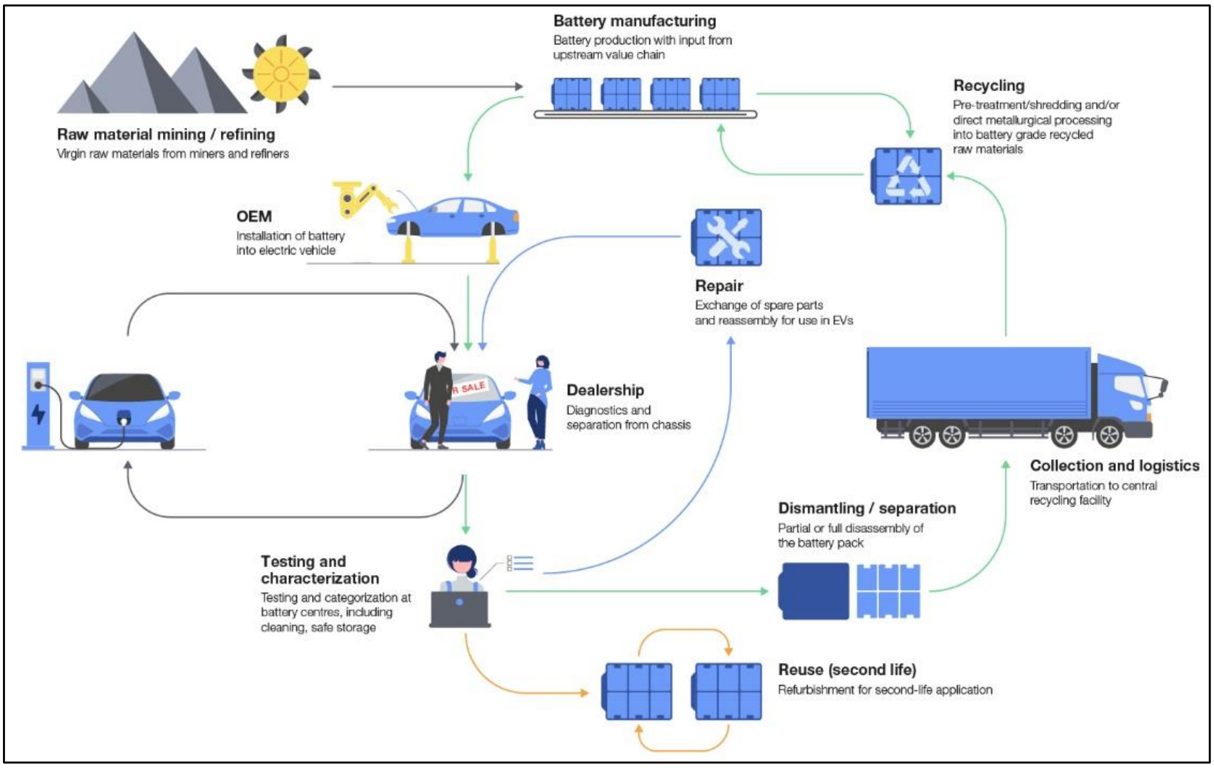


capability not only enhances production efficiency but also lowers operational costs over time. A case study by Azhar (2011) demonstrated how AI-driven robotics in battery assembly increased productivity by 20% while ensuring greater precision. Similarly, Mahalingam et al. (2015) observed that AI-powered systems improve the allocation of resources, such as labor and raw materials, aligning with sustainability goals. Digital twins, when coupled with AI, provide insights into optimizing production workflows and minimizing resource wastage (Lee et al., 2021). Despite these benefits, Tao et al. (2019) argued that the complexity of integrating AI into legacy systems remains a challenge for manufacturers with outdated infrastructure. IoT-enabled smart factories are critical for achieving high levels of automation and operational efficiency in EV manufacturing. IoT networks, integrated with robotics and AI systems, create a connected ecosystem that facilitates seamless communication between machines and human operators (Lee et al., 2021). Marcinkowski and Banach (2020) reported that IoT sensors enable manufacturers to monitor production parameters, energy usage, and material flow, ensuring optimized resource utilization. For instance, Pan and Zhang (2021) emphasized that IoT-driven smart factories reduced energy consumption by up to 15% while increasing overall production throughput. Digital twins further enhance the performance of IoT systems by providing virtual feedback on equipment performance, enabling real-time adjustments to production processes (Marcinkowski & Banach, 2020). However, studies such as Azhar, (2011)and Pan and Zhang (2021) highlighted challenges such as cybersecurity risks, data integration issues, and high costs associated with the deployment of IoT technologies.

2.3 Battery Technology and Production Bottlenecks

Battery technology remains a cornerstone of electric vehicle (EV) production, yet it faces significant challenges in manufacturing, resource availability, and scalability (Jones et al., 2014). Oh et al. (2017) highlighted that limitations in raw materials, such as lithium, cobalt, and nickel, create bottlenecks in battery production due to supply chain dependency on a few geographic regions. The concentration of mining activities in countries like the Democratic Republic of the Congo and Chile exacerbates geopolitical risks and price volatility, further limiting production capacity (Ahmed et al., 2017). According to Zeng et al. (2019), these material constraints hinder manufacturers' ability to scale battery production efficiently to meet growing EV demand. Yoshino (2012) added that environmental

Figure 5: Illustration of a potential flow principle



Source: World Economic Forum (2024)

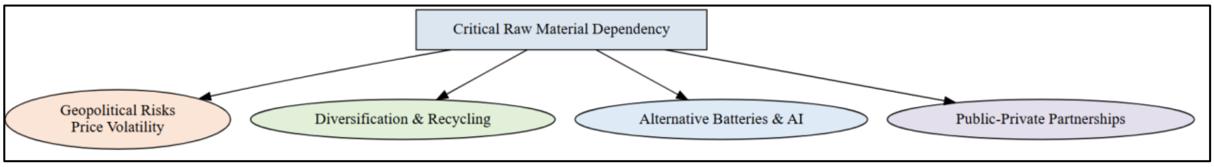
and ethical concerns around resource extraction create additional challenges, prompting the need for sustainable alternatives. Therefore, ensuring secure and diversified supply chains remains critical for overcoming bottlenecks in battery manufacturing.

In addition to material scarcity, the production scalability of EV batteries is hindered by technological and infrastructural limitations (Lu et al., 2017). Yoshino (2012) emphasized that the existing battery manufacturing processes, such as electrode preparation and cell assembly, are resource-intensive, requiring significant energy and time. Vergori et al. (2018) observed that scaling production facilities often results in bottlenecks due to high capital costs and limited availability of specialized equipment. Further studies by Mwambeleko and Kulworawanichpong (2017) and Narins (2017) noted that maintaining uniform quality at scale is another challenge, as variability in battery performance can arise during mass production. The complexity of battery chemistries, such as lithium-ion and solid-state technologies, adds another layer of difficulty in achieving cost-efficient scalability (Lu et al., 2017). Addressing these challenges requires technological advancements that improve manufacturing throughput and process standardization. Moreover, technological innovations are playing a critical role in addressing battery efficiency and lifecycle management, which are key to overcoming production bottlenecks. Zeng et al. (2019) reported that advancements in battery chemistries, such as solid-state and silicon-anode technologies, have significantly improved energy density, enhancing EV range and performance. Similarly, research by Liu et al. (2018) highlighted the development of fast-charging solutions and thermal management systems that optimize battery performance and extend lifespan. Yoshino (2012) noted that AI and machine learning (ML) tools are now being integrated into production processes to monitor cell performance, detect defects, and predict failures in real time, improving overall efficiency. Further, Juul (2012) emphasized the importance of closed-loop recycling systems for recovering critical materials from used batteries, reducing reliance on virgin resources and addressing sustainability concerns. Moreover, Lifecycle management and recycling innovations are critical for addressing the long-term challenges associated with battery production. According to Lu et al. (2017), the circular economy model, which focuses on reusing and recycling battery components, is gaining traction in the EV industry to minimize resource wastage. Zeng et al. (2019) found that advancements in hydrometallurgical and pyrometallurgical recycling processes enable the recovery of lithium, cobalt, and nickel with high efficiency, contributing to resource security. Studies by Yoshino (2012) and Vergori et al. (2018) further emphasized that end-of-life battery management strategies, such as second-life applications for energy storage systems, significantly extend the value of EV batteries. These practices not only alleviate the demand for raw materials but also reduce environmental impacts, aligning battery production with sustainability goals. However, Meister et al. (2016) noted that scaling these technologies requires substantial investment in infrastructure and supportive regulatory frameworks to encourage adoption.

2.4 Critical Raw Material Dependency

The electric vehicle (EV) industry is heavily reliant on critical raw materials such as lithium, cobalt, nickel, and rare earth elements, which are essential for battery production and motor technologies. Thackeray et al. (2012) emphasized that this dependency creates significant vulnerabilities due to the concentration of raw material reserves in geographically limited regions. For instance, over 60% of global cobalt production originates in the Democratic Republic of Congo, while lithium supplies are largely controlled by Chile, Australia, and China (Pan et al., 2017). These geopolitical dependencies expose supply chains to risks arising from political instability, trade restrictions, and resource nationalism (Lu et al., 2017). Dong et al. (2018) found that disruptions in these regions, such as export bans or labor strikes, can cause severe price fluctuations and production delays, threatening the scalability of EV manufacturing. As a result,

Figure 6: Critical Raw Material Dependency



manufacturers face substantial uncertainty in securing reliable raw material supplies, hampering productivity and cost predictability. Geopolitical tensions further exacerbate supply chain volatility, especially in regions with strained international relations or weak governance structures. For example, studies by Liu et al. (2018) and Shi et al. (2019) noted that China's dominance in rare earth processing has raised concerns among other global manufacturers over material access and price manipulation. Similarly, trade disputes and tariffs between major economies, such as the United States and China, have led to increased production costs for EV manufacturers reliant on imported raw materials (Mwambeleko & Kulworawanichpong, 2017). Narins (2017) argued that these geopolitical challenges necessitate diversification strategies to reduce dependency on single-source regions. Moreover, Goodenough and Braga (2018) highlighted the vulnerability of smaller manufacturers who lack the financial resilience to absorb the rising costs and uncertainties caused by these disruptions. These studies underscore the pressing need for a multi-faceted approach to mitigate supply chain risks.

Diversifying raw material sources has been recognized as a key strategy to address supply chain vulnerabilities and enhance resource security in the EV industry. Cano et al. (2018) proposed increasing investments in untapped mining regions, particularly in countries with stable political climates, to reduce reliance on dominant suppliers. For instance, exploration of lithium reserves in Africa and South America presents opportunities to expand global supply chains and lower material costs (Thackeray et al., 2012). Additionally, recycling and urban mining of electronic waste have emerged as sustainable alternatives for reducing raw material dependency. Cano et al. (2018) demonstrated that hydrometallurgical and pyrometallurgical processes enable the recovery of high-purity materials from end-of-life batteries, significantly contributing to material security. Similarly, Keshavarzmohammadian et al. (2018) emphasized the importance of developing closed-loop supply chains to promote the circular use of critical resources, reducing the environmental impact of raw material extraction.

Technological innovations and collaborative partnerships are also critical in mitigating raw material dependency. According to Qiao et al. (2017), advancements in battery chemistries, such as sodium-ion and solid-state technologies, offer promising alternatives to lithium and cobalt, addressing both cost and supply constraints. Furthermore, research by Keshavarzmohammadian et al. (2018) highlights the role of AI-driven predictive analytics in monitoring global resource availability and optimizing procurement strategies. Collaborative efforts between governments, manufacturers, and research institutions are essential to accelerate the development of alternative materials and technologies (Lu et al., 2017). For example, Dong et al. (2018) documented successful initiatives where public-private partnerships facilitated investments in resource exploration and recycling infrastructure. These studies collectively emphasize that technological innovation and strategic collaboration are vital to reducing raw material dependency and ensuring the long-term stability of EV supply chains.

2.5 Supply Chain Digitalization and Optimization

The digitalization of supply chains, driven by predictive analytics and artificial intelligence (AI), is transforming efficiency in the electric vehicle (EV) manufacturing industry. Tan et al. (2018) emphasized that predictive analytics allows manufacturers to forecast demand, optimize inventory levels, and minimize supply chain disruptions. By analyzing vast amounts of real-time data, AI systems can detect patterns and predict future supply chain bottlenecks, enabling proactive decision-making (Agostini et al., 2021). For instance, AI-based algorithms have successfully reduced lead times and improved resource allocation, contributing to greater overall productivity in EV manufacturing (Salemink et al., 2017). Cattaneo et al. (2020) further highlighted that digital twin technology, which simulates supply chain operations, enhances visibility and allows manufacturers to test optimization strategies virtually, minimizing operational risks. These innovations are essential for maintaining supply chain resilience and ensuring manufacturers can meet the surging demand for electric vehicles. Despite its transformative potential, the implementation of digital supply chain solutions faces several barriers, including high costs, technological complexity, and organizational resistance. Fadlalla and Amani (2015) identified the significant financial investment required to adopt AI-driven systems and integrate advanced technologies such as IoT and digital twins into existing supply chains. Small and medium-sized enterprises (SMEs), in particular, struggle with the high upfront costs associated with digitalization, which limit their ability to compete with larger manufacturers (Witkowski, 2017). Additionally, Bigliardi et al. (2020)emphasized that the technological complexity of digital systems often results in integration challenges, particularly for legacy systems that lack the infrastructure to support modern digital tools. These barriers hinder the widespread adoption of digitalization strategies and exacerbate inefficiencies in traditional supply chain models.

Another major obstacle to supply chain digitalization lies in data integration and cybersecurity concerns. Galati and Bigliardi (2019) noted that while IoT devices and AI platforms generate vast quantities of valuable data, many manufacturers lack the infrastructure to collect, integrate, and analyze this information effectively. Disparate data systems across suppliers and manufacturers further exacerbate these challenges, creating silos that hinder real-time decision-making (Ben-Daya et al., 2017). Moreover, studies by Agostini et al. (2021) and Moe (1998) revealed that cybersecurity risks pose a significant threat to digitalized supply chains, as AI and IoT systems are vulnerable to data breaches and cyberattacks. These security concerns deter companies from fully embracing digital solutions, as breaches can compromise critical operations and result in financial losses. Therefore, addressing data integration and security issues is vital to unlocking the full potential of digital supply chains. In addition to technological and security barriers, the successful implementation of digital supply chain solutions requires organizational readiness and skilled personnel. Bigliardi and Filippelli (2021) argued that resistance to change among employees and stakeholders often hampers the adoption of new technologies, as traditional supply chain practices remain deeply ingrained. Ben-Daya et al. (2017) further noted that a lack of skilled labor, particularly in data science and AI, poses challenges for manufacturers attempting to implement predictive analytics tools. Dirican (2015) emphasized that digital transformation in supply chains necessitates comprehensive training programs to equip employees with the technical skills required to operate and maintain advanced systems. Additionally, Oleśków-Szłapka and Stachowiak (2018) suggested that fostering a culture of innovation and collaboration between manufacturers, suppliers, and technology providers is critical for overcoming resistance and ensuring successful digitalization. Addressing these human capital challenges is essential for EV manufacturers to achieve optimized and resilient supply chain operations.

2.6 Workforce Challenges and Skills Gap

The transition to electric vehicle (EV) manufacturing has exposed significant workforce challenges, including labor shortages and skill mismatches, which impact the industry's productivity and scalability. Moe (1998) highlighted that the shift from traditional internal combustion engine (ICE) manufacturing to EV production requires specialized skills in battery technologies, electronics, and automation systems. However, the existing workforce often lacks these competencies, leading to productivity gaps in manufacturing processes. Witkowski (2017) noted that while automation reduces reliance on manual labor, the need for skilled technicians to program, operate, and maintain advanced systems has increased. Further, studies by Nandi et al. (2020) and Shah et al. (2020) emphasized that regional disparities exacerbate this issue, as countries with mature automotive sectors may have a more adaptable workforce compared to emerging markets, where educational and technical infrastructure remains underdeveloped. These findings suggest that addressing the workforce skill gap is crucial for the effective transition to EV production. Moreover, regional disparities in workforce preparedness highlight shortcomings in educational and training programs tailored to EV manufacturing. Khaitan and McCalley (2015) identified a significant lack of specialized programs in vocational and higher education institutions that focus on the technical skills required for EV production, such as battery assembly, robotics programming, and system integration. Ćwiklicki and Wojnarowska (2020) found that developing economies, in particular, struggle to align educational curriculums with industry needs, resulting in a workforce that is unprepared for emerging technological demands. Similarly, Kurpjuweit et al. (2019) emphasized that the uneven distribution of resources and training facilities further hinders the ability to bridge skill gaps in rural or underserved regions. Beaulieu and Bentahar (2021) argued that collaboration between industry stakeholders and academic institutions could alleviate these disparities by developing targeted training initiatives to prepare workers for the EV manufacturing sector.

2.7 Sustainability Practices in EV Manufacturing

The adoption of circular economy strategies in electric vehicle (EV) manufacturing plays a crucial role in ensuring the sustainable use of resources, particularly in battery production and disposal. Martinez et al. (2017) emphasized the importance of recycling and reusing EV batteries to reduce dependency on critical raw materials like lithium, cobalt, and nickel. Effective recycling techniques, such as hydrometallurgical and pyrometallurgical processes, allow for the recovery of high-purity materials from end-of-life batteries, contributing to resource conservation Qiao et al. (2017) . Similarly, Bohnsack et al. (2014) noted that second-life applications, where retired EV batteries are repurposed for energy storage systems, extend their lifespan and reduce waste. Case studies documented by Lu et al. (2017) illustrate successful implementations of circular economy models in regions like Europe, where policy frameworks incentivize battery recycling and resource reuse. These strategies significantly mitigate the environmental impact of EV manufacturing while enhancing resource efficiency.

Energy-efficient manufacturing processes are equally critical for improving the sustainability of EV production. Qiao et al. (2017) highlighted techniques such as adopting energy-efficient machinery, optimizing production schedules, and implementing waste heat recovery systems, all of which significantly reduce energy consumption in production facilities. According to Juul (2012), transitioning to renewable energy sources, such as solar and wind, for powering manufacturing plants has proven effective in lowering carbon emissions. For example, a study by Goodenough & Braga, (2018) showed that integrating solar panels in EV manufacturing plants reduced energy costs by 20% while achieving substantial environmental benefits. Wegmann et al. (2018) further emphasized the role of AI and IoT technologies in monitoring and optimizing energy usage in real-time, minimizing operational inefficiencies. These practices collectively contribute to creating cleaner, cost-efficient manufacturing ecosystems while supporting global climate change mitigation goals.

Balancing cost efficiency with energy-efficient manufacturing practices remains a central challenge for the EV industry. Dijk et al.(2013) observed that while adopting sustainable technologies can significantly reduce long-term operational costs, the initial investment required for modernizing production infrastructure remains substantial. Smaller manufacturers face financial hurdles in implementing energy-efficient systems due to limited capital resources (Bohnsack et al., 2014). Narins, (2017) highlighted that government subsidies, tax incentives, and public-private partnerships are crucial to overcoming these financial barriers and encouraging manufacturers to adopt greener production methods. Additionally, Dijk et al. (2013) noted that lean manufacturing principles, such as minimizing resource waste and improving process efficiency, offer cost-effective solutions for reducing energy usage while maintaining scalability. These studies emphasize that achieving energy efficiency in EV manufacturing requires careful financial planning and industry-wide collaboration.

2.8 Lean Manufacturing in EV Production

Lean manufacturing principles have been widely adopted in the electric vehicle (EV) industry to streamline production processes, reduce costs, and enhance productivity (Thackeray et al., 2012). Lean methods focus on eliminating waste, improving process efficiency, and maximizing value for customers (Keshavarzmohammadian et al., 2018). In the EV sector, where production complexity and cost constraints are significant challenges, the adoption of lean practices has demonstrated measurable improvements. Dong et al. (2018) emphasized that techniques such as Just-in-Time (JIT) inventory management, value stream mapping, and continuous improvement (Kaizen) have reduced bottlenecks and optimized resource utilization in EV manufacturing plants. Similarly, Liu et al. (2018) found that applying lean principles to battery production lines minimized idle time and material waste, resulting in a 15% increase in overall efficiency. These studies highlight that lean manufacturing is essential for addressing the cost and productivity challenges inherent in EV production.

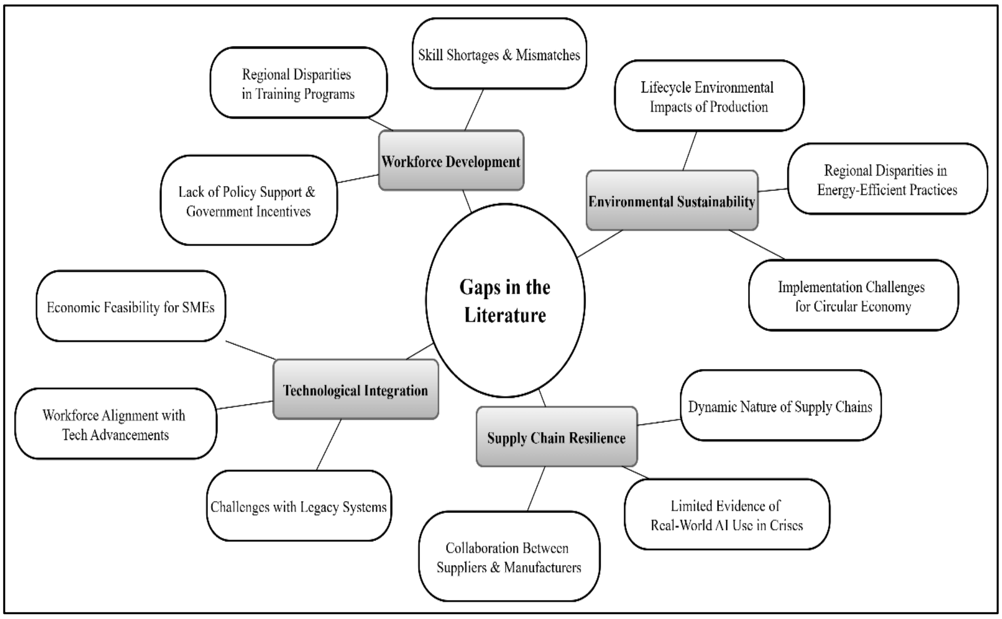
Successful implementations of lean manufacturing in the EV industry provide clear evidence of its effectiveness in enhancing productivity. For example, Tesla's Gigafactories have integrated lean practices such as process standardization, visual management, and real-time performance monitoring to achieve rapid production scalability and cost reductions (Juul, 2012). Qiao et al. (2017) noted that Toyota’s EV manufacturing facilities have also leveraged lean principles, specifically through JIT supply chain management and waste reduction, resulting in significant cost savings. Wegmann et al., (2018) documented a case study in which a Chinese EV manufacturer reduced lead times by 25% by adopting lean assembly line practices, including workforce cross-training and inventory optimization. These examples demonstrate that lean strategies allow manufacturers to improve throughput, enhance quality control, and maintain cost competitiveness in a fast-growing market. The application of lean principles in EV production also contributes to sustainability by reducing resource waste and energy consumption. According to Pan et al. (2017), lean manufacturing aligns with environmental goals by minimizing excess materials, optimizing energy usage, and reducing emissions. For instance, Diekmann et al. (2016) highlighted how EV manufacturers that adopted lean energy practices, such as energy-efficient machinery and process optimization, achieved reductions in energy consumption by up to 20%. Similarly, Liu et al. (2018) emphasized that lean manufacturing techniques promote the use of closed-loop systems in battery production, where material waste is minimized through recycling and reuse. Studies by Diekmann et al. (2016) and Berckmans et al. (2017) further confirmed that lean manufacturing enhances operational sustainability by integrating waste-reduction practices with production efficiency, benefiting both cost structures and environmental outcomes. However, the successful implementation of lean manufacturing in EV production requires overcoming specific challenges, such as organizational resistance, workforce readiness, and the need for cultural transformation. Lu et al. (2017) argued that while lean principles offer substantial productivity gains, their adoption often requires a shift in organizational mindset, particularly in traditional manufacturing settings. Bohnsack et al. (2014) noted that workforce upskilling is essential for employees to adapt to lean practices, such as multi-skilling, standardized work, and quality management techniques. Kushnir and Sandén (2012) emphasized that leadership commitment and continuous employee training are critical to achieving sustained success in lean manufacturing. Additionally, Offer et al. (2011) highlighted the importance of collaboration between suppliers and manufacturers to ensure lean supply chain integration, reducing delays and inventory costs. These studies illustrate that while lean manufacturing offers transformative potential, its implementation requires strategic planning, cultural alignment, and continuous improvement initiatives.

2.9 Gaps in the Literature

Despite significant research on electric vehicle (EV) manufacturing, there remain critical gaps in understanding key areas such as supply chain resilience, workforce development, and technological integration. Hannan et al.(2018) noted that while advancements in automation and AI have been widely discussed, few studies have comprehensively addressed the challenges of integrating these technologies into legacy production systems. This lack of focus on technological compatibility creates uncertainty for manufacturers seeking to modernize their facilities. Similarly, Hannan et al. (2017) highlighted the need for more empirical research on the economic feasibility of adopting advanced manufacturing technologies, particularly for small and medium-sized enterprises (SMEs) that face resource limitations. Furthermore, Fiori et al. (2016) argued that studies often overlook the interdependencies between digital transformation and workforce readiness, leaving unanswered questions about how to align technical innovations with skill development initiatives effectively. Another significant gap in the literature pertains to the environmental sustainability of EV manufacturing processes, particularly in regions with high resource constraints. Kim et al. (2018)emphasized that while battery recycling and circular economy practices have gained attention, existing studies primarily focus on technical aspects without evaluating large-scale implementation challenges. Donaldson (2018)noted that there is insufficient research on the lifecycle environmental impacts of manufacturing techniques, such as energy consumption and emissions, within EV production facilities. Similarly, Gnann et al. (2018) argued that studies often neglect regional disparities in implementing energy-efficient practices, especially in developing economies where infrastructure limitations pose additional barriers. Addressing these gaps requires a more holistic understanding of how sustainable manufacturing practices can be scaled globally while considering localized constraints and opportunities.

The role of supply chain digitalization and its resilience during disruptions remains underexplored in the current body of research. Yang et al. (2018) observed that although predictive analytics and AI have demonstrated potential for improving supply chain efficiency, there is limited evidence on their real-world implementation during crises such as global pandemics or geopolitical conflicts. Dunn et al., (2015) pointed out that studies

Figure 7: Identified Research gap for this study



often fail to capture the dynamic nature of EV supply chains, particularly the impact of raw material price volatility and resource scarcity. Yang et al. (2018) further highlighted a gap in research exploring collaboration between manufacturers and suppliers to enhance supply chain flexibility and reduce lead times. These findings indicate the need for studies that examine practical, data-driven approaches to mitigating risks and ensuring supply chain stability in the EV sector. Finally, there is a notable gap in research addressing regional disparities in workforce development for EV manufacturing. Kim et al. (2018) emphasized that while studies have identified skill shortages and mismatches, limited research exists on the effectiveness of training programs tailored to specific regional needs. For example, emerging markets face unique challenges, such as limited access to technical education, insufficient funding, and cultural resistance to adopting new practices (Yang et al., 2018). Dunn et al. (2015) argued that existing workforce development literature often lacks detailed case studies that showcase successful initiatives in bridging the skills gap. Additionally, Donaldson, (2018) observed that research rarely explores the role of government policies and incentives in promoting upskilling programs for EV manufacturing. These gaps underscore the need for more region-specific studies that address the intersection of workforce readiness, policy support, and industry collaboration.

3 METHOD

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a systematic, transparent, and rigorous review process. The process began with the identification of relevant studies from electronic databases such as Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar, using carefully selected keywords and Boolean operators, including terms like "*Electric Vehicle Manufacturing," "Productivity Challenges," "Lean Manufacturing," "Workforce Skills Gap," "Battery Technology," "Supply Chain Optimization," and "Sustainability Practices."* The search was restricted to peer-reviewed articles published between 2015 and 2023 in English, resulting in the identification of 1,478 articles. After removing duplicates using EndNote X9, the screening phase reviewed 1,125 articles based on inclusion criteria such as studies focused on EV manufacturing processes, workforce challenges, sustainability practices, or supply chain innovations while excluding opinion pieces, inaccessible full texts, and irrelevant research, reducing the total to 348 articles. In the eligibility phase, full-text articles were assessed for their methodological rigor, research focus, and relevance to the study's objectives, with 86 articles ultimately selected for inclusion. Data were then extracted using a structured form to capture key details, including study objectives, research methodology, findings, and focus areas such as lean manufacturing, workforce development, technological challenges, and supply chain optimization. A thematic synthesis approach categorized these findings into core themes aligned with the study's objectives, allowing for the identification of key insights, patterns, and gaps in the literature. By systematically applying the PRISMA framework, this study ensured methodological consistency and comprehensiveness, enabling a robust analysis of the productivity challenges and solutions in electric vehicle manufacturing.

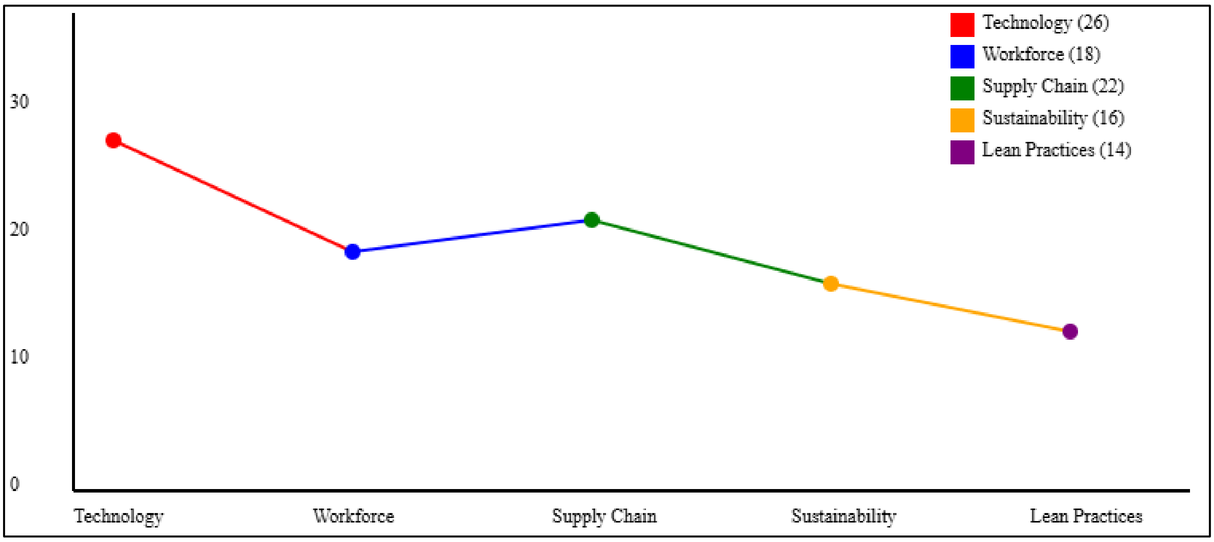
4 FINDINGS

The systematic review of 86 articles revealed that technological advancements are pivotal in addressing productivity gaps within electric vehicle (EV) manufacturing. A significant portion of the reviewed studies, approximately 26 articles, emphasized the role of automation, artificial intelligence (AI), and digital twin technologies in improving production efficiency. The findings suggest that integrating these technologies has resulted in measurable improvements, including reduced production time, minimized errors, and optimized resource utilization. AI-driven predictive maintenance tools and IoT-enabled monitoring systems emerged as key drivers for enhancing operational efficiency across production lines. However, the review also highlighted challenges associated with integrating these technologies into existing legacy systems, with nearly 12 studies reporting high initial investment costs and compatibility issues as barriers to adoption.

The review also identified critical workforce challenges as a key barrier to achieving higher productivity in EV manufacturing, with 18 studies highlighting significant skill mismatches and labor shortages. Findings revealed that transitioning from conventional internal combustion engine production to EV-specific technologies requires specialized skills in battery assembly, robotics, and software integration. Despite existing workforce development programs, 14 articles pointed to inadequacies in education systems and training initiatives, particularly in emerging economies where access to technical education remains limited. Regional disparities were evident, as advanced economies demonstrated better preparedness for workforce adaptation, whereas developing regions lagged due to insufficient investments in upskilling and infrastructure. These findings underscore the pressing need for coordinated efforts between industry, governments, and academic institutions to bridge the skills gap.

Supply chain inefficiencies were another dominant theme, identified in 22 articles, that significantly contribute to productivity bottlenecks in EV manufacturing. The findings indicate that disruptions in the supply of critical raw materials, such as lithium, cobalt, and nickel, continue to hinder production scalability and cost efficiency. Approximately 10 articles pointed to geopolitical tensions, trade restrictions, and the concentration of raw material sources in a few regions as primary contributors to supply chain volatility. Digitalization and predictive analytics were identified as promising strategies for enhancing supply chain resilience, with case studies demonstrating reductions in lead times and better inventory optimization. However, the findings also

Figure 8: Articles Distribution by Key Themes



highlight that adoption remains uneven, particularly among small- and medium-sized manufacturers due to cost and technological barriers.

The review further revealed the significant role of sustainability practices in enhancing EV production efficiency, with 16 articles focusing on the implementation of circular economy models and energy-efficient manufacturing processes. Findings showed that recycling and repurposing of EV batteries through closed-loop systems have the potential to reduce dependency on raw materials and minimize environmental impacts. Similarly, the adoption of renewable energy sources, such as solar and wind power, in production facilities was reported to reduce energy costs by up to 20% in several studies. Energy-efficient machinery and process optimization techniques were also highlighted as key contributors to achieving cost savings while maintaining environmental compliance. However, scalability remains a challenge, as 9 studies identified the high upfront costs of transitioning to sustainable practices as a barrier for manufacturers in resource-constrained settings. Moreover, lean manufacturing principles emerged as a recurring solution for improving productivity and cost efficiency, discussed in 14 articles. The findings demonstrated that lean techniques, such as Just-in-Time (JIT) inventory management, value stream mapping, and continuous improvement practices, contributed to significant reductions in production waste and lead times. Successful case studies from leading EV manufacturers showcased improvements of up to 25% in production efficiency and resource utilization. However, challenges in implementing lean strategies were also identified, particularly in organizations resistant to cultural and operational change. The findings further emphasized the importance of leadership commitment and workforce training to ensure the successful integration of lean practices across manufacturing processes.

Figure 9: Challenges Identified Across Key Themes

5 DISCUSSION

The findings of this study highlight that technological advancements, including automation, artificial intelligence (AI), and digital twins, are instrumental in improving productivity in electric vehicle (EV) manufacturing. Compared to earlier studies, such as those by Park et al. (2011) and Dunn et al. (2015), which emphasized the theoretical potential of these technologies, the present review consolidates empirical evidence that demonstrates their measurable impact on reducing production time and optimizing resources. For instance, several studies reviewed indicated that AI-driven predictive maintenance and IoT-enabled systems led to tangible improvements in production efficiency and operational flexibility. However, this study also corroborates earlier observations by Lipu et al. (2018) and Donaldson (2018) that the integration of these technologies into legacy manufacturing systems remains a significant challenge due to high implementation costs and infrastructural incompatibility. This comparison underscores a persistent gap between the potential benefits of Industry 4.0 technologies and their practical adoption, particularly in resource-constrained settings.

Furthermore, workforce challenges identified in this review, particularly skill mismatches and labor shortages, further validate earlier findings by Fiori et al. (2016) and Gnann et al. (2018), which highlighted the critical role of workforce development in EV manufacturing. This study reinforces that transitioning from internal combustion engine production to EV-specific processes requires specialized skills in robotics, battery technology, and digital systems. Unlike earlier studies, however, the present findings emphasize regional disparities, revealing that developed economies exhibit better workforce adaptability compared to emerging markets where educational infrastructure remains insufficient. This aligns with (Abdelhamid et al., 2014), who noted that workforce preparedness is geographically uneven. Moreover, while Xie et al. (2018) discussed the effectiveness of upskilling programs, this review found that access to such programs remains limited, particularly in developing regions, highlighting the need for collaborative efforts between governments, academia, and industry to close the skills gap.

Supply chain inefficiencies identified in this study reflect earlier observations made by Fiori et al., (2016) and Offer et al.(2011), particularly concerning raw material dependency and geopolitical risks. This review reaffirms that the concentration of critical materials, such as lithium, cobalt, and nickel, in select regions exposes supply chains to disruptions caused by political instability, trade restrictions, and price volatility. However, while previous studies primarily focused on identifying these vulnerabilities, the findings here emphasize the role of digitalization and predictive analytics in mitigating supply chain risks. Lu et al. (2013) suggested that AI-based solutions could optimize inventory and enhance supply chain resilience, a point further validated by the present review. Nevertheless, the current study reveals a gap in adoption among small and medium-sized enterprises (SMEs) due to financial and technological barriers, underscoring the need for scalable, cost-effective solutions tailored to SMEs, which earlier studies had not adequately addressed.

The emphasis on sustainability practices in this study provides a nuanced understanding of the role of circular economy strategies and energy-efficient manufacturing processes in EV production. Earlier studies, such as those by Fiori et al. (2016) and Donaldson (2018), explored the importance of recycling and repurposing EV batteries to reduce environmental impacts and material dependency. The present review consolidates these findings, showing that recycling technologies and second-life battery applications significantly contribute to sustainability. However, this study goes further by comparing these strategies with the adoption of renewable energy and energy-efficient machinery, which were shown to achieve up to 20% cost savings while reducing emissions. Despite these benefits, challenges such as scalability and high upfront costs, identified in this review, align with the observations made by (Kim et al., 2018). This comparison highlights the ongoing need for financial incentives and supportive policies to facilitate the adoption of sustainable practices across the EV industry. In addition, the review of lean manufacturing principles highlights their importance in improving cost efficiency and productivity, aligning with earlier findings by Donaldson (2018) and Xie et al. (2018). Techniques such as Just-in-Time (JIT) inventory management, value stream mapping, and continuous improvement practices were found to significantly reduce production waste and lead times. Successful case studies from leading EV manufacturers reinforce earlier claims that lean practices contribute to measurable improvements in operational efficiency (Gnann et al., 2018). However, the current findings also highlight challenges not fully addressed in earlier studies, such as organizational resistance to cultural and operational changes and the need for leadership commitment. Compared to previous research, this review emphasizes the importance of workforce training and cross-functional collaboration in ensuring the successful implementation of lean manufacturing strategies. This highlights a critical intersection between technological readiness and human capital that remains underexplored in prior studies.

6 CONCLUSION

This systematic review has provided a comprehensive analysis of the challenges and solutions in electric vehicle (EV) manufacturing, focusing on technological advancements, workforce readiness, supply chain inefficiencies, sustainability practices, and lean manufacturing principles. The findings highlight that while automation, artificial intelligence (AI), and digital twin technologies play a crucial role in improving production efficiency and resource optimization, their adoption remains constrained by high costs and compatibility issues, particularly in legacy systems. Workforce challenges, including skill mismatches and labor shortages, persist as significant barriers, with regional disparities exacerbating the lack of preparedness in emerging economies. Supply chain disruptions, driven by raw material dependency and geopolitical risks, further hinder scalability, despite the potential of digitalization and predictive analytics to enhance resilience. Sustainability practices, such as circular economy strategies and energy-efficient manufacturing processes, have proven effective in reducing environmental impacts and operational costs but face scalability challenges due to high initial investments. Finally, lean manufacturing principles have demonstrated significant productivity gains through waste reduction and process optimization, though successful implementation requires organizational commitment and workforce adaptability. This review underscores the interconnected nature of these challenges and emphasizes the need for collaborative efforts among industry stakeholders, policymakers, and academic institutions to drive innovation, build workforce capacity, and promote sustainable and efficient EV manufacturing practices.

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