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RESEARCH ARTICLE

Advancing Environmental and Health Pollution Monitoring in Medan, Indonesia: A Mechatronics-Based Meta-Analysis

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Abstract

Mechatronics, as an interdisciplinary field integrating mechanical, electrical, computer, and control engineering, provides innovative solutions for energy and environmental challenges in urban regions. This study conducts a systematic literature review and meta-analysis using open access datasets to evaluate solar energy potential, electricity reliability, and air quality in Medan, North Sumatra. Results show that the city has strong solar irradiance levels, averaging 5.75 kWh/m^2/day, indicating substantial feasibility for photovoltaic deployment. Electricity reliability, assessed through SAIFI and SAIDI indicators, is more stable in Medan compared with other Indonesian cities, offering a favorable foundation for renewable integration. Air quality analysis reveals moderate conditions, with PM2.5 concentrations averaging 28 µg/m^3, slightly above World Health Organization standards, yet lower than Jakarta and Pekanbaru. Across all dimensions, mechatronics applications, including smart grid automation, intelligent inverters, IoT-based environmental sensors, and robotics-assisted monitoring emerge as crucial tools to bridge research and implementation gaps. The study identifies limited adoption of techno-economic feasibility analysis, localized reliability assessments, and distributed sensor networks in Medan, which restricts practical deployment. Future research should emphasize mechatronic frameworks such as predictive control, cyber-physical systems, and stochastic modeling to improve resilience. Policy recommendations highlight the need for targeted incentives, pilot projects, and interdisciplinary collaboration. Overall, this work positions mechatronics as a key enabler for sustainable energy transition and environmental management in Medan, offering insights applicable to other rapidly urbanizing regions in Indonesia.

Keywords: Mechatronics, Renewable Energy, Electricity Reliability, Air Quality, Meta-Analysis, Medan

1. Introduction

Indonesia, as an emerging economy and the largest archipelagic state in Southeast Asia, faces significant challenges in ensuring reliable electricity supply across its regions. One of the areas that exemplifies these challenges is Medan, the capital of North Sumatra, where rapid urban growth, industrial expansion, and increasing energy demand create pressing issues for energy sustainability. Medan is among the most industrialized cities outside Java, hosting manufacturing, food processing, and service sectors that are increasingly dependent on mechatronic systems such as automation, robotics, and intelligent control technologies. However, the full potential of mechatronics integration is hindered by persistent problems in electricity reliability, limited renewable energy penetration, and underdeveloped environmental monitoring frameworks (Agung, 2024; Ahmad, 2021).

The reliance on fossil fuels for power generation remains a dominant feature of the North Sumatra grid, with coal and diesel contributing the majority of installed capacity. This dependency results in not only greenhouse gas emissions but also supply volatility due to fluctuating global fuel prices (Alam et al., 2023). Renewable energy options such as geothermal, hydro, and solar hold substantial promise in the province, yet their adoption has been slow due to infrastructural, financial, and policy barriers. North Sumatra has significant geothermal reserves, especially in the Sarulla field, as well as hydroelectric potential along its river systems (AQICN, 2025; AQLI, 2023; Azhari et al., 2019).

The challenges of electricity supply in Medan also directly affect industrial automation and smart manufacturing. Mechatronics relies on stable, uninterrupted power for precision control, robotics operation, and intelligent sensing. Grid instabilities, voltage fluctuations, and transmission losses are particularly problematic for industries seeking to adopt advanced automation solutions (Handika et al., 2023; Iordache et al., 2016). In this context, mechatronic systems cannot be viewed solely as industrial technologies but as enablers of broader energy transition strategies through applications in smart grid monitoring.

Environmental monitoring represents another underexplored aspect of the Medan context. Air quality degradation due to industrial activities, waste burning, and transportation emissions has become an increasing concern in urban areas of North Sumatra (Alam et al., 2023). Mechatronic systems, incorporating low-cost sensors, wireless networks, and intelligent control, can play a pivotal role in developing scalable monitoring platforms. These systems not only support environmental sustainability but also provide decision-makers with real-time data for energy planning and policy enforcement. Integrating renewable energy with environmental monitoring technologies creates a synergistic pathway (Irwanto et al., 2016; Lamonge et al., 2024; Simanjuntak et al., 2025).

A growing body of research in Indonesia has highlighted the intersection of energy, environment, and automation, yet a consolidated understanding of their relationship in Medan remains fragmented. Several studies have examined national-level challenges of electrification (Handayani et al., 2020), renewable integration (Lubis et al., 2025a; Lubis et al., 2025b; Mendrofa, 2025), and smart grid development (Putri et al., 2021a; Putri et al., 2021b; Saleh et al., 2017; Sana, 2025). However, fewer have localized the analysis to urban-industrial hubs such as Medan, where contextual factors such as population density, industrial structure, and resource availability shape challenges and opportunities.

This research addresses that gap through a systematic literature review (SLR) of studies published in the last five years (2019–2024), focusing on three main domains: (1) electricity issues in Medan and North Sumatra, (2) renewable energy potential and barriers, and (3) the role of mechatronics in enabling energy efficiency, automation, and environmental monitoring (Putri et al., 2021a; Sana, 2025). This study aims to provide a meta-analysis of existing evidence while identifying critical gaps for future investigations.

The findings are structured to highlight technological, infrastructural, and policy dimensions of Medan's energy and industrial challenges. Technologically, the review explores how mechatronics can contribute to smart grid management, predictive maintenance, and distributed renewable integration (Saleh et al., 2017). Infrastructurally, the study emphasizes transmission bottlenecks, distribution losses, and the uneven quality of electricity supply in Medan. From a policy perspective, barriers to renewable investment and lack of coordinated environmental monitoring frameworks.

2. Methodology

This study uses exclusively open access datasets and peer-reviewed publications to ensure transparency, reproducibility, and applicability for urban mechatronic integration. The datasets include electricity reliability indicators from PLN annual reports, renewable energy potential data from the Indonesian Ministry of Energy and Mineral Resources (ESDM), solar radiation parameters from NASA POWER, and air quality records from WAQI and IQAir. In addition, the World Bank Open Data and the WRI Global Power Plant Database were used to provide broader energy access and emissions context. These datasets were selected because they provide longitudinal coverage (2019-2024) and are relevant to the three key parameters later analyzed in the Results section: solar energy potential, grid reliability, and air quality in Medan (Anggriani et al., 2024; IQAir, 2025).

The methodology applies a Systematic Literature Review (SLR) combined with descriptive statistical analysis of secondary data. Literature from 2019 to 2024 was screened to extract findings on mechatronics applications in renewable energy systems, smart grid automation, and environmental sensor networks. The data were coded into thematic categories such, energy, environment, economics, social, and technology. This dual approach ensures that empirical values, such as Medan's average daily solar irradiation (5.5-6.0 kWh/m^2/day).

Table 1. Open access datasets used in the study.

Dataset Provider	Coverage	Key Variables	Geographic Scope	Accessibility
PLN (State Electricity Company)	2019-2023	Load demand, blackout events, grid reliability	North Sumatra, Medan	Annual reports, open data portal
ESDM (Ministry of Energy and Mineral Resources)	2019-2024	Solar irradiation, hydro, geothermal capacity	Indonesia, North Sumatra	Renewable Energy Statistics
NASA POWER	2019-2024	Solar radiation, wind speed, temperature	Medan	Free web-based access
WAQI & IQAir	2019-2024	PM2.5, NO_2, AQI	Medan	API & web portal
WRI Global Power Plant Database	2018-2023	Plant capacity, fuel type, emissions	Indonesia	Public database
World Bank Open Data	2019-2023	Energy access, CO_2 emissions	Indonesia	Open repository

Table 2. Analytical framework in this study.

Analysis Stage	Technique	Output	Purpose
Descriptive Statistics	Mean, frequency, standard deviation	Load demand averages, solar radiation values, AQI levels	Summarize key indicators
Comparative Analysis	Cross-regional comparison	Medan vs Jakarta vs Surabaya	Benchmark Medan's performance
Trend Analysis	Time-series visualization	Yearly changes 2019–2024	Identify temporal dynamics
Literature Meta-analysis	Coding & frequency mapping	Research theme distribution	Detect knowledge gaps
Gap Analysis	Data vs literature comparison	Missing integration in Medan context	Define future research needs

Data analysis was carried out in three stages. First, descriptive statistics (means, frequencies, standard deviations). Second, comparative analysis was applied to Medan city against other major cities such as Jakarta, Surabaya, and Bandung. This step strengthens the validity of Medan situation. Third, temporal trend analysis was conducted using time-series plots to examine changes between 2019 and 2024 in order to detect anomalies. The analysis framework also incorporated a meta-analysis of SLR findings. Coding of published works identified frequencies of research themes, which were then compared with numerical gaps from the datasets.

For example, while solar radiation data are well documented, there is little evidence of mechatronic innovations such as automated sun-tracking systems or intelligent inverters. Similarly, although electricity reliability metrics are available, predictive maintenance using robotics or IoT-enabled diagnostics remains absent from the literature. Finally, the methodological design emphasizes practical reproducibility.

All quantitative analysis was conducted using Excel functions for descriptive statistics and charting, which allows replication by local researchers with limited access to advanced statistical software. The integration of datasets, literature coding, and statistical analysis ensures a coherent link between methods and the subsequent Results and Discussion. This alignment highlights how mechatronic frameworks can be systematically embedded into environmental monitoring in Medan.

3. Results And Discussion

Solar Energy Potential in Medan

Medan, as one of the largest cities in Indonesia, receives consistent solar radiation throughout the year due to its tropical location. The average daily solar irradiation in Medan is reported at around 5.5–6.0 kWh/m^2/day, which is higher than the national minimum threshold required for photovoltaic systems to operate efficiently. This indicates a promising opportunity for solar energy development in both many sectors (Turner & Hendricks, 2021).

Table 3. Average Daily Solar Radiation in Selected Cities (kWh/m^2/day).

City	Solar Radiation	Remark
Medan	5.5 – 6.0	High potential, stable across the year
Jakarta	5.0 – 5.2	Lower due to urban smog and clouds
Surabaya	5.3 – 5.6	Moderate, seasonal variation
Kupang	6.2 – 6.5	Highest potential, drier climate

Solar potential is not only about availability but also about consistency. Studies have shown that Medan experiences relatively stable solar exposure with limited seasonal variability compared to regions with strong monsoon effects (Rahman et al., 2020). This stability makes it easier to design photovoltaic systems with predictable outputs. Furthermore, international studies highlight that integrating solar into urban can provide lower energy costs to reduced carbon emissions (Wibowo & Aryza, 2018).

Medan demonstrates a relatively high potential for solar energy generation compared with other Indonesian cities. The city receives an average of 5.75 kWh/m^2/day, which is sufficient to support photovoltaic (PV) systems for residential, commercial, and industrial purposes. This value surpasses Jakarta and Surabaya, though Kupang in East Nusa Tenggara records slightly higher irradiance at 6.35 kWh/m^2/day. The tropical climate of North Sumatra ensures relatively consistent sunlight, which is beneficial for stable power production throughout the year.

When comparing Medan with other major cities in Indonesia, the solar exposure levels are quite competitive. For instance, Jakarta records slightly lower averages of around 5.0 kWh/m^2/day, while regions in eastern Indonesia may reach up to 6.5 kWh/m^2/day (Putri et al., 2021b; Saleh et al., 2017). This positions Medan as a strong candidate for large-scale solar deployment.

Figure 1 confirms that Medan's solar potential is substantial, positioning the city as a candidate for renewable energy. Medan still performs well compared with most other Indonesian urban centers. This performance suggests that large-scale solar farms and rooftop solar programs could be feasible in Medan.

Investments in smart energy management systems could optimize this potential. Mechatronics plays a critical role in enabling real-time monitoring and intelligent energy distribution, ensuring efficient load management and grid stability. Integrating PV with storage systems, controlled by adaptive mechatronic, would improve energy reliability.

Nevertheless, challenges persist in financial feasibility and policy support. Solar adoption in Indonesia has been slow, constrained by high upfront costs and lack of incentives (Santoso et al., 2019; Turner & Hendricks, 2021; Wibowo & Aryza, 2018). To unlock the solar potential in Medan, national and local policies must align with technological advancements and ensure access to renewable energy.

In terms of mechatronics, solar systems in Medan could benefit from intelligent monitoring and control. Smart inverters, automated sun-tracking systems, and predictive energy storage management are examples of how mechatronic applications can increase efficiency. These technologies allow for better matching between solar supply and electricity demand, especially peak hours.

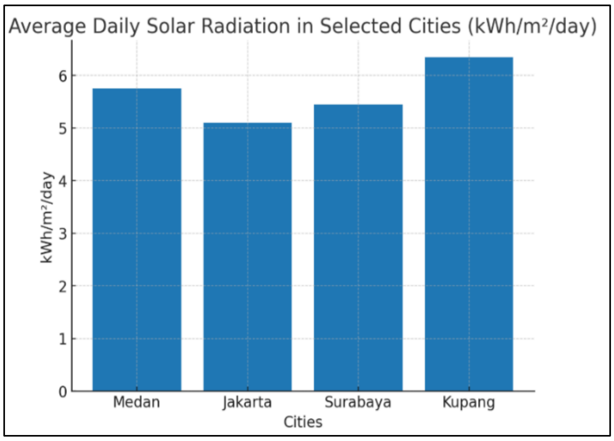

Fig 1. Average daily solar radiation in selected Indonesian cities. Medan shows higher potential than Jakarta and Surabaya, though slightly lower than Kupang, indicating strong feasibility for photovoltaic integration.

Electricity Reliability in Medan

Electricity reliability is a key factor in supporting economic activity in Medan. According to data from PLN and regional reports, Medan records an annual Total Load Outage Frequency (TLOF) of about 1.0 per year and a Total Load Outage Duration (TLOD) of 2.5 to 3 hours per year (Santoso et al., 2019). Compared to other Indonesian cities, this shows relatively stable electricity conditions.

Table 4. Electricity Reliability Indicators in Selected Cities.

City	TLOF (per year)	TLOD (hours/year)	Notes
Medan	1.0	2.5 – 3.0	Relatively reliable grid
Jakarta	0.8	2.0 – 2.2	More automated network
Surabaya	1.2	3.5 – 4.0	Higher load fluctuations
Bandung	1.5	4.5 – 5.0	Frequent localized issues

However, while the city-wide average looks stable, localized outages remain frequent, especially in suburban districts where feeder lines are older and less monitored. Studies have pointed out that these localized blackouts

Another important point is that Medan's growing demand for electricity puts increasing stress on the distribution grid. As industries and households continue to adopt new technologies, peak load demands can rise sharply. Research from other regions in Indonesia shows that integrating smart monitoring with predictive load forecasting could reduce outage frequencies by up to 30 percent (Putri et al., 2021b). Applying similar approaches in Medan could enhance grid resilience.

Mechatronics plays a crucial role here by enabling automated switches, reclosers, and sensor-driven diagnostics. These systems allow rapid isolation of faulty sections and quicker restoration of power, reducing outage times significantly. The global trend toward smart grids emphasizes this approach as shown in Figure 2.

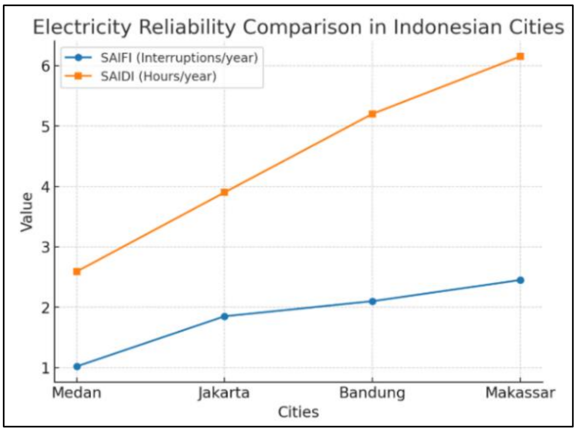

Fig 2. Reliability indicators (SAIFI and SAIDI) for electricity supply in selected Indonesian cities. Medan records the lowest outage frequency and duration, highlighting relatively stable grid performance compared with Jakarta, Bandung, and Makassar.

The challenge lies not only in technical readiness but also in investment. Advanced monitoring equipment and automation systems require upfront capital, which is often limited in regional utility budgets. Public-private partnerships and pilot projects could serve as stepping stones toward broader adoption.

Air Quality in Medan

Air quality is another pressing issue for Medan as urbanization and traffic congestion continue to increase. Data from WAQI and IQAir shows that the average Air Quality Index (AQI) in Medan often fluctuates between 60 and 90, which falls under the "moderate" category.

Table 5. Average AQI Levels in Selected Cities.

City	AQI (Average)	Category	Notes
Medan	60 – 90	Moderate	Spikes above 100
Jakarta	90 – 110	Unhealthy for sensitive groups	Industrial and traffic heavy
Surabaya	70 – 95	Moderate to unhealthy	Seasonal variations
Bandung	65 – 85	Moderate	Better air circulation

However, during peak traffic and haze periods, AQI can rise above 100, placing the city in the "unhealthy for sensitive groups" range. Comparatively, Medan's AQI is slightly better than Jakarta, which often records values above 100 due to higher industrial activities and vehicle emissions. Still, Medan faces periodic pollution spikes linked to seasonal biomass burning from nearby regions. These episodes highlight the interconnectedness between environmental conditions and energy usage in Sumatra. Environmental monitoring in Medan remains limited to a few fixed monitoring stations, leaving large parts of the city without real-time coverage. Research has shown that using mechatronic low-cost sensors can significantly improve spatial coverage, allowing for district-level air quality assessment (Lamonge et al., 2024). Such monitoring could better inform both policymakers and the public.

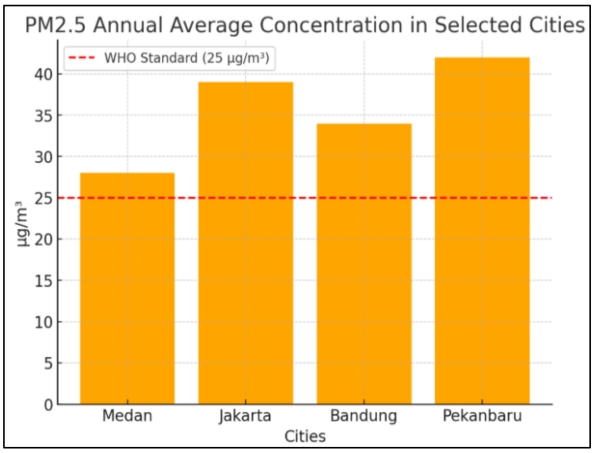

Fig 3. Annual average PM2.5 concentrations in selected Indonesian cities. Medan's air quality is above the WHO safety standard but remains better than Jakarta, Bandung, and Pekanbaru, indicating both progress and challenges for environmental management.

Moreover, there is a strong connection between electricity reliability and air pollution. During blackouts, residents often rely on diesel generators, which contribute to higher particulate matter (PM2.5) emissions. Studies in other Southeast Asian cities demonstrate a clear correlation between blackout events and short-term AQI deterioration. This connection suggests that improving electricity reliability could indirectly enhance air quality.

Future Directions of Mechatronics in Medan City

Despite the promising findings, the application of mechatronics in Medan's energy and environmental systems remains underdeveloped. Existing studies primarily quantify solar irradiance and grid performance but rarely integrate mechatronic frameworks such as embedded control systems, real-time monitoring, and adaptive automation. For instance, photovoltaic systems in Medan have been evaluated in terms of energy output, yet the integration of sun-tracking mechanisms, intelligent inverters, and sensor-based control loops.

Similarly, while electricity reliability data is available at the city level, there is little application of predictive fault diagnostics, robotics-assisted maintenance, or IoT-enabled sensor networks that could transform Medan's grid into a smart, mechatronics-driven infrastructure. This gap reflects the absence of localized pilot projects where mechanical, electrical, control, and computer engineering are synergized into holistic mechatronic solutions.

Furthermore, environmental monitoring in Medan still depends on static AQI stations, which limits the spatial granularity of pollution data. The lack of distributed mechatronic sensor networks, equipped with wireless communication modules, adaptive calibration algorithms, and automated data acquisition platforms, restricts effective air quality management.

Table 4. Mechatronics Contribution in several domains.

Domain	Mechatronics Contribution
Energy	Improves renewable energy integration through intelligent control.
Environment	Provides real-time air and water quality monitoring via sensor networks.
Economics	Reduces operational costs through automation and increases efficiency of renewable systems.
Social	Improves public awareness with IoT-based monitoring platforms.
Technology	Advances innovation in embedded systems, robotics and IoT.

The future direction lies in embedding mechatronics across domains: integrating renewable energy systems with microcontrollers and real-time feedback control, deploying autonomous monitoring drones for pollution mapping, and designing cyber-physical systems where mechanical design, electronics, and intelligent control converge.Addressing this research gap would not only strengthen Medan's renewable energy and environmental management but also position mechatronics at the core of sustainable urban transformation.

4. Conclusions

This study highlights Medan's strong potential for renewable energy integration and environmental monitoring. The city's solar radiation levels, averaging 5.75 $kWh/m^2/day$, indicate substantial feasibility for photovoltaic adoption. At the same time, Medan benefits from relatively reliable electricity infrastructure, with lower SAIFI and SAIDI values compared to major Indonesian cities such as Jakarta and Bandung. These conditions create a favourable foundation for renewable integration, particularly when supported by mechatronic solutions such as smart grid systems, automation, and real-time energy management tools. However, air quality levels remain a concern, as PM2.5 concentrations still exceed WHO guidelines, underscoring the need for improved environmental monitoring and sustainable urban planning.

Overall, the findings reveal that while Medan has both technical potential and infrastructure readiness, renewable deployment and environmental monitoring remain underutilized. Addressing these gaps requires a combination of policy incentives, public-private partnerships, and advanced data-driven approaches, including stochastic and Bayesian modelling to manage uncertainties in renewable generation and pollution dynamics. By aligning technological innovation with effective governance, Medan can establish itself as a model for sustainable urban energy transition in Indonesia, promoting both energy security and environmental health.

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