

Data-Driven Analysis of Environmental Sustainability Practices in Modern Engineering Applications

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ABSTRACT

The current focus on energy consumption, carbon emissions, material consumption, waste production, and resource efficiency has made environmental sustainability a key concern in engineering applications today. The present study reviews the environmental sustainability practices by adopting an information-based approach and analyzing the impact of selected engineering practices on the overall engineering sustainability practices. The study utilizes a structured quantitative dataset with 220 observations from various engineering application domains such as civil/construction, manufacturing, energy systems, transportation, environmental engineering, mechanical systems and electrical systems. The sustainability practices discussed are: energy-efficient design, renewable energy measures, sustainable materials, waste management, water management, environmental monitoring, and green technology. To analyze the relationship between sustainability practices and environmental performance, descriptive statistics, Pearson correlation analysis, multiple linear regression analysis and comparative sector-wise analysis were used. The results show that each of the selected sustainability practices has positive and significant relationships with overall sustainability performance. The regression model accounts for 91% of the variation in sustainability performance, meaning that the model has high predictive value. The highest-ranked contributions were from energy-efficient design and waste management practices, followed by sustainable materials use and renewable energy adoption. The analysis by the sectors revealed that transportation engineering and environmental engineering had improved sustainability performance compared to other sectors. Based on the above study, the conclusion can be drawn that data-driven sustainability assessment can be used to support engineering decisions with evidence, enhance environmental performance, and foster sustainable engineering practices.

1. Introduction

In recent times, the concerns of engineering with energy consumption, materials utilization, industrial emissions, waste generation and resource efficiency make it a central topic of environmental sustainability in modern engineering. Engineering applications have become much more than a productivity game in recent years and have come to rely on sustainability-oriented practices to minimize impacts on the environment while maintaining operational efficiency (de Sousa Jabbour et al., 2018). Today, modern engineering industries like manufacturing, construction, transport, energy and industrial processes are now demanded to combine environmental concern and technological innovation. This transition has fueled the movement towards data-driven approaches in tracking environmental performance and enhancing sustainability impacts among engineers, industries and policymakers (Belhadi et al., 2020).

In recent years, the implementation of Industry 4.0 technologies has revolutionized the perception and realization of environmental sustainability, especially in engineering applications. Engineering organisations are able to gather real-time data, track performance metrics and make better decisions thanks to the digital technologies of the IoT, big data analytics, AI, automation and cyber-physical systems. These technologies enable the detection of energy use and production inefficiencies, material flow inefficiencies, waste generation and production system inefficiencies. Environmentally sustainable manufacturing and circular economy practices (CEP) are therefore important Industry 4.0 enablers (Bai et al., 2020; de Sousa Jabbour et al., 2018). By embedding digital systems into sustainability processes, the shift from a reactive approach to environmental management to an active one and a more evidence-based approach to sustainability planning can be achieved.

Data-driven analysis is a big factor in the evaluation of sustainability practices, as it offers a measurable way to make decisions. Sustainability cannot be judged by general observation or policy statements in engineering applications, but must be measured in terms of such indices as energy efficiency, reduction of carbon emissions, minimization of waste, use of renewable energy, adoption of sustainable materials, water conservation, productivity of resources and other factors. Big data analytics and artificial intelligence are becoming more prevalent for enhancing operational efficiency and environmental performance, by identifying trends, predicting outcomes, and providing informed decision-making (Bag, Gupta, et al., 2021; Bag, Pretorius, et al., 2021). These analytical tools enable organizations to gain insights into what aspects of sustainability practices are most effective in improving environmental performance.

The importance of sustainable product design and development as a component of environmental sustainability issues is also increasing in engineering. Sustainable design is about minimising the environmental impact of a product or system by enhancing material choice, decreasing waste, improving recyclability and reducing energy use throughout the life of the product or system. To facilitate environmentally responsible innovation (Ahmad et al., 2018), Sustainable product design should use suitable tools and assessment methods. Sustainable design is also closely related to the principles of the circular economy in modern engineering applications, which seek to extend the useful life of products, materials and resources by maximizing their re-use, recycling and recovery. Digital technologies can also contribute to the implementation of circular economy activities by enhancing the traceability of products and their use, and by optimizing resource flows (Bressanelli et al., 2018; Chauhan et al., 2021).

Furthermore, the Internet of Things has gained a lot of attention in the scope of sustainability-related engineering, as it allows for ongoing monitoring and data collection through supply chains, production systems, infrastructure and environmental control systems. In real time, IoT based systems can monitor energy use, machine operation, waste generation, emissions, and resource use. This helps with effective environmental management and enables engineering firms to take prompt action when they spot inefficiencies or risks in the environment. With the increasing role of IoT in supply chain and production systems, it has been emphasized that it enhances the visibility, coordination, and operational performance (Ben-Daya et al., 2019). This transparency is critical in engineering that cares about sustainability, where tangible environmental benefits are sought.

Even though there is a growing interest in sustainable engineering and digital transformation, studies are still needed that can investigate the interaction between various sustainability practices and their combined effect on the environment in integrated data-driven studies. While Industry 4.0, circular economy, sustainable manufacturing, and digital technologies have been talked about in existing studies, there is a need to statistically analyze how certain sustainability practices relate to sustainability performance as a whole, within the context of contemporary engineering applications. The use of big data analytics, lean six sigma and green manufacturing has proven to enhance environmental performance (Belhadi et al., 2020) and industry 4.0 drivers are found to support the implementation of circular economy (Abdul-Hamid et al., 2021). But more in-depth research is required to understand the synergic effect of these different factors on sustainability outcomes.

In this sense, main focus on studying environmental sustainability from a quantitative and data perspective. The study assesses the impact of selected sustainability practices on the overall sustainability performance of engineering applications. The main objective are to evaluate impact of environmental sustainability practices on overall sustainability performance in modern engineering applications and identify the most significant sustainability practices contributing to environmental performance using a data-driven approach.

2. Literature Review

2.1 Industry 4.0 and Sustainable Engineering

Industry 4.0 and environmental sustainability are emerging as a significant research field in current engineering applications. Industry 4.0 is the use of digital technologies, including automation, cyber physical systems, artificial intelligence, big data analytics, cloud computing and the Internet of Things in industrial and engineering systems. The technologies help ensure sustainability by optimizing use of resources, minimizing waste, maximizing energy efficiency, and enhancing environmental monitoring. Industry 4.0 offers the technical enabler for data-driven sustainability practices, as it allows for the collection of real-time data and evidence-based decision making in engineering applications. The principles of circular economy can be fostered with Industry 4.0, by generating new opportunities for sustainable operations and resource optimisation (de Sousa Jabbour et al., 2018). Likewise, digitization also offers major opportunities for sustainability by enhancing operational control, mitigating inefficiencies and enabling sustainable production systems (Ghobakhloo, 2020).

2.2 Circular Economy and Sustainable Operations

The need for a circular economy has become one of the primary models of sustainability in engineering and industrial systems. The circular economy is an alternative to the linear one, which is based on three main principles: minimizing waste, reusing materials and products, and recycling resources. In today's engineering applications, the principles of circular economy are interrelated with sustainable design, reverse supply chain, green manufacturing, and responsible resource use. Industry 4.0 technologies can support the enhancement of the implementation of circular economy by better material tracking, process integration and operational efficiency (de Sousa Jabbour et al., 2018). Industry 4.0 and circular economy can, at the same time, enhance reverse supply chain performance by boosting operational excellence and sustainability results (Dev et al., 2020). According to these studies, there is a need to combine digital systems and data-driven decision-making with circular economy practices to make them more effective.

2.3 Artificial Intelligence and Data-Driven Sustainability

AI is playing a key role in enhancing sustainability in engineering and business models. AI algorithms can analyse vast amounts of data, detect underlying trends, make accurate environmental projections, and inform decision-making. In this regard, AI can be leveraged to monitor the use of energy resources, minimize environmental impacts, predict waste generation, schedule maintenance, and help with sustainable resource allocation. AI can play a role in achieving sustainable development goals, through innovative business models and through strategic decision making (Di Vaio et al., 2020). It is important to apply to the modern applications of engineering since the sustainability

performance is increasingly dependent on the capacity of converting environmental data into useful decisions. Data-driven tools enable engineers and managers to assess sustainability practices using sustainable metrics and not just relying on inspection or "experience based" judgment.

2.4 Digital Transformation and Environmental Sustainability

Digital transformation plays an important role in improving environmental sustainability as it changes the manner in which organisations collect, process and apply information on environmental sustainability. Digital platforms, sensors, monitoring and analytics systems enable engineering groups to monitor environmental performance and pinpoint areas for improvement on an ongoing basis. The correlation between Digital transformation and environmental sustainability is also directly linked to achieving transparency, operational efficiency and environmental decision making (Feroz et al., 2021). Measuring carbon and energy efficiency, water, materials or waste digitally is new application in engineering. This enables the measurement of more sustainable evaluations to be more systematic. Digital Transformation means that data-driven assessments of sustainability practices for modern engineering systems are improved.

2.5 Implementation of Industry 4.0 in Manufacturing and Supply Chains

The implementation of Industry 4.0 technologies varies across organizations and engineering sectors. Manufacturing companies adopt Industry 4.0 technologies in different patterns depending on their operational goals, technological readiness, and production requirements (Frank et al., 2019). This indicates that sustainability outcomes may also vary across engineering applications because not all sectors adopt digital technologies at the same level. Industry 4.0 implementation affects supply chains by improving connectivity, visibility, flexibility, and responsiveness (Ghadge et al., 2020). These improvements are important for environmental sustainability because supply chain activities influence material use, transportation efficiency, waste generation, and emission levels. When supply chains become more visible and data-driven, organizations can better identify environmental inefficiencies and improve sustainability performance.

3. Research Methodology

3.1 Research Design

The research design used in the present study is quantitative and data driven research design which is used to investigate the practices of environmental sustainability in modern engineering applications. Selected sustainability practices are focused on the research, with an emphasis on estimating the contribution of these practices to the overall environmental performance. A quantitative design is indicated if the number of engineering applications that rely on measurable indicators is growing, then it would be indicated to use performance monitoring and analytical tools to find patterns, relationships and predictive effects between the selected variables. The analysis of this study is carried out in various engineering applications such as Civil engineering, Mechanical engineering, Electrical engineering, Manufacturing engineering, Energy systems, Transportation engineering and Environmental engineering. The areas identified are where the sustainability of the environment is important.

3.2 Nature of the Dataset

The data for the study is structured quantitative data with 220 observations of environmentally sustainable practices in modern engineering applications. The observations are engineering applications, project units, operational contexts, and technical engineering practices that were evaluated using selected sustainability indicators. It incorporates measures that involve energy efficient design, the utilization of renewable energy sources, sustainable materials use, waste management, water conservation, monitoring of the environment, adoption of green technology, and general sustainability performance. This data can be used for descriptive statistics, correlation analysis, regression analysis and comparative analysis in various engineering application fields.

3.3 Study Variables

There are one dependent and independent variable in the study. The independent variables are the important practices of environmental sustainability that are used in modern engineering applications such as energy efficient design, utilization of renewable energy, use of sustainable materials, waste management, water conservation, environmental monitoring and adoption of green technology. These variables are indicative of the key practices adopted for minimizing energy consumption, increasing the efficiency of the resources, controlling waste, conserving water, monitoring environmental impacts and supporting cleaner engineering operations. Overall sustainability performance is the dependent variable, which is the overall environmental outcome of engineering applications related to energy savings, emission reduction, waste minimisation, resource efficiency, environmental compliance and sustainable operational performance.

3.4 Measurement of Variables

Structured numerical scores are used to measure the variables and appropriate for quantitative analysis. Scores of higher magnitude represent a higher level of adoption of sustainability practices and scores of lower magnitude represent a lower level of adoption of sustainability practices. This measurement method enables engineers to compare their applications and enables statistical analysis of how the relationship between sustainability practices and overall sustainability performance can be expressed. The overall sustainability performance is considered the composite outcome variable, which considers the added value of various sustainability practices on environmental performance.

3.5 Data Collection Framework

The data collection structure follows the sustainability indicators which apply to contemporary engineering applications. It links the engineering industries, sustainable practices and environmental impact. The framework starts with identification of engineering application areas and then takes a look at practices related to energy efficiency, renewable energy use, selection of sustainable materials, control of waste, conservation of water, monitoring of the environment and the adoption of green technologies. The indicators are correlated to overall sustainability performance to evaluate environmental effectiveness and to make sustainability performance comparisons between the engineering fields.

3.6 Data Analysis Techniques

For this analysis, quantitative statistical method is used. The descriptive statistics are computed by providing the mean, the standard deviation, minimum and maximum values of the variables to summarize the general characteristics of the variables. To investigate the association between each sustainability practice and overall sustainability performance, the strength and direction of the relationship between them are analyzed using Pearson correlation analysis. The combined effect of the selected sustainability practices on the overall sustainability performance is analysed by multiple linear regression analysis. Comparative analysis is also used to compare differences between civil engineering, mechanical engineering, electrical engineering, manufacturing engineering, energy systems, transportation engineering and environmental engineering in terms of sustainability.

3.7 Ethical Considerations

Structured numerical data is used for academic analysis of the study and there is no personally sensitive data. The analysis process is carried out for research purposes and the analysis results are interpreted objectively. A high level of effort is made to show the results clearly and accurately.

4. Results

4.1 Overview of the Dataset

The 220 observations are analyzed based on the data and are all related to various application areas of modern engineering. As part of the data set, civil/construction systems, manufacturing systems, energy systems, transportation systems, environmental engineering systems, mechanical systems and

electrical systems were included. The relationship between the major practices of environmental sustainability and the environmental sustainability performance was analyzed. The energy-efficient design, renewable energy, sustainable materials use, waste management practices, water conservation and environmental monitoring (and green technology) were chosen as sustainability practices. The overall sustainability performance (a composite of the environmental outcome of the engineering applications) was measured.

The data was found to have enough variation in all the sustainability practice variables with scores of between 1 and 5. This implies that it was suitable to use this data to analyse engineering application adoption differences. Some large variances in the environmental performance indicators (sustainability performance 36.00 to 92.80) as well. This variation of the data necessitated the use of descriptive statistics, correlation analysis, regression analysis and comparative sector-wise analysis. The experience of the practices and measurement of the sustainability indicators is summarized overall in Table 1.

Table 1. Descriptive Statistics of Sustainability Practices and Environmental Performance Indicators

Variable	Mean	Standard Deviation	Minimum	Maximum
Energy-Efficient Design	3.60	1.02	1.00	5.00
Renewable Energy Adoption	3.42	1.06	1.00	5.00
Sustainable Materials Use	3.43	1.13	1.00	5.00
Waste Management Practices	3.62	1.01	1.00	5.00
Water Conservation	3.36	1.14	1.00	5.00
Environmental Monitoring	3.56	1.09	1.00	5.00
Green Technology Adoption	3.59	1.04	1.00	5.00
Carbon Emission Reduction Index	68.34	13.73	32.92	98.43
Energy Savings Index	67.62	13.64	36.25	94.83
Waste Reduction Index	65.42	14.11	31.26	95.55
Resource Efficiency Index	68.50	14.30	24.75	98.33
Overall Sustainability Performance	67.66	13.46	36.00	92.80

Descriptive statistics indicate that the highest mean score for the waste management practices was for sustainability practice in waste management (3.62). The next two most common responses were for the adoption of green technology (mean 3.59) and design of energy efficient technology (mean 3.60). The least mean value was found for the water conservation with a value of 3.36 which suggests that water conservation aspects must be focused in particular in engineering application in the modern era. In the context of environmental performance indicators, resource efficiency attained the highest mean value of 68.50 followed by reduction of carbon emission with mean value of 68.34. The mean value of sustainability performance score across all the applications was 67.66 and the sustainability performance of the applications was determined as "moderate to good level of environmental sustainability performance". It is presented in terms of sustainability performance by sector with variation by engineering application areas as presented in Figure 1.

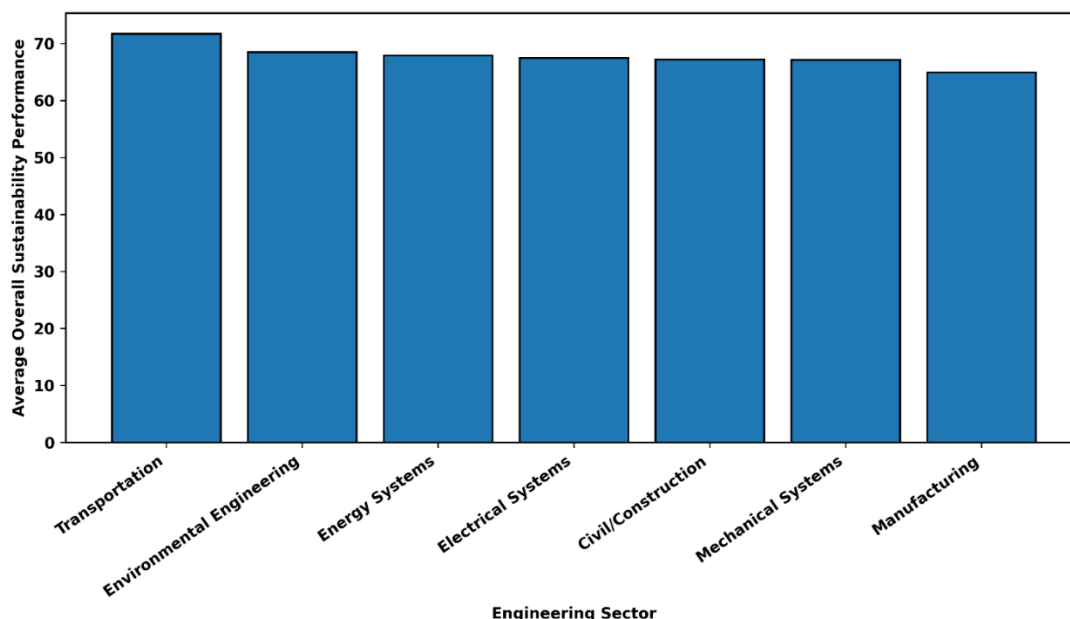


Figure 1. Sector-wise comparison of average overall sustainability performance across modern engineering applications

The results of the sector-wise analysis revealed that transportation engineering demonstrated the maximum average sustainability performance having a mean score of 71.77. Environmental engineering came as the second best with a mean score of 68.51, and energy systems with a mean score of 67.97. The average overall sustainability performance was the lowest for manufacturing with a mean score of 64.95. The results indicate that there are different levels of sustainability adoption and environmental performance among various engineering fields, with environmental engineering and transportation having better performance than manufacturing based engineering applications.

4.2 Correlation Analysis

Pearson correlation analysis was used to explore the relationship of each sustainability practice and sustainability performance overall. The findings revealed that these selected sustainability practices were all positively and significantly related to the overall sustainability performance. This means that the more sustainable engineering practices that are used, the better the environmental sustainability results. The correlation results are presented in Table 2, which shows that there are positive relationships between sustainability practices and overall sustainability performance, with some of the relationships being statistically significant.

Table 2. Pearson Correlation between Sustainability Practices and Overall Sustainability Performance

Sustainability Practice	Pearson Correlation with Overall Sustainability Performance	p-value
Energy-Efficient Design	0.791	< 0.001
Renewable Energy Adoption	0.779	< 0.001
Sustainable Materials Use	0.795	< 0.001
Waste Management Practices	0.781	< 0.001
Water Conservation	0.713	< 0.001
Environmental Monitoring	0.780	< 0.001
Green Technology Adoption	0.743	< 0.001

The correlation analysis results show a high positive correlation between the indicators of sustainability practices and sustainability performance. Sustainable materials use was the most

correlated with the overall sustainable performance (0.795). There was also a close relationship with the others, with the energy-efficient design having a correlation of 0.791 closely followed by waste management practices of 0.781 and environmental monitoring at 0.780. The positive correlation was also seen in the case of adoption of renewable energy with a correlation coefficient of 0.779. The use of green technology and water usage conservation were also statistically significant and had correlation coefficients (r) of 0.743 and 0.713 respectively. The p -values of all the relationships were < 0.001 , which means that they were highly statistically significant. Figure 2 shows the strength of the correlation between the selected sustainability practices, with the highest correlations seen between the selected sustainability practices.

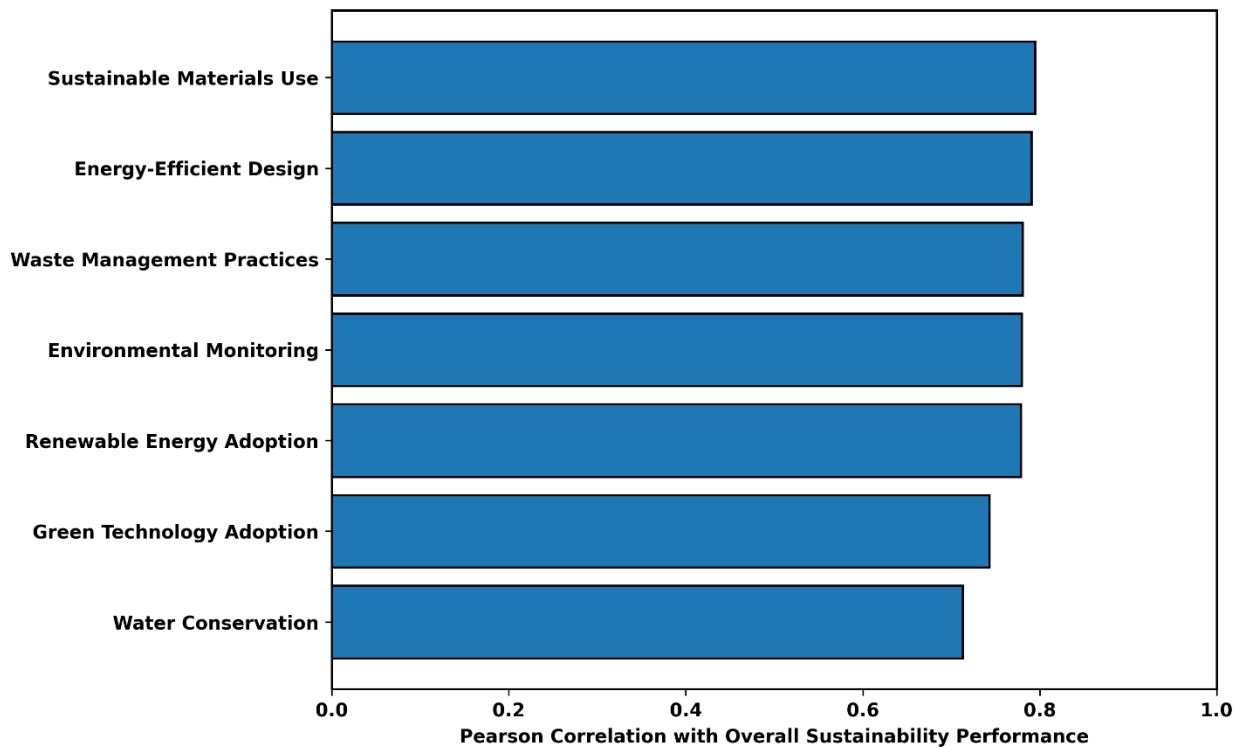


Figure 2. Correlation strength between environmental sustainability practices and overall sustainability performance

The correlation pattern indicates that all the sustainability practices positively contributed to the overall sustainability performance. The highest correlations were seen for sustainable materials use; energy-efficient design; waste management practices and environmental monitoring. The discovery indicates that incorporating sustainability into material selection, design efficiency, waste management, and performance monitoring systems in engineering applications can lead to improved environmental results.

4.3 Regression Analysis

As the combined effect of the sustainability practices on the overall sustainability performance was not obvious, multiple linear regression analysis was conducted. The dependent variable in the regression model was overall sustainability performance and independent variables included seven sustainability practice variables. The model fit was an $R^2 = 0.91$, which means that the variation in sustainability performance could be explained by the selected sustainability practices to 91%. This indicates the model would have a good explanatory strength and be well suited for the analysis of environmental sustainability practices in contemporary engineering applications based on data. The result of regression analysis is shown in Table 3 in terms of the significant predictors of sustainability performance for the overall project.

Table 3. Multiple Regression Results for Predicting Overall Sustainability Performance

Predictor	Coefficient	Standard Error	t-value	p-value
Intercept	15.1211	1.1939	12.665	< 0.001
Energy-Efficient Design	3.2695	0.3966	8.245	< 0.001
Renewable Energy Adoption	2.2425	0.3943	5.688	< 0.001
Sustainable Materials Use	2.4349	0.3757	6.481	< 0.001
Waste Management Practices	3.0835	0.3979	7.749	< 0.001
Water Conservation	1.3445	0.3420	3.932	< 0.001
Environmental Monitoring	1.3844	0.4058	3.412	< 0.001
Green Technology Adoption	1.1561	0.3963	2.917	0.0039

The regression results revealed that the seven sustainability practices studied positively and significantly affected the overall sustainability performance. The largest coefficient was found to be 3.2695 for Energy-efficient design, meaning that, as this parameter was increased, the sustainability performance improved the most (other factors being equal). The coefficient of waste management practices was 3.0835, which had a strong positive impact. The coefficient of Sustainable materials use and Renewable energy adoption were 2.4349 and 2.2425 respectively. Other positive factors were also water saving, monitoring the environment and using green technology, however, with smaller coefficients.

There were no p-values greater than 0.05 in all of the predictors, which means none of them missed the significance level of 5 percent. The majority of the predictors were significant at the $p < 0.001$ level and green technology adoption was significant at $p = 0.0039$. The results support the significance of using environmental sustainability practices as key indicators in the context of overall sustainability in modern engineering applications. The regression coefficient comparison analysis is used to illustrate this relative impact of each sustainability practice in Figure 3.

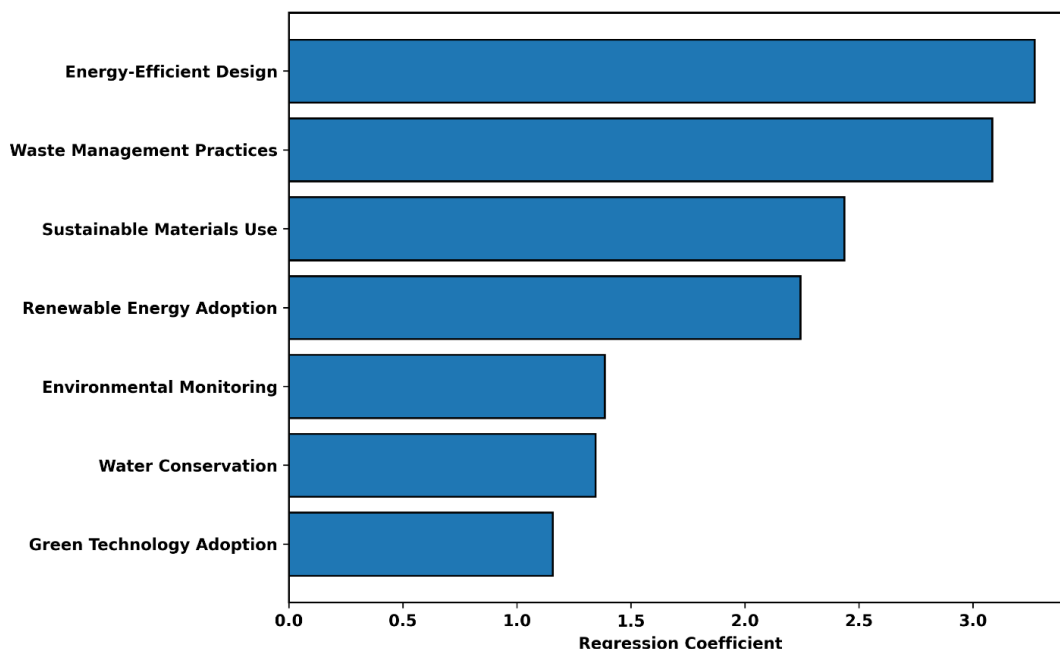


Figure 3. Regression coefficient comparison showing the relative influence of sustainability practices on overall sustainability performance

The energy efficient design and waste management practices were the strongest predictors for overall sustainability performance as highlighted by the regression coefficient comparison. Therefore, energy optimization and waste reduction are key areas of focus for the engineering applications aimed at enhancing environmental sustainability. Important contributors were also sustainable materials use

and renewable energy adoption, so that material selection and renewable energy integration are key aspects of sustainable engineering performance.

4.4 Comparative Analysis across Engineering Applications

Clear differences were seen between the engineering sectors when considered in comparative analysis. The top three overall performances for sustainability were transportation engineering, followed by environmental engineering and energy systems. The civil/construction, electrical systems, and mechanical systems had moderate sustainability performance, and manufacturing had the lowest average score. This pattern suggests that there are no uniform engineering sector sustainability practices. Certain sectors seem to be more advanced in integrating sustainable technologies and environmental performance systems into their processes, or they could be more advanced in a specific aspect of the integration. For transportation engineering, the average overall sustainability performance score was 71.77 with high scores for carbon emission reduction, energy savings, waste reduction and resource efficiency.

5. Discussion

The present study's results showed that the practices of environmental sustainability have a strong and statistically significant impact on overall sustainability performance in modern engineering applications. Results indicated that there exists a positive correlation between sustainability performance and energy-efficient design, adoption of renewable energy, sustainable use of materials, waste management, water conservation, environmental monitoring, and adoption of green technology. This shows that the sustainability of engineering cannot be achieved by just one operational activity, but it relies on multiple engineering activities. It is important to note that the regression model is powerful in its ability to explain the data, and that is the result of engineering organizations treating sustainability as a measurable and data-driven process. The result is aligned with the overall perspective that sustainability value in Industry 4.0 is provided through efficiency, visibility and decision making in industrial and engineering systems (Ghobakhloo et al., 2021; Kamble et al., 2018).

Results reveal that data-based evaluation is useful in identifying most impactful sustainability practices. This is crucial as engineering decisions are increasingly made with real-time information, digital monitoring, predictive data and evidence-based planning. Big data analytics can be used to enable stakeholders to better understand resource flows, waste patterns, and the environment's performance to support circular economy practices (Gupta et al., 2019). Likewise, the use of digital for circular strategies can help manufacturing companies act more sustainably by using the resources more wisely and by making decisions based on data (Kristoffersen et al., 2020). The findings of the present study confirm these arguments as it demonstrates that sustainability practices are more meaningful when measured and assessed in quantitative terms.

The adoption of renewable energy also had a positive and significant impact, suggesting that integrating renewable energy sources can enhance sustainability results. These results are very pertinent in the context of the global energy system is undergoing a substantial shift towards less carbon emissions and more energy security. Efficiency improvement, clean energy deployment and technological innovation have become key aspects of energy technology pathways as they gain importance for sustainable development (Pales & Bennett, 2020). In the same vein, in recent Energy Outlook reports by the (IEA, 2022), importance of speeding up energy transition, enhancing energy management and promoting the adoption of low carbon technology in response to the global environmental challenges is emphasized. The results also indicate that sustainable materials use and waste management practices have a strong positive impact on the sustainability performance. Industry 4.0, circular economy and sustainable development are closely related via the triple bottom line, sustainable business models and resource efficiency (Khan et al., 2021). But there are also challenges to implementing circular economy. Previous studies identified several barriers to the CE adoption, which include cultural, regulatory, market and technological barriers (Kirchherr et al., 2018). The current results indicate that the implementation of circular economy practices is beneficial, but

engineering organizations need to address the barriers to their implementation by improving the monitoring of these practices, planning them and using technology to manage resources.

A traceability system based on blockchain can enhance transparency and performance in supply chain systems (Kamble et al., 2020). The concept of traceability was used in this work in relation to agriculture supply chains, but can be similarly applied to engineering projects where the environmental performance of materials, processes and outputs is to be monitored. In addition, Industry 4.0 sustainability value drivers are related to data integration, smart systems and technological readiness (Ghobakhloo et al., 2021). Thus, the present results support the assertion that green technology and monitoring systems are crucial to the shift of sustainability from a vague goal to a tangible engineering practice.

The results have implications for engineering firms, project managers, and policymakers. Energy-efficient design, renewable energy systems, sustainable materials, and waste reduction strategies should be the focus of engineering firms when investing in energy efficiency. Concurrently, they need to use digital technologies that enable ongoing environmental monitoring and performance assessment. The building and infrastructure sectors also require specific mitigation focus, due to the energy efficiency, low carbon materials, and enhanced environmental design of strategies that will be implemented in buildings (Limmeechokchai et al., 2023). The overall discussion demonstrates the benefits of implementing circular economy concepts, Industry 4.0 technologies, and data-based decision-making in the context of engineering applications to enhance environmental sustainability. The study thus contributes to sustainable engineering literature by illustrating how the environmental performance is enhanced when the sustainable practices are measured, analysed and continuously improved using data-driven approaches.

6. Conclusion

Based on the above study, it could be concluded that the data-driven approach is a very valuable tool in understanding and enhancing the environmental sustainability practices in current engineering applications. The results indicate that the overall implementation of energy efficient design, renewable energy, sustainable materials, waste management, water conservation, environmental monitoring and green technology adoption has a significant impact on sustainability performance. The statistical findings verified that these practices are positively and significantly related to the overall sustainability performance, proving that measurable and integrated sustainability practices are critical to engineering systems' environmental improvement. The research also identifies some of the most important factors that drive sustainability performance: energy efficient design and management of waste. This indicates that there are opportunities for meaningful environmental improvements to be realised by engineering organisations by, amongst others, reducing energy demands, optimising operating efficiency, reducing waste, and moving towards more resource efficient processes. Tools that use data are also influential, as they can be used for tracking environmental indicators, determining performance gaps, and evidence-based decision making. Overall, the study is a contribution to the field of sustainable engineering because it has shown that environmental sustainability should not be considered just an overall policy goal but a measurable performance outcome. Digital monitoring, analysis, and continuous improvement systems facilitate the integration of sustainability practices into modern engineering applications, making them more environmentally responsible. Thus, data-driven sustainability assessment offers a pragmatic approach to lower emissions, save resources, increase efficiency, and enhance sustainable engineering performance.

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