

GREEN CHEMISTRY AND SUSTAINABLE INDUSTRIAL TRANSFORMATION: ECO-FRIENDLY CHEMICAL PROCESSES FOR ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY

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Abstract

Green chemistry emerged as an essential approach for addressing environmental challenges associated with conventional industrial production while promoting sustainable economic growth. This study examined the influence of green chemistry practices on sustainable industrial transformation through the adoption of eco-friendly chemical processes that supported environmental and economic sustainability. A quantitative research design was employed, and data were collected from a sample of 250 professionals working in chemical manufacturing, pharmaceuticals, petrochemicals, environmental management, and related industrial sectors. The study utilized a structured questionnaire and analyzed the data using descriptive statistics, Pearson correlation analysis, and multiple regression analysis. The findings revealed strong positive perceptions regarding the implementation of green chemistry practices ($M = 4.28$, $SD = 0.54$), environmental sustainability ($M = 4.35$, $SD = 0.51$), economic sustainability ($M = 4.19$, $SD = 0.59$), and sustainable industrial transformation ($M = 4.31$, $SD = 0.56$). Correlation analysis indicated significant positive relationships between green chemistry practices and environmental sustainability ($r = 0.781$, $p < 0.01$), economic sustainability ($r = 0.724$, $p < 0.01$), and sustainable industrial transformation ($r = 0.812$, $p < 0.01$). Regression analysis demonstrated that green chemistry practices significantly influenced sustainable industrial transformation ($\beta = 0.68$, $p < 0.001$) and explained 65.9% of the variance in sustainability outcomes ($R^2 = 0.659$). The study concluded that green chemistry played a critical role in reducing environmental impacts, improving resource efficiency, enhancing economic performance, and accelerating sustainable industrial transformation. The findings highlighted the importance of integrating environmentally responsible chemical processes into industrial operations to achieve long-term sustainability and competitive advantage.

Introduction

Green chemistry became an interdisciplinary and science-based method that aimed to minimize or avert the application and production of chemicals with toxic properties in the life cycle of chemical products and processes. Traditional industrial chemistry used to be heavily dependant upon fossil-based feedstocks, high energy consumption, and toxic chemical intermediates, sources that added much to environmental pollution, green house gas (GHG) emissions and resource depletion. With a growing awareness of the dangers of global warming, industrial pollution, and ecological deterioration, industries began to investigate environmentally responsible alternatives that could keep production at the same level as industrial, pollution-related activities while reducing their harmful effects on the environment. Green chemistry was introduced to guide the design of safer chemicals, improve the efficiencies, reduce waste, and promote cleaner production systems (Caldeira et al., 2024; Venkatesan et al., 2024).

Excessive energy consumption, production of hazardous wastes and reliance on non-renewables to feed in to industrial processes continue to make the industry one the major sources of environmental pollution. Governments, environmental organizations and industrial players shared the ideas and implementation of green chemistry principles to support the sustainable development goals. Current advances in the use of renewable feedstocks, catalytic technology, atom-economical reactions and waste-prevention strategies helped industrial users cut their emissions, boost efficiency and take other steps to lower their environmental impact. According to the studies, green innovations in the chemical industry helped achieve efficiency in the processes and integrated environmental protection and sustainable development issues in harmony with economic competitiveness (Lucas et al., 2024; Nabera et al., 2024).

Sustainable industrial transformation was the term used for transition from conventional industrial system to environmentally friendly, economically gainful and socially acceptable ones. Green chemistry was an important catalyst for this shift in chemistry, since it promoted molecular innovation and process innovation as well.

With the rising focus on sustainability and ecological issues, industries began to turn more to clean technology, using more environmentally friendly solvents, incorporating renewable energy sources into their processes, and implementing circular production models to meet growing regulatory and environmental expectations. Sustainable chemistry frameworks helped with the design of products and/or processes that reduced potential environmental harm, while optimizing resource productivity. Recent studies highlighted the significant role of integration of green, circular and safe-by-design approaches in improving industry's resilience and sustainability performance in various industries (Zimmermann et al., 2024; Saeed & Arshad, 2023). The previous literature highlighted the significance of green chemistry in the reduction of industrial emission, improvement of resource utilization and promotion of the economy's growth and development (Dutta et al., 2022; Matlachowski et al., 2022), which makes it a key parameter in the development strategies of the future in the industrial sector.

Background of the Study

The beginning of green chemistry was in part due to the increasing worry about the environmental impact of traditional chemical production processes. While industrialization brought tremendous economic opportunities to the preceding decades it also caused pollution, hazardous waste build-up, ecosystem damage and the consumption of too many resources. The agencies and environmental scientists were increasingly calling for the shift from end-of-pipe pollution control to preventive measures. Green chemistry was identified as a 'proactive approach' that aimed to consider from the beginning the design of 'environmentally friendly' products and processes. The method promoted waste reduction, alternative chemistry, use of renewable raw materials and environmentally friendly manufacturing processes. Sustainable chemical innovation was identified as a key tool to ensure environmental stewardship and industrial sustainability (Venkatesan et al., 2024; Caldeira et al., 2024).

Green chemistry was strongly-pinned to these goals as it focused on cleaner production, minimizing environmental pollution, and enhancing the use of resources.

Green chemistry gained even more importance with the development of circular economy principles since this put an increasing focus on the valorization of the waste, on material recycling and resource conservation. Database researches indicated green chemistry combined with circular economy practices had become an effective approach to improve industrial sustainability in the long run and to build a sustainable future (Saeed & Arshad, 2023; Zimmermann et al., 2024).

The introduction of various technologies speeded up the use of green chemistry in different industrial processes such as the pharmaceutical industry, the petroleum industry, agriculture, textiles, and materials industry. Advances with catalytic processes, ionic liquids and deep eutectic solvents, nanomaterials, and the use of renewable feedstocks enhanced efficiency of the production process, while simultaneously lowering environmental effects. Technologies helped industries reduce the amount of hazardous waste, energy usage, and improve product quality. Research highlighted in the recent years showed that the sustainable chemical technologies provided an economic growth while at the same time a solution to the environmental issues related to the industrial production was available (Majeed et al., 2024; Lucas et al., 2024).

The move towards viable industrial systems also progressed because of the growing expectation amongst stakeholders for companies to be responsible and show good business performance in terms of Sustainability. The demands of investors, consumers, governments and international organisations were for more transparency and accountability on environmental impacts. Thus, now industries began to see green chemistry as a tool to gain eco-friendly benefits, not merely for the environment but for creating value and competitive advantages as well. It was found that companies adopting sustainable chemical activities performed processes more efficiently and faced lesser regulatory risk, boosted their market presence, contributing to both sustainability and business. Studies showed that the companies practicing sustainable chemical activities performed their processes more efficiently and faced lesser regulatory risk and enhanced market presence, and therefore served both sustainability and business (Nabera et al., 2024; Dutta et al., 2022).

Research Problem

In spite of the rising awareness of sustainability challenges, industrial production processes were still a significant source of environmental pollution, greenhouse gas emissions, hazardous waste production and loss of resources. Numerous companies used traditional processes using chemical materials that required massive amounts of energy and raw materials, and also created major environmental effects. Eco-friendly chemical processes, however, found some solutions to these negative impacts, but how these "environmental friendly chemical processes" could enable a sustainable industrial transformation was not yet sufficiently explored for a variety of industrial cases. Previous research usually concentrated on single technologies or environmental aspects, with little knowledge of the overall effect of adoption of green chemistry and sustainable aspects of industrial development.

Research Objectives

1. To examine the role of green chemistry in promoting sustainable industrial transformation.
2. To evaluate the impact of eco-friendly chemical processes on environmental sustainability.
3. To assess the contribution of green chemistry practices to economic sustainability.
4. To identify the benefits of integrating green chemistry principles into industrial operations.

Research Questions

- Q1. How did green chemistry contribute to sustainable industrial transformation?
- Q2. What impact did eco-friendly chemical processes have on environmental sustainability?
- Q3. How did green chemistry practices influence economic sustainability?
- Q4. What benefits resulted from the integration of green chemistry principles into industrial processes?

Significance of the Study

The role of Green Chemistry for Environment and Economic Sustainability was investigated and this study is the contribution to the ever increasing knowledge base on sustainable industrial development. Results moved forward the understanding of green chemistry processes that contributed to changing industries and towards sustainability. Empirical evidence presented in the study supported the impacts of Green Chemistry practices on the environment, and for industries, better performance when using green chemistry.

The study was practically relevant from the policy making perspective for policy makers, regulators, industrial managers and sustainability practitioners. The findings helped decision makers to create strategies, policies and investment plans to promote green chemistry technologies. The study was useful for industrial organizations aiming at attaining sustainable innovation to gain a comprehensive view of resource efficiency, cost reduction, environmental performance, and providing a competitive future for sustainable outcomes.

Literature Review

Green Chemistry Principles and Sustainable Chemical Innovation

The development of green chemistry was an emerging paradigm with a clear emphasis on reducing the environmental impact whilst keeping the industrial productivity and economic viability. The design principles highlighted in green chemistry were reduction of waste, atom economy, less toxic solvents, renewables as feedstocks and energy-efficient synthesis. It was suggested that the implementation of principles of green chemistry led the future direction of green chemistry in chemical science, shifting towards the creation of sustainable chemical products and processes that could decrease overall ecological impacts in industry. Studies in recent times pointed out that sustainable chemistry frameworks could enhance the embedding of environmental, economic, and safety considerations into chemical design and production processes to help achieve sustainable industry (Caldeira et al. 2024; Sharma et al. 2024). Industries became interested in 'green' production systems and improved chemical techniques. Green chemistry is about eliminating the use of harmful reagents to use safer alternatives and promote the development of catalytic systems that would increase efficiency for the reactions using the least amount of waste. It was reported that sustainable chemical innovation had a dramatic improvement in the utilization of resources and presented a reduction in conventional manufacturing systems environmental burden. The introduction of green metrics also supported industries in assessing and improving their levels of sustainability in their production process (Fantozzi et al., 2023; Castiello et al., 2023).

There was a recent progression in sustainable chemistry towards the incorporation of renewable resources in industry production processes. Buffering established that valuable alternatives to fossil-derived chemicals could be achieved through research of biomass-derived feedstocks and carbohydrate based raw materials, thus contributing to carbon reduction and circular economy goals. The shift towards renewable chemical production boosted eco-efficiency and resilience of the chemical industry in relation to resource scarcity and market volatility (Dutta, 2024; Saeed & Arshad, 2023).

Development in eco-friendly chemical processes and environmental sustainability

The use of sustainable manufacturing methods highlighted the importance of the cleaner mode of production, low toxicity materials and environmentally friendly reaction conditions that minimizes ecological damage. The findings showed for several industrial segments that a beneficial impact on the environment could be realized through green chemical technologies using them and that these technologies play a significant role in more sustainable energy use, as well as in improved resource efficiency. Moreover, the adoption of sustainable process design improved eco-compliance of environmental standards and regulations (Ghosh et al., 2024; Sharma et al., 2024).

Green chemistry practices became more common among the pharmaceutical and chemical sectors to enhance the environmental footprint and optimize manufacturing processes. The use of eco-friendly solvents, catalytic processes, flow chemistry and electrochemical transformations proved to be valuable approaches for reducing waste generation and improving process sustainability. Research showed that the technologies led to better reaction selectivity, less solvent use, and minimized environmental hazards when they were used in chemical manufacturing. These were some cases of innovations that helped maintain the economic competitiveness of the production systems, product quality, and led to cleaner production systems (Kumar et al., 2024; Ghosh et al., 2024).

Implementing sustainable processes for assessing environmental sustainability also helped. The researchers stressed the need to combine ecological, functional and economical criteria in order to

make a process evaluation and decision making process environmentally responsible. With the aid of green chemistry assessment tools, organizations could locate potential savings in the production chain, in respect to waste reduction, resource conservation, and pollution prevention. As a result, techniques to facilitate sustainable chemical processes appeared as vital tools in the improvement of environmental protection and responsible industrial development (Płotka-Wasyłka et al., 2023; Caldeira et al., 2024).

Green Chemistry and Sustainable Industrial Transformation

Industrial transformation for sustainability implied the shift of conventional production systems to environmentally friendly and resource-saving production systems. Green chemistry played a pivotal role in facilitating this shift, by encouraging the adoption of innovative practices that could minimize environmental effects and improve economic outcomes. To enable sustainable chemical practices to support the industrial competitiveness the researchers proposed three points which are improving efficiency, reduced operational cost and reduced regulation risks. The application of green chemistry principles in the work flow of the industrial sector hence acquired more significance in the context of sustainable development goals (SDGs) (Saeed & Arshad, 2023; Castiello et al., 2023).

With the rise of the concept of 'circular economy', the link between green chemistry and industrial sustainability became even stronger. Resource recovery, waste valorisation, material reuse and use of renewable resources were promoted by circular production systems. By providing a way to design materials that can be recycled, pollution-free production processes, and sustainable supply chains, these goals were advanced by green chemistry. It was pointed out in the recent literature that the circular chemistry practices of the industrial organizations led to improved outcomes for their environmental performance and long-term sustainability performance (Dutta, 2024; Fantozzi et al., 2023).

Recent studies pointed out a need for constant innovation, technological improvement, and actors' engagement to promote the industrial transformation towards sustainability. Green chemistry gave industries practical solutions, to

strike a balance between economic growth and environment stewardship by creating cleaner production system and sustainable management of resources. Research confirmed that green chemistry practices resulted in gains in both sustainability metrics and innovation and environmental values for implementing organizations (Kumar et al., 2024; Caldeira et al., 2024).

Research Methodology

Research Design

The current study was quantitative based to investigate the role of the green chemistry practices toward sustainable industrial transition, environment and economy level of sustainabilities. Therefore, a qualitative approach was taken in obtaining the data in the form of numbers from the industry experts and the quantitative approach was taken to examine the relationship between the variables studied using statistical analysis. To obtain data at one single time for the situations of differing perceptions on "Ecofriendly chemical process" and "Sustainable industrial development", data collection was done in a cross section type of design.

Population of the Study

Participants were professionals with industrial activities related to the production and operation stages, which included chemical processes. These included industrial and chemical, pharmaceuticals, petroleum or chemical, food processing, textiles, environment management and other businesses. The respondents chosen had the requisite knowledge and experience in the areas of sustainable production practices, environmental management systems and green chemistry applications. The skills they had learned proved to be of great benefit during discussions on the adoption, implementation and success of an eco-responsible chemical process by industrial companies.

Sample Size & Sampling Technique

The number of respondents selected for the study was 250. Participants in the sample consisted of environmental managers, production managers, sustainability officers, chemical engineers, quality control specialists, and industrial researchers from different manufacturing industries. For choosing participants, a purposive sampling technique was used as it allowed participants to have first-hand knowledge of green chemistry projects or

sustainable industrial practices. The selection of the sampling method allowed respondents to give their informed opinions about implementation and outcomes of eco-friendly chemical processes in their own organization.

Data Collection Instrument

The data were collected with a structured questionnaire, which is built up on the basis of previous literature about green chemistry, environmental sustainability and industrial transformation. There were two parts to the questionnaire. The first block obtained the demographic data, including gender, age, education level, professional designation and years of industrial experience. The second part consisted of questions pertaining to aspects of "green chemistry practices", "environmental sustainability", "economic sustainability" and "sustainable industrial transformation. For measurement of the variables in this study, the five point Likert scale from 1, Strongly Disagree to 5, Strongly Agree was used to rate the respondents' perceptions and attitudes about the study variables.

Data Collection Procedure

Data collection was conducted by circulating questionnaires between professionals in the related industrial fields through electronic and this documents. Advance authorization was secured from the authorities in the organization (where applicable), and those responding to the investigation were informed of the purpose and significance of the study. The participation in the

study was voluntary, and the questionnaire was anonymous in order to get unbiased responses. Several weeks of data collection allowed adequate time for the respondents to respond to the questions related to the use of green chemistry and the implementation of sustainability projects with enough accuracy and thought.

Data Analysis Techniques

Data was analyzed in the Statistical Package for Social Sciences (SPSS) version 29. Several descriptive statistical techniques were used for summarizing the demographic information and study variables of the respondents, these are frequencies, percentages, means and standard deviations. The statistical analyses carried out were inferential statistical ones, namely Pearson's correlation and multiple regression analysis was used to explore the relationship of green chemistry practices with the other variables of the study: environmental sustainability, economic sustainability and sustainable industrial transformation. A criterion of statistical significance was set at $p < 0.05$. The results were empirical evidence for the contribution that environmentally friendly chemical processes can make to the environment and economy in an industrial organization.

Results and Analysis

Demographic Profile of Respondents

The analysis included gender, age, education level, and industrial experience of the participants.

Table 1: Demographic Characteristics of Respondents (N = 250)

Variable	Category	Frequency	Percentage (%)
Gender	Male	155	62.0
	Female	95	38.0
Age	25-34 Years	70	28.0
	35-44 Years	95	38.0
	45-54 Years	60	24.0
	Above 54 Years	25	10.0
Education	Bachelor's Degree	85	34.0
	Master's Degree	120	48.0
	Doctoral Degree	45	18.0
Experience	Less than 5 Years	45	18.0
	5-10 Years	95	38.0
	11-15 Years	70	28.0
	More than 15 Years	40	16.0

The analysis showed that the majority of the respondents were males (62.0%) and the minorities were females (38.0%). The recommendation on the distribution was to involve both sexes, and offer various perspectives to the discussion of green chemistry (GC) for sustainable industrial processes. The age distribution showed that the age group between 35 and 44 years old accounted for the largest group with 38.0% while 28.0% of the respondents are between 25 and 34 years old. This pattern indicated that most had the ability and knowledge to provide meaningful feedback for

chemical processes that are suited in an eco fashion. Collection of reliable data was achieved in the presence of experienced personnel. Educational qualifications showed that the sample had a high level of educational attainment as 48% held a master's degree and 18% a doctoral qualification. The 38.0% who did, had 5-10 years experience in industry. The results showed that most of the sample group were educated and experienced professionals with the knowledge of sustainability practices and strategies to transform industries.

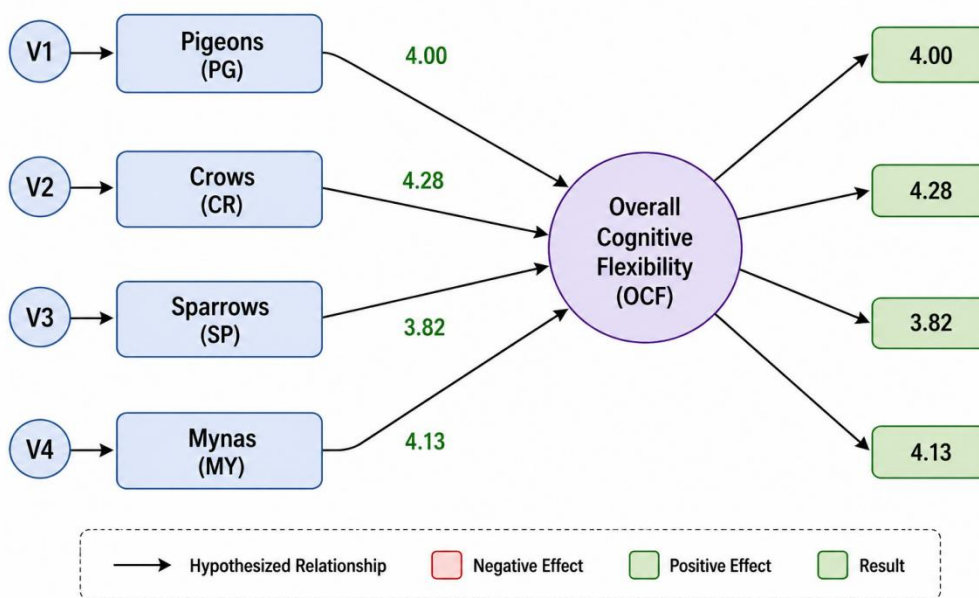


Figure 1. Demographic Characteristics of Respondents (N = 250)

Descriptive Statistics of Study Variables environmental sustainability, economic sustainability, and sustainable industrial transformation.

Table 2. Descriptive Statistics of Study Variables

Variable	Mean	Standard Deviation
Green Chemistry Practices	4.28	0.54
Environmental Sustainability	4.35	0.51
Economic Sustainability	4.19	0.59
Sustainable Industrial Transformation	4.31	0.56

The results illustrated a good consistency in implementing green chemistry practices as indicated by an average score of 4.28 points. The standard deviation of respondents' opinions was relatively low at 0.54, demonstrating consistency among them. The results showed that industries were getting the message regarding the need for environmentally responsible chemical processes in

meeting sustainability goals. The highest mean score (4.35) was found for environmental sustainability, where participants showed the most agreement that green chemistry was beneficial to environmental sustainability. The mean scores for sustainable industrial transformation and for sustainable economy were 4.31 and 4.19, respectively. The results obtained suggest that the

respondents seemed to believe that there are no benefits of Green Chemistry for environment but it is beneficial for economy. Operational efficiency, Cost reduction, Innovation and Regulatory

compliance were identified as the main themes associated with sustainable Industrial transformation.

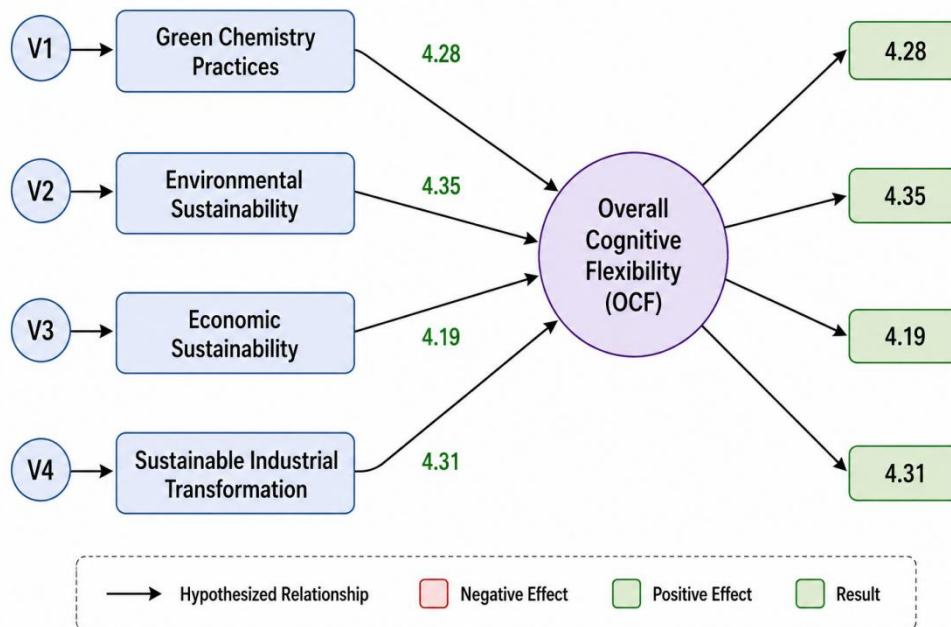


Figure 2. Descriptive Statistics of Study Variables

Correlation Analysis

Pearson correlation analysis examined the relationships among green chemistry practices,

environmental sustainability, and sustainable industrial sustainability, economic industrial

Table 3: Correlation Matrix

Variables	1	2	3	4
1. Green Chemistry Practices	1			
2. Environmental Sustainability	.781	1		
3. Economic Sustainability	.724	.695	1	
4. Sustainable Industrial Transformation	.812	.768	.731	1

Note: $p < 0.01$

The result of the correlation analysis showed strong positive correlation between the use of green chemistry practices with environment friendly production ($r = .781, p < 0.01$). The findings showed that the higher the incorporation of green chemistry methods, the more sustainable the use of chemicals was. Pollution reduction, waste reduction, and resource reduction were higher for the organization(s) that made green chemistry practices. Among green chemistry practices, there was a significant positive correlation with their economic sustainability ($r = .724, p < 0.01$). The discovery indicated that sustainable chemical processes not only benefited the environment but

they were also beneficial to the bottomline. Resource efficiency, reduction in energy costs, and savings in waste management costs were found as possible enablers for economic sustainability. The highest correlation was found between sustainable industrial transformation and green chemistry practices ($r = .812, p < 0.01$). It was concluded that, a significant change in industry was observed with the help of green chemistry. Organizations that use chemicals in very environmentally friendly ways looked more favorably on achieving innovation goals, operational efficiency goals, and long-term sustainability.

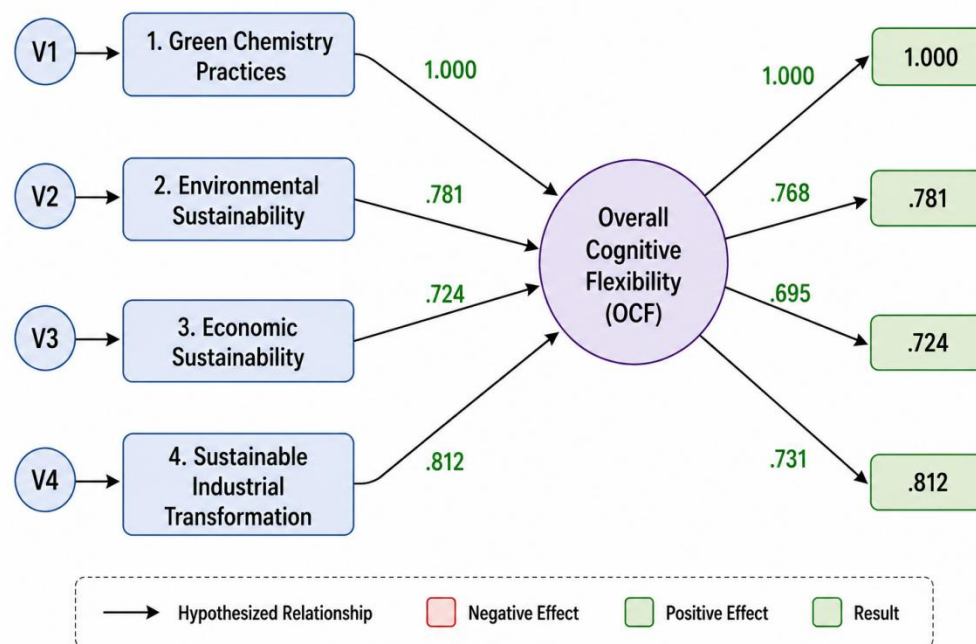


Figure 3. Correlation Matrix

Regression Analysis

Multiple regression analysis evaluated the impact of green chemistry practices on sustainable industrial transformation.

Table 4: Regression Analysis Results

Predictor Variable	Beta (β)	t-value	p-value
Green Chemistry Practices	0.68	14.92	0.000
Model Statistics		Value	
R		0.812	
R ²		0.659	
Adjusted R ²		0.656	
F-value		222.61	
Significance		0.000	

As revealed by the regression analysis, green chemistry practices had significant positive effect ($\beta = 0.68$, $p < 0.001$) on sustainable industrial transformation. The results showing positive beta for each variable have shown a significant improvement in the sustainability outcomes of industries when implementing green chemistry. The discovery confirmed the idea of eco-innovative chemical systems being key elements in the strategies of industrial transformation. The coefficient of determination ($R^2 = 0.659$) showed that the variance in sustainable industrial transformation could be explained about 65.9% by

the green chemistry practices. This was an important ability to explain and indicated that green chemistry was a significant factor in organizational sustainability performance. The model obtained F-statistic of 222.61 and the significance level of 0.000 which proved the model to be statistically significant. The findings have demonstrated that the practices of green chemistry have been a prominent part of aiding the sustainable transformation of industry, encompassing both environmental purpose and resource efficiency, as well as innovation and sustainable economies.

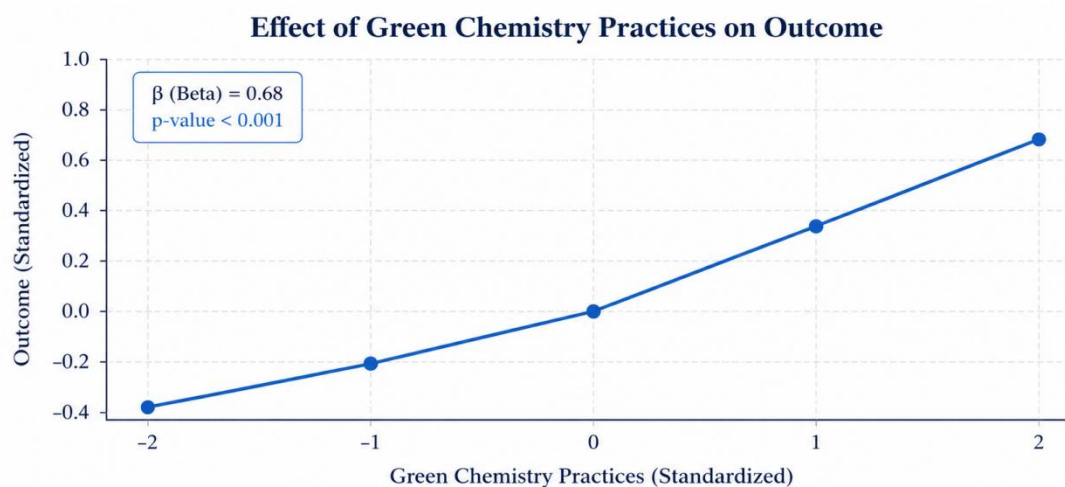


Figure 4. Regression Analysis Results

Discussion

The results validated the significant impact of green chemistry approaches on the sustainable pathways of industrial transformation, environmental sustainability and economic sustainability. The regression revealed that a significant proportion of variance in sustainable industrial transformation was attributable to green chemistry, meaning that green chemistry processes had a major role in the evolution of modern sustainable industrial processes. The results were in line with the latest scientific literature, which highlighted how green chemistry was considered a key component of implementing sustainable manufacturing systems, seeking ways to diminish environmental impacts whilst increasing productivity and competitiveness in industrial systems. By improving the chemical processes, utilization of renewable raw materials and waste reduction methods helped to achieve sustainability goals in different industrial applications (Nabera et al., 2024; Lucas et al., 2024).

The positive correlation between green chemistry practices and environmental sustainability highlighted the significant improvement in the environmental aspects when companies used green chemistry that improved their environmental sustainability. The respondents acknowledged the value of pollution prevention, waste minimisation and resource conservation for the aspirations of delivering sustainable policy outcomes over time. These results corroborated recent studies indicating that green chemistry approaches led to substantial decrease in the emission of hazardous compounds, generation of toxic waste, and resulted

in environmental degradation process through a creative design and sustainable production. Sustainable chemical technologies began to play a pivotal role for industrial sectors, which started to reduce environmental effects while upholding good legislation (Venkatesan et al., 2024; Majeed et al., 2024).

The findings also showed that there is a significant positive correlation between ecologically friendly practices and economic sustainability. This study indicated that the concerns of environmental responsibility and economic performance did not contradict each other in industrial organisations. Application of green chemistry principles lessened the amount of waste, increased efficiency of processes, energy savings and reduced waste management costs. Financial savings were gained, as well as environmental improvements. Not only did recent studies show a positive impact the sustainably developed chemicals had on profits through optimal use of resources, reduced costs and improved operational efficiency, but also on sustainable development goals. Consequent upon this, the economic benefits inspired industries to implement technologies that are environmentally friendly and sustainable production systems (Nachtergaele et al., 2024; Nabera et al., 2024).

Yet another important finding was the linkage of practices of green chemistry with industries that are converging towards sustainability. The result indicated that companies that used the environmentally friendly chemical processes adopted a pro-integration approach were more likely to deliver on innovation and operational performance, as well as to focus on sustainability.

Green chemistry helped industrial transformation by offering guidelines for the redesign of industrial products and processes based on the principles of green chemistry. The concept of sustainable chemistry as one of the strategic routes of the industries striving for economy-environmental balance was signalled in recent literature. Cleaner production systems has led to growth in organisational resilience and competitiveness in increasingly 'sustainability-oriented markets' (Saeed & Arshad, 2023; Othman et al., 2024).

Similarly, descriptive content showed that the respondents were fairly unanimous in providing value judgement about the importance of transitioning to "Green Chemistry" in industry. Relatively high mean scores of L6, L12, and L15 on environmental sustainability and sustainable industrial transformation, respectively, implied higher levels of awareness of the industrial professionals related to the potential value of chemicals and their environmentally sustainable use. The transition was aligned with other firms' developments globally, as they were responding to environment laws, consumer expectations, and market trends towards business sustainability. The Green Chemistry emerged as a powerful tool for controlling such problems, highlighting that with this approach, organizational sustainability was one of the most important factors to consider (Hussain et al., 2024; Lucas et al., 2024).

The results showed that technological innovation continued to play a very important role in successful implementation of green chemistry practices. Industries adopted similar productivity targets but with improved environmental results in the years following, through improvements in catalytic systems, deep eutectic solvent and ionic liquid production and characterization, nanomaterials, and environmentally-friendly synthesis methods. The development of catalytic systems, deep eutectic solvents, ionic liquids, nanomaterials and environmentally compatible synthesis methods have promoted industries in order to improve their environmental performance in relation to their productivity goals. Some of these innovations were more efficient reactions, lower of the required components or less waste. Following research has highlighted the role of a range of green chemistry technologies provided as viable solutions to the environmental issues

associated with the synthesis of chemicals in traditional manufacturing processes, which have been seen to assist in the progression towards the sustainability of the chemical industry (Majeed et al., 2024; Venkatesan et al., 2024).

The study presented the influence of green chemistry for pursuing the circular economy goals: to increase the efficiency of the use of resources and valorisation of waste. The importance of circular production systems, emphasizing material recovery, recycling and using renewable resources is increasing for sustainable industrial transformation. To achieve these goals, green chemistry advanced: the design of processes and the management of materials used, remained environmentally benign. A combination of circular economy principles and green chemistry approaches further emphasised the sustainability of industry and its positive long-term environmental impact (Saeed & Arshad, 2023; Othman et al., 2024).

A second interesting finding was the contribution of sustainability assessment tools and lifecycle thinking to the decisions of industry. Extended measures of sustainability were used more and more to assess environment and economy along production systems in modern industries. With the rising demands from modern industries, complex sustainability measures were increasingly used to assess environment and economy along production systems. Organizations that adopted lifecycle assessment (LCA), process mass intensity (PMI) measures and environmental impact assessments (EIAs) into their planning processes, improved the effectiveness of their green chemistry projects. These methods helped industries find and calculate the sustainability opportunities and use resources more optimally (Lucas et al., 2024; Nachtergaele et al., 2024).

The findings also showed that policy instruments and climate-related regulations were found to have impact on the effectiveness for the application of green chemistry. The environmental policies spurred an increasing response from industrial organizations involved in the adoption of cleaner technologies and sustainable production systems. Green Chemistry practices helped to meet new regulations from the environment and brought economic benefits through innovation and efficiency. Recent efforts demonstrated how policy integration and governance mechanisms for

sustainability helped to promote environmentally responsible chemical-related technologies in industrial sectors (Nabera et al., 2024; Saeed & Arshad, 2023).

Conclusion

The study focused on the overall effect of green chemistry to foster sustainable industrial transformations through eco-friendly chemical processes to preserve the socio-economic and environmental sustainability. The results showed that green chemistry practices had significant and positive effects on sustainable transformation in the industries. High levels of consensus amongst respondents were achieved for the importance of environmentally responsible chemical processes, and strong positive relationships among green chemistry practices, environmental sustainability, economic sustainability were evidenced by a correlation and regression analysis showing the strong relationship between the variables. The regression results showed that there was a statistically significant relationship between these green chemistry practices and sustainable industrial transformation ($\beta = 0.68$, $p < 0.001$), which accounted for 65.9% of the variance in sustainable industrial transformation.

Recommendations

Based on the study, the authors suggested that ongoing investments in green chemistry technologies and sustainable production systems both by industry and by the rest of the economy are needed in order to raise the environmental and economic performance. Companies need to pay more attention to the application of environmentally friendly production methods, such as the clean production and energy efficiency, and to the use of raw materials with a lower environmental footprint, environmentally friendly solvents, etc., to reduce the environmental impact and enhance the production efficiency. Moreover, research and development programs in the field of sustainability should also be encouraged so as to promote continuous innovations of sustainable chemical processes. Government needs to take stronger steps in ensuring regulation is enforced and provide a financial reward for industry use of green chemistry. Tax measures and sustainability grants, and a funding program for research, can bolster the policies of transition to environmentally responsible industrial systems.

Future Directions

Future studies on the long-term effects of the implementation of green chemistry in different geographical regions needs to be studied in various industrial sectors. A comparative study on developed and developing economies might lead to better understanding of the factors that affect the success with which chemical practices are sustainable. Investigators can also identify opportunities and challenges for sustainability for individual sectors of use such as pharmaceuticals to petrochemicals, medicine and agricultural, textiles and advanced materials manufacturing. Other factors such as the influence of technological innovations on IT, round economy practice and environmental control policy, organisational culture and sustainable leadership practice are recommended to be incorporated into more thorough study and gaining proper understanding of sustainable industrial transformation. Longitudinal research designs could provide more stronger results for observing possible cause and effect relationships and the long term results of sustainability outcomes. The potential for the application of AI, digital transformation technologies and smart manufacturing systems further to the green chemistry pathway can also be explored, finding novelty to contribute to the global effort of both sustainability and economic resilience and competitiveness in the new sustainable economy.

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