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***Research paper***

# Transforming the steel industry supply chain: strategies for optimization, sustainability and resilience

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## Abstract

The steel supply chain, a critical component of the global economy, is increasingly facing inefficiencies. The challenges reduce efficiency-cy and present an opportunity to enhance sustainability. This study will deal with three main aspects: First, it will forecast steel prices based on global GDP trends so that demand volatility can be miti-gated by linear regression model; second, it will reduce land trans-portation costs by a linear programming approach which means minimizing the number of trips needed for delivery; and third, it will make regulatory compliance better by studying sector feedback on environmental policies for suggesting ways of better collaborating with the regulators. This study results in a strong, data-backed structure intended for addressing the major ineffectiveness in the steel industry supply chain. The price forecasting model created using linear regression with GDP growth shows a good correlation between macroeconomic indicators and steel price trends. It enables downstream steel producers to mitigate risks of overproduction or understocking. In logistics optimization, the linear programming model minimizes transportation costs by reducing the delivery trips. The study demonstrates that even minor improvements in route planning and truck load distribution can save a lot of money and carbon emissions as well. Regarding regulatory issues, the survey results bring out the key issues that are being faced by the players in the industry. This lays down an understanding path on how to align industrial practices with sustainability goals while keeping operational efficiency intact.

***Keywords***: *Environmental Compliance; Logistics Optimization; Price Forecast-Ing; Steel Industry; Sustainable Development.*

## 1. Introduction

The steel industry is one of the key sectors in global manufacturing. It is very critical in producing goods for infrastructure, transportation, and even household items. However, due to several factors that make their supply chain very complex and large, it poses a lot of challenges toward achieving efficiency, sustainability, and resilience in the system. This paper proposes and explores strategies for optimizing the steel supply chain under such circumstances. It will identify possible breakthroughs and methods through which the steel supply system could be made more responsive to external disturbances. It is within this context that Michael Porter asserts," Competitive advantage does not rest solely on product innovation; it is equally dependent on optimizing the processes through which goods are produced and delivered." [1]. The supply chain of the steel industry covers right from lying on the entire process from raw material extraction, production, transportation, and distribution has many points where there is an opportunity for good optimization. But to get optimal output and at the same time reduce its environmental footprint, it needs to adopt a multi-pronged approach involving strategic planning and the practice of sustainability. Supply chain experts have added weight to this view. John Elkington, for example, introduced the "Triple Bottom Line," which relates to the balancing of social, environmental, and economic responsibilities of a business operation. He contends that "the future of business lies in the ability to deliver sustainable performance across three dimensions: people, planet, and profit." [2].

### 1.1. The problem statement

The steel industry has a prime role in world development because it undertakes the key sectors. However, due to the importance of this sector, it is very unfortunate that the supply chains have many problems which are very complicated and linked in such a way that they are reducing the efficiency, sustainability as well as resilience of the entire sector. This calls for an urgent understanding and response by all stakeholders if sustainable growth and green accountability in this industry are to be achieved. Challenges will be covered in the research as follows:

#### 1.1.1. Demand volatility

One of the most pressing challenges is demand volatility. The steel sector typically shows heightened sensitivity to demand dynamic swings, which are frequently induced by general economic cycles, periods of industrial contraction, or alternation between extremes that characterize major infrastructure and construction projects. This fact alone makes precise forecasting an almost impossible task. Consequently, it is rather common for producers to find misaligned levels of output with the actual needs of the market at any given moment. When imbalances tip in favor of lower demand suddenly, it poses the risk of high inventories and associated holding costs; when surges unexpectedly turn out to be the case, then it is a case of under-supply and pronounced delays affecting downstream sectors. In Figure 1 a quick visual of just how volatile the market has been, and it shows annual average hot-rolled coil (HRC) prices going back to 2015 [3].

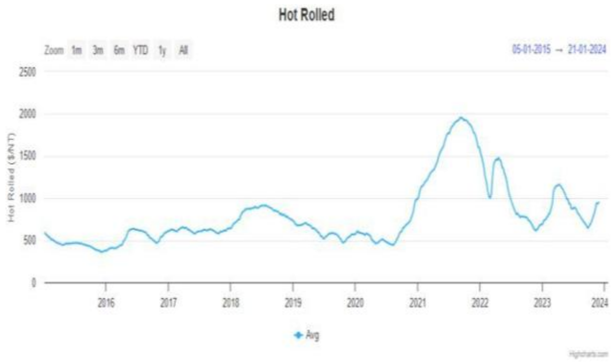



**Fig. 1:** Annual Average Hot-Rolled Coil Prices.

From Figure 1, we can see the fluctuation of HRC prices, which were around 500$ for each MT in 2016 and jumped to around 2000$ in 2021.

Despite having significant iron ore reserves, many steel-producing countries, including Saudi Arabia, still rely on imports for key raw materials like scrap metal. Fluctuations in global material prices or supply chain disruptions can lead to increased costs and instability in production. In Figure 2, we can see how much annual imports in Saudi Arabia [4]

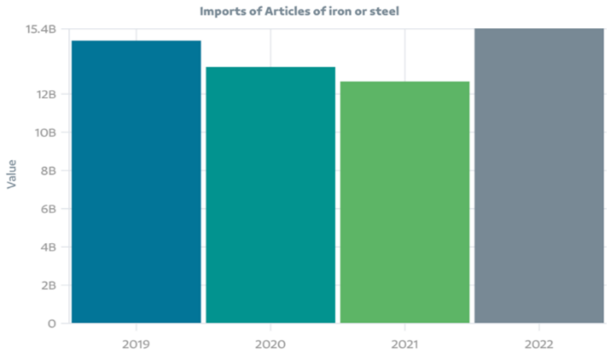



**Fig. 2:** Steel Annual Imports in Saudi Arabia.

We can see from Figure 2 the imports to Saudi Arabia from 2019 to 2022. The minimum import amount was in 2021 with 12 billion SAR, and the maximum was in 2022 with 15.4 billion SAR.

#### 1.1.2. High transportation costs

The nature of steel, so heavy, bulky, and often needing special handling, makes the supply chain a steel transport cost driver. Unlike goods that are lighter or more compact, products in steel like beams, coils, and rebar require substantial logistics planning substantial just like detail heavy-duty transport equipment, and fuel consumption is greater. These factors make steel especially vulnerable to transportation cost increases, which has added a problem increasingly intensified in recent years. For instance, in Saudi Arabia, transportation costs shot up by close to 30% in 2023; this was mainly due to an increase in fuel prices and the oil market being bullish globally [5] .In such a country where there is a high dependence on overland transport to haul steel from its place of fabrication to the port or site of construction, such cost increments trickle down directly to the manufacturers and distributors' bottom lines.

#### 1.1.3. Regulatory challenges

Besides the logistical barriers, regulatory complexity forms another giant impediment to the steel industry all over the globe and even in Saudi Arabia. On top of new regulations that are often dynamic, governments are also imposing stricter rules on sustainability in industrial practices and environmental standards. This puts more responsibility on the shoulders of steel producers to adhere to new and frequently changing regulations. Such policies are indeed essential for environmental protection as well as public health, but they stand a huge possibility of creating unintended pace-structure bottlenecks for the very industries concerned.

### 1.2. Aims

The main aims of the study are given below:

#### 1.2.1. Analyzing demand volatility and price fluctuations

The supply chain of steel is most prominently challenged by market demand and price of steel, which predictably fluctuate. These are largely influenced by the global economic trends, infrastructure cycle, and availability of raw materials, among other things, not to mention the geopolitical happenings. To this end, the study shall observe patterns and volatility roots relating to steel prices in both regional and international markets. An integral part of this is building a forecasting model that takes historical pricing data, economic indicators, and market trends into account in projecting future price movements. This tool is meant to assist steel manufacturers in making more informed decisions regarding procurement timing, pricing strategy, and inventory management.

#### 1.2.2. Minimize transportation cost

This research narrows its focus on a practical and targeted strategy: reducing the number of transport trips required to move steel products between key points in the supply chain. Fewer trips mean lower fuel usage, less wear and tear on vehicles, reduced driver hours, and ultimately reduced overall logistics costs.

#### 1.2.3. Enhancing regulatory compliance and industry collaboration

This study intends to investigate the regulatory environment for steel manufacturers, especially focusing on environmental compliance. This has been a challenge for many firms that do not understand or follow the frequent changes in regulations, which also delays their operations development. Thus, this paper will contribute to greater communication between government bodies and the steel industry.

### 1.3. Literature review

The studies that will be summarized in the following sections take into consideration some very critical issues such as emissions reduction in steel production, supply chain transparency enhancement through blockchain, the possibility of green steel production, and cost & sustainability improvement logistics & infrastructure roadmaps. In addition to these aspects, a few papers also highlighted technical & environmental impacts on this industry, along with regulatory challenges & road infrastructure impact on the performance of the supply chain.

The first study on sustainable steel production deploys a life-cycle analysis combined with economic modeling to assess several low-emission technologies like the Direct Reduced Iron DRI process and Carbon Capture and Storage CCS. The study shows that switching to low-emission processes like DRI, powered by green hydrogen, along with CCS, is a feasible strategy for decarbonizing the steel sector. The analysis suggests that substantial investment in these technologies is necessary for the sector to achieve net-zero emissions by 2050, but it also highlights the potential economic benefits, such as job creation and energy savings. [6]

The second paper undertakes a case study to examine how blockchain may enhance supply chain resilience via the supply chains of steel manufacturing amid major disruptions such as the COVID-19 pandemic. This was conducted through interviews of professionals in the supply chain and some archival data to check how integration works out. The paper found that blockchain technology can enhance supply chain resilience in the steel industry by improving transparency, traceability, and operational efficiency. It enables better monitoring of raw material sources, production processes, and logistics, thus improving overall supply chain performance during disruptions. [7]

The third paper presents a modeling approach for assessing green steel production in Ukraine, involving economic impact assessment and simulation for cost-benefit appraisal regarding renewable energy adoption in green steel production. The study concludes that transitioning to green steel could generate significant economic benefits, estimating a gross value added of $164 billion over 20 years. However, this transition requires substantial investments in renewable energy infrastructure and green hydrogen production. [8]

The fourth paper is about machine learn ML techniques, more precisely Support Vector Regression, predicting steel demand propensity towards green supply chain efficiency. The data covered 131 countries for 31 years and included GDP per capita plus lagged consumption as variables in one of the sketches. The study found that using machine learning models, specifically support vector regression, led to more accurate predictions of steel demand per capita compared to linear regression models. The inclusion of lagged consumption data and GDP per capita as input variables improved the forecasting accuracy for most countries, though some regions require more dynamic, country-specific models due to fluctuating demand trends. [9]

In another instance, a study employed survey methodology to gather information from 359 senior managers belonging to beverage manufacturing firms based in Ghana regarding the impact of road infrastructure on supply chain cost reduction. The study showed a positive relationship between improved road infrastructure and supply chain cost reduction. The findings suggest that better roads lead to reduced transportation costs, lower fuel consumption, and fewer delays. [10]

The paper on regulatory challenges in the European steel industry forms another exception as it adopts a qualitative approach, conducting in-depth interviews with 21 experts from steel companies, industry associations, and related suppliers. This qualitative information is further supplemented by archival analysis to examine how firms usually anticipate and react to changes in regulation. The study found that firms exhibit heterogeneous responses to anticipated regulatory shifts, such as Scope 3 emissions reporting. Some firms proactively prepared for these changes, while others hesitated or resisted, fearing financial costs or competitive disadvantages. The study emphasizes that early compliance can provide competitive advantages, but firms must balance the costs of adaptation with long-term sustainability goals. [11]

One of the foundational contributions to supply chain theory comes from Chopra and Meindl, who emphasize the critical role of demand forecasting in enhancing supply chain efficiency. In their work Supply Chain Management, they argue that mathematical models, particularly time series models and causal regression techniques, serve as essential tools for predicting future demand based on historical trends and influencing variables such as GDP or market dynamics. Accurate forecasting, they assert, reduces the need for excess safety stock, thereby minimizing holding costs and improving responsiveness. Furthermore, they highlight the importance of integrating forecasting models with modern information systems, such as ERP platforms and predictive analytics, to support real-time and data-driven decision-making. This theoretical foundation reinforces the current study's use of regression modeling as a practical approach to understanding and mitigating demand volatility in the steel industry. [12]

These studies collectively highlight the complexity and multifaceted nature of addressing sustainability and efficiency challenges in the steel industry and supply chains. This research addresses several critical gaps in the current literature on the steel industry supply chain, especially in Saudi Arabia. While existing studies have focused more on decarbonization technologies and green steel production, along with advanced manufacturing process integration, they have largely neglected major challenges such as high transportation costs, as well as permitting and regulatory frameworks that severely impact the efficiency of the supply chains of steel.

## 2. Methodology

This research will explore strategies for optimizing the steel industry supply chain by focusing on three key areas: mitigating demand volatility, minimizing transportation costs, and addressing regulatory and environmental challenges. Rather, the methodology used is intended to provide actionable ideas for steel industry decision makers to be more competitive, and get more operations efficient, and sustainability approaches.

### 2.1. Demand volatility

One of the solutions this research aims to propose is a predictive model that reduces the effect of demand volatility in the steel market by predicting steel prices. The research will use GDP growth rates of the largest steel-consuming countries as a major driver in steel price prediction. As an important driver of construction, manufacturing, and infrastructure development, GDP growth is often seen as a bright sign for future economic health and industrial performance, and so is the steel demand. This analysis includes the following data:

- Steel Price Data: Average steel price (in USD per ton) between 2014 and 2024
- GDP Growth Rates: The GDP growth rates (in %) for each year.

The table below summarizes the data for GDP growth rates and steel prices for the chosen countries (China, India, Japan, USA, and Russia) [13].

**Table 1:** Annual GDP Growth Rate and Steel Prices (2014–2024)

| Year | GDP Growth Rate (%) | Steel Price (USD/ton) |
|---|---|---|
| 2014 | 3.7 | 400 |
| 2015 | 3.5 | 450 |
| 2016 | 3.6 | 526 |
| 2017 | 3.9 | 616 |
| 2018 | 3.9 | 829 |
| 2019 | 2.9 | 598 |
| 2020 | -2.5 | 587 |
| 2021 | 6.5 | 1612 |
| 2022 | 2.3 | 1015 |
| 2023 | 4.3 | 886 |
| 2024 | 4.2 | 890 |

The five countries chosen to conduct the study, China, India, Japan, the USA, and Russia, are among the biggest steel consumers in the world. With a sizeable chunk of the demand of world's steel demand coming from these countries, they serve as an emblem for the rest of the world as far as the trend in the market goes.
Specification of a Regression Model:
The linear regression model used in this analysis is defined as:

$$y = \beta_0 + \beta_1 \cdot x \quad (1)$$

To obtain the solution for the developed model, Microsoft Excel Solver was employed as the primary tool. Solver was chosen for its accessibility, ease of use, and capability to handle such problems.

### 2.2. Linear programming to minimize transportation cost

Here we use linear programming (LP) for minimizing the transportation cost of an industry of steel industry. Transportation will account for a large portion of the logistics associated with delivering steel to customers, and minimizing it can result in large savings.
Problem Setup: We take the case of a steel manufacturer, and we know that the manufacturer can make a maximum of 150 tons of steel, and we want to deliver the order of 5 customers, each has their own demand. Some details of the transportation system are that we only use trucks, which can carry 30 tons per truck. Each truck incurs a transportation cost of 500 SR.

#### 2.2.1. Given data

- 150 tons of factory production capacity
- Truck cost: 500 SR per truck.
- Truck capacity: 30 tons.

Customer demand: Each customer has a steel demand that needs to be fulfilled by a set of trucks. Customer Demand:

- Customer 1: Demand of 20 tons.
- Customer 2: Demand of 27 tons.
- Customer 3: Demand of 27 tons.
- Customer 4: Demand of 10 tons.
- Customer 5: Demand of 10 tons.

Thus, the linear programming model for this problem is as follows:

#### 2.2.2. Objective function

$$\text{Minimize} Z = 500 * (x1/30 + x2/30 + x3/30 + x4/30 + x5/30) \quad (2)$$

Subject to:

$$x1 + x2 + x3 + x4 + x5 <= 150 \quad (3)$$

$$x1 = 20 \tag{4}$$

$$x2 = 27 \tag{5}$$

$$x3 = 27 \tag{6}$$

$$x4 = 10 \tag{7}$$

$$x5 = 10 \tag{8}$$

Excel Solver was used to implement the process to assign trucks considering customer requirements, factory production limits, and truck capacity.

## 2.3. Regulation and environmental challenges in the steel industry

This piece of the research included a qualitative survey used to explore the regulatory and environmental barriers confronted by decision makers in the steel sector. This survey aimed to offer insight into industry perception of current environmental regulation, compliance obligations, and the effects of such challenges on operations. It was comprised of Yes/No questions that were purposely created to elicit straightforward answers based on the perception and experience of those taking the survey.
Respondents and Sample Size: The survey consisted of a sample of 19 decision makers corresponding to the steel sector.

### 2.3.1. Demographic summary of respondents

To enhance the context of the survey findings, basic demographic data about the respondents was also collected. All 19 participants held senior-level positions within their organizations, including roles such as:

- Plant Managers
- Environmental and safety managers
- General managers
- Production managers and production in charge

In terms of industry experience, all of the respondents had spent over 8 years in the steel industry, and half of them over 14 years.

### 2.3.2. Steel industry survey on regulatory and environmental challenges

General Environmental Regulations:

1) Are you aware of the environmental regulations that impact the steel industry in your region?
   - Yes / No
2) Do you think the current environmental regulations are effectively enforced within the steel industry?
   - Yes / No
3) Has your company faced significant challenges in complying with environmental regulations?
   - Yes / No
4) Do you believe the steel industry is doing enough to reduce its environmental impact?
   - Yes / No
5) Is your company actively working on initiatives to reduce emissions and improve sustainability?
   - Yes / No
6) Do you find that environmental regulations are frequently updated, creating challenges for compliance?
   - Yes / No

Energy Consumption and Carbon Emissions

7) Is reducing energy consumption a priority for your company?
   - Yes / No
8) Has your company invested in renewable energy sources to reduce carbon emissions?
   - Yes / No
9) Do you believe there is enough government support for the steel industry to transition to greener technologies?
   - Yes / No
10) Does your company face any challenges in adopting cleaner technologies due to high costs or technical limitations?
   - Yes / No

Waste Management and Recycling

11) Does your company have a waste management strategy in place to minimize industrial waste?
   - Yes / No
12) Are you currently using recycled steel in the production process?
   - Yes / No
13) Do you face challenges in sourcing recycled materials for your steel production?
   - Yes / No
14) Is your company involved in any initiatives to reduce waste or improve recycling practices?
   - Yes / No

Compliance and Future Regulations

15) Do you think stricter environmental regulations will be imposed on the steel industry in the near future?
   - Yes / No

16) Is your company prepared to comply with potential future environmental regulations?
- Yes / No

17) Do you feel that current regulations are hindering innovation and technological advancements in your company?
- Yes / No

18) Do you believe that stricter environmental regulations will lead to an increase in production costs for the steel industry?
- Yes / No

Industry Collaboration and Policy

19) Do you think collaboration between industry stakeholders and government bodies is essential for addressing environmental challenges in the steel industry?
- Yes / No

# 3. Results and discussion

## 3.1. Demand volatility

### 3.1.1. Model development

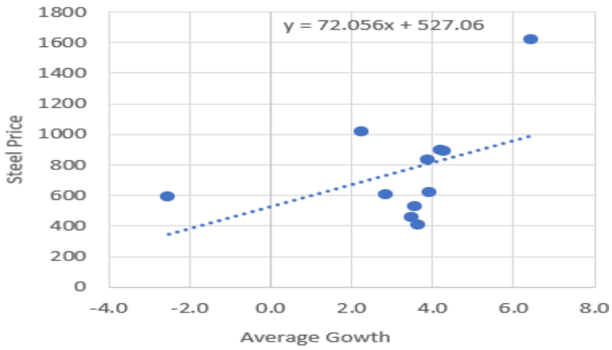


**Fig. 3:** Annual GDP Growth Rate and Steel Prices.

The linear regression equation used in this study is represented as:

$$y = 72.056x + 527.06 \quad (9)$$

This equation suggests that for every 1% increase in GDP growth, the steel price increases by approximately 72.056 USD per ton. The intercept of the model is 527.06 USD, representing the estimated steel price when GDP growth is zero.

R Square (coefficient of determination) represents the proportion of the variance in the dependent variable (steel price) that is explained by the independent variable (GDP growth rate) = 0.211.

### 3.1.2. Forecasting steel prices for 2025

One of the primary applications of this model is forecasting future steel prices. Given the expected GDP growth rate of 3.18% for the year 2025, we can predict the steel price for 2025 using the linear regression equation.

Substituting the expected GDP growth rate of 3.18% into equation 9, thus, the predicted steel price for 2025 is 756 USD per ton.

## 3.2. Application of the linear regression model

The primary application of this linear regression model is in forecasting steel prices based on GDP growth projections. The model offers a simple yet effective tool for predicting how changes in economic growth will affect the steel market. This is particularly useful for industry practitioners in making informed decisions about production schedules, procurement, and inventory management.

- Forecasting Steel Prices: By inputting future GDP growth estimates, the model provides an estimated steel price for the coming years. For example, using the model to predict steel prices for 2025 based on the expected GDP growth rate of 3.18% results in an estimated price of 756 USD per ton. This prediction can be used by industry professionals to plan their procurement strategies and determine optimal pricing for steel products.
- Price Sensitivity Analysis: The model can be used to assess how sensitive steel prices are to changes in GDP growth. The slope coefficient of 72.056 suggests that even small changes in GDP growth rates can have significant impacts on steel prices, making the model a valuable tool for risk management.
- Inventory Management: Steel producers and distributors can use the model to anticipate price fluctuations and adjust their inventories accordingly. If steel prices are expected to rise significantly, they may choose to stockpile steel in anticipation of higher future prices, while if prices are expected to drop, they can adjust their buying strategies to avoid overstocking.
- Long-term Strategic Planning: For policymakers and large-scale manufacturers, understanding the relationship between economic growth and steel prices helps in making long-term strategic decisions. Governments may use this model to predict future demands for steel in infrastructure projects or construction, while companies can factor in expected price movements when planning their capital expenditures.
- Accurately forecasting steel demand supports Vision 2030's goals of sustainable infrastructure development and industrial diversification. As Saudi Arabia expands its mega-projects, such as NEOM and the Red Sea Project, reliable demand predictions become essential for planning resource allocation and managing market volatility. The regression model in this study, although basic,

provides a foundational tool that, when improved with machine learning, can enhance strategic decision-making in line with Vision 2030's emphasis on growth and economic resilience.

#### 3.2.1. Limitations of the model

While the model provides valuable insights, it is important to acknowledge its limitations:

- External Shocks: As seen in 2020, external factors like the COVID-19 pandemic can cause disruptions that the model cannot predict. While GDP growth is an important factor, other macroeconomic conditions may also play a significant role in determining steel prices.
- Regional Variations: The model assumes a global average and does not account for regional differences in steel demand or production, which could affect prices in different countries or markets.
- The relatively low $R^2$ value of 0.211 highlights that only about 21% of the variation in steel prices is explained by that Linear regression assumes a constant relationship between the independent variable (GDP growth) and the dependent variable (steel price), which may not fully capture the dynamics of the steel market. For example, the impact of GDP growth on steel prices may vary depending on external factors such as technological disruptions or shifts in trade policies. Moreover, shifts in international trade policies, such as the imposition of tariffs, changes in export and import regulations, or new trade agreements, can have a significant effect on global steel prices. These types of disruptions may not correlate directly with GDP growth but can still cause sharp fluctuations in price. In such cases, the linear model's ability to predict outcomes based on GDP growth alone becomes limited. To improve the accuracy of steel price forecasting, future studies could explore the use of advanced machine learning techniques, such as Support Vector Regression (SVR), which have shown greater predictive power compared to traditional linear models. As demonstrated in [9], incorporating additional variables can significantly enhance model performance. Adopting such approaches could allow for the inclusion of more nuanced, country-specific factors and better capture the complex dynamics of global steel demand.

The linear regression model presented in this study provides a solid foundation for understanding the relationship between GDP growth and steel prices. By analyzing data from the past decade, we have been able to quantify how economic growth drives steel prices and predict future trends. The model's application in forecasting, inventory management, and strategic decision-making makes it a valuable tool for industry practitioners. However, it is important to recognize the model's limitations, particularly its inability to account for external shocks or complex market dynamics. Future research may seek to refine this model by incorporating additional factors to enhance its accuracy and predictive power.

### 3.3. Linear programming to minimize transportation cost

LP Model led to the following allocation of Trucks in the following table:

**Table 2:**Truck Allocation for Each Customer

| Truck | Customer | Quantity Delivered (tons) | Total Load (tons) | Remarks |
|---|---|---|---|---|
| Truck 1 | Customer 1<br>Customer 4 | 20<br>10 | 30 | Full capacity utilized |
| Truck 2 | Customer 2 | 27 | 27 | Slightly under capacity, full demand met |
| Truck 3 | Customer 3 | 27 | 27 | Slightly under capacity, full demand met |
| Truck 4 | Customer 5 | 10 | 10 | Under capacity, required for order delivery |

#### 3.3.1. Cost of transportation

Irrespective of whether the truck is full or part load, the cost incurred will be 500 SR per truck. The transport cost is then computed according to the truck allocations described above as:

$$\text{Total Transportation Cost} = 500 \times 4 = 2000\ \text{SR} \tag{10}$$

This model is perfect because it allows the sharing of truck capacity amongst customers. If it had assigned a separate truck to all customers (which might be inefficient), the model instead consolidated deliveries and filled the truck as much as possible. Example: One truck 1 delivered 20MT to customer 1 and 10MT to customer 4, perfectly filling the truck. This model was not abstract; it was based on actual data from a steel factory and, therefore, is practical and transferable to any other steel manufacturer. Our work demonstrates that the TOSSES method allows steel manufacturers to effectively lower their logistics expenses without ever compromising on being able to serve their customers.

Optimizing logistics networks is one component of a broader industry that must undergo to stay competitive in today's changing environment. The linear programming strategy outlined in this research serves as an exemplary model of how optimization techniques can help transform steel supply chains through enhancing efficiency, environmental responsibility, and responsiveness to disruption.

#### 3.3.2. Let us analyze this further

Optimization: By focusing on lowering the number of trucks for deliveries, the LP approach helps steel factories in streamlining their transportation operations for scheduling shipments, like simply assigning one truck per customer regardless of vehicle capacity. This can lead to ineffective vehicles returning half empty, wasting both time and fuel. Employing the LP model allows companies to allot trucks more efficiently, ensuring full use of each vehicle and decreasing the number of trips necessary.

Moreover, by maximizing truck filling, this strategy not only cuts costs but also increases delivery speed. Customers receive orders more promptly, and companies can handle more requests in less time, essential in dynamic industries like construction, where timing is often critical.

Sustainability: By optimizing the number of trucks in the logistics process, this model directly contributes to sustainability aims. Fewer trucks mean decreased fuel use and emissions, assisting companies in aligning with environmental regulations and fulfilling sustainability targets.

Additionally, the model can be adapted to consider eco-friendly transportation methods. For instance, it could comprise variables accounting for electric trucks or alternative fuels, further reducing the environmental impact of transportation.

Resilience: The LP model not only helps optimize transportation but can also be adapted to handle these types of disruptions. For example, if demand suddenly varies or a truck breaks down, the model can realign to ensure deliveries still transpire on time, leveraging accessible resources efficiently.
The ability to adapt to unexpected changes in real time is a crucial facet of a responsive supply chain. By employing the LP model, steel manufacturers can be better equipped to handle disruptions without sacrificing customer service or profitability.
The linear programming model aligns with Vision 2030's focus on improving logistics efficiency and reducing environmental impact. By minimizing transportation costs and optimizing truck use, steel manufacturers can lower carbon emissions and operational waste, key targets in the Vision's sustainability pillars. Efficient supply chains are vital as Saudi Arabia aims to become a global logistics hub, and applying such optimization tools contributes to cost-effective, environmentally responsible operations across industrial sectors.

### 3.4. Future considerations and potential extensions

Although this study has proven that linear programming is an effective method for minimizing the transportation costs in the steel industry, it highlights some gaps for future studies and improvements. Subsequent research can expand on the present research by considering variables such as variable fuel prices as part of the optimization model. Stuff like that could make the model even stronger and more applicable to a greater variety of industries.
Furthermore, data analytics and machine learning can be leveraged with the LP model for real-time decision making. Similar technologies may also enable the re-adjustments of the transportation schedules based upon the changing conditions in real-time and thus making the supply chain of steel more agile.
This study shows that the application of linear programming in the domain of steel transportation logistics has the potential to reduce the cost to manufacturers, improve the efficiency of these operations, and serve environmental sustainability efforts. The optimization model developed in this work serves as a useful tool for steel companies to minimize transportation expenses at higher levels of customer satisfaction. These findings make a strong case for expanding the application of optimization methods to the steel industry, with the prospect of changing the nature of efficiency as well as environmental and economic sustainability in steel supply chains.

### 3.5. Regulation and environmental challenges in the steel industry

Insights into the current state of environmental awareness, regulatory compliance, and sustainability actions in the steel sector have been obtained by carrying out a formal survey on the professionals and stakeholders of this sector. This 19-question form was made on important subjects like regulatory enforcement, environmental initiatives, challenges facing cleaner technology adoption, and industry preparedness regarding future regulations. The answers, shown in the table below, show different levels of knowing, paying attention to, and worrying about environmental problems faced by firms in the steel industry. The information traces how far we have come in areas like waste management and following rules, while also showing the trouble that still exists with high costs, tech limits, and getting recycled materials. These findings serve as a basis for further discussion on the regulatory landscape and environmental performance of the steel industry.

**Table 3:** Survey Responses on Environmental Regulations in the Steel Industry

| Question | Responses | |
|---|---|---|
| | YES | NO |
| 1. Are you aware of the environmental regulations that impact the steel industry in your region? | 18 | 1 |
| 2. Do you think the current environmental regulations are effectively enforced within the steel industry? | 15 | 4 |
| 3. Has your company faced significant challenges in complying with environmental regulations? | 10 | 9 |
| 4. Do you believe the steel industry is doing enough to reduce its environmental impact? | 9 | 10 |
| 5. Is your company actively working on initiatives to reduce emissions and improve sustainability? | 9 | 10 |
| 6. Do you find that environmental regulations are frequently updated, creating challenges for compliance? | 13 | 6 |
| 7. Is reducing energy consumption a priority for your company? | 12 | 7 |
| 8. Has your company invested in renewable energy sources to reduce carbon emissions? | 5 | 14 |
| 9. Do you believe there is enough government support for the steel industry to transition to greener technologies? | 9 | 10 |
| 10. Does your company face any challenges in adopting cleaner technologies due to high costs or technical limitations? | 15 | 4 |
| 11. Does your company have a waste management strategy in place to minimize industrial waste? | 15 | 4 |
| 12. Are you currently using recycled steel in the production process? | 6 | 13 |
| 13. Do you face challenges in sourcing recycled materials for your steel production? | 6 | 13 |
| 14. Is your company involved in any initiatives to reduce waste or improve recycling practices? | 9 | 10 |
| 15. Do you think stricter environmental regulations will be imposed on the steel industry in the near future? | 14 | 5 |
| 16. Is your company prepared to comply with potential future environmental regulations? | 17 | 2 |
| 17. Do you feel that current regulations are hindering innovation and technological advancements in your company? | 10 | 9 |
| 18. Do you believe that stricter environmental regulations will lead to an increase in production costs for the steel industry? | 16 | 3 |
| 19. Do you think collaboration between industry stakeholders and government bodies is essential for addressing environmental challenges in the steel industry? | 17 | 2 |

Table 3 presents survey responses from professionals in the steel industry regarding environmental regulations and sustainability practices. It highlights levels of awareness, compliance challenges, and readiness for future environmental demands.

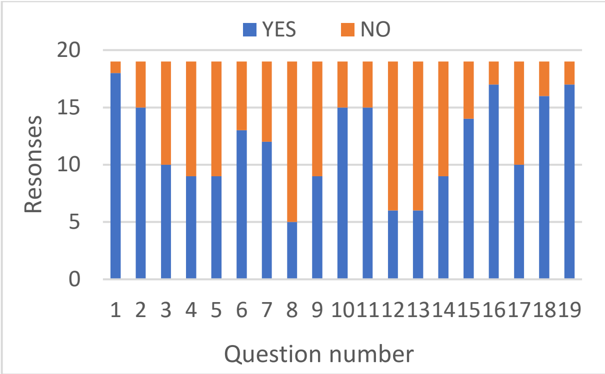
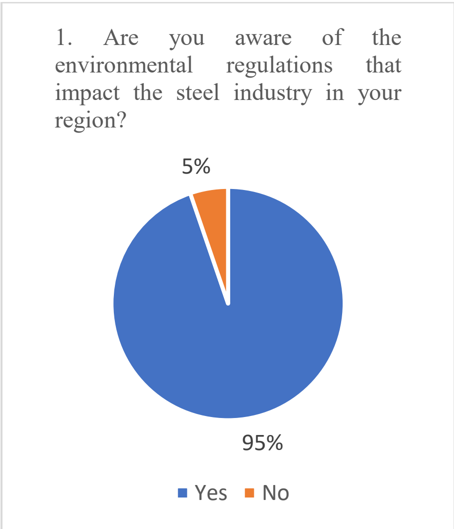
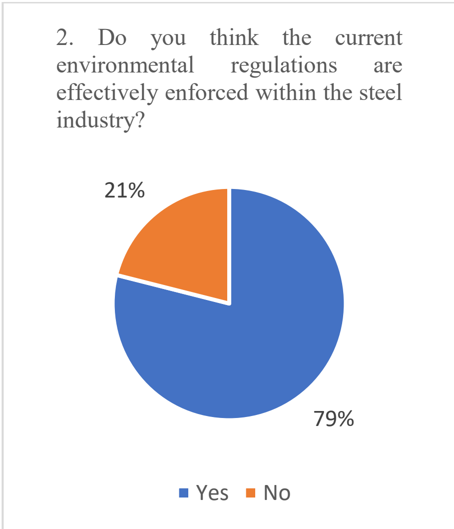
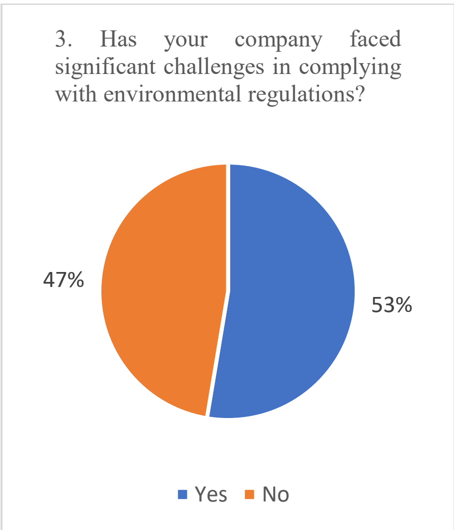
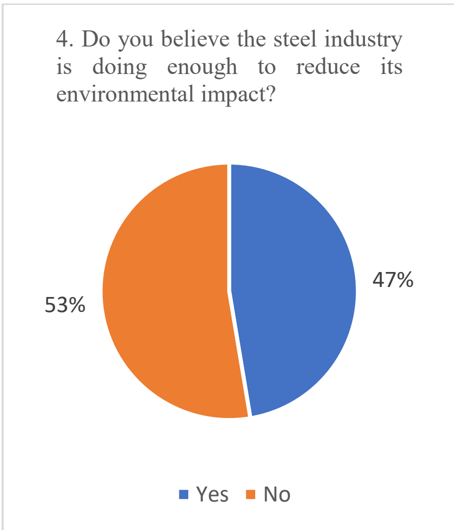


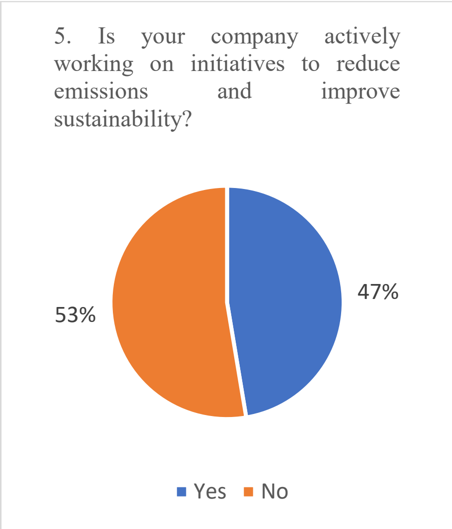

**Fig. 4:** Survey Results.

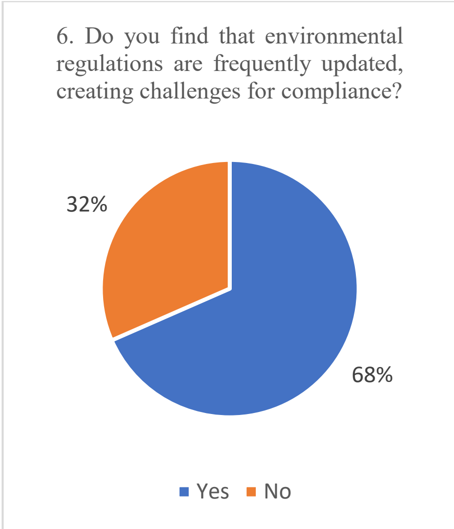


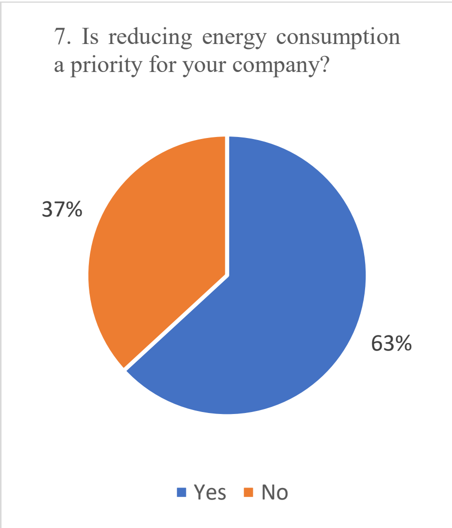



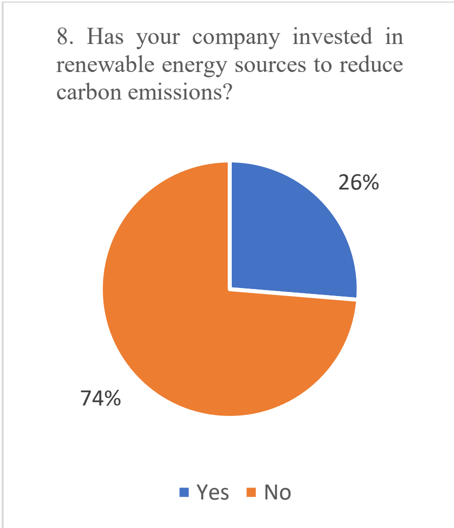



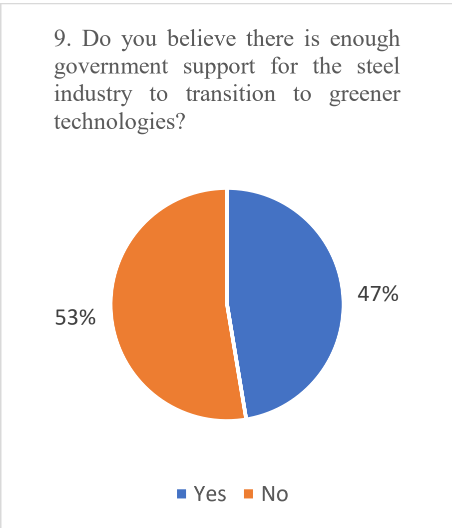



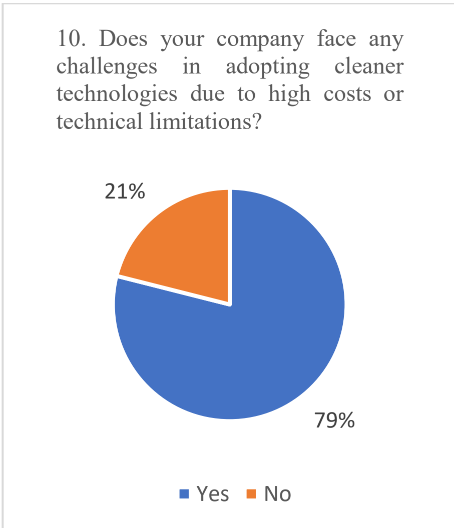

5. Is your company actively working on initiatives to reduce emissions and improve sustainability?
47%
53%
Yes No

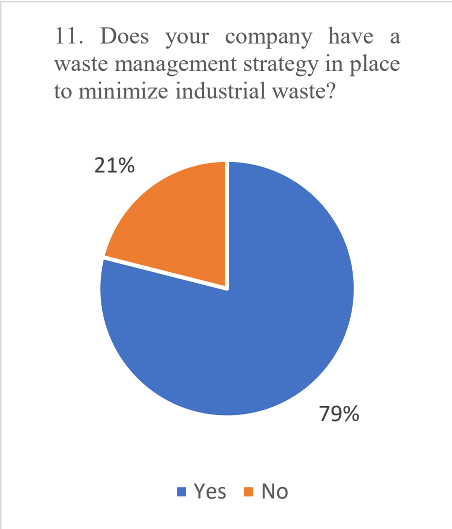

6. Do you find that environmental regulations are frequently updated, creating challenges for compliance?
32%
68%
Yes No

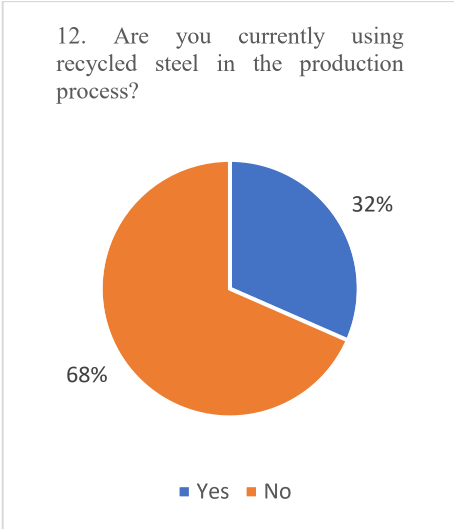

7. Is reducing energy consumption a priority for your company?
37%
63%
Yes No

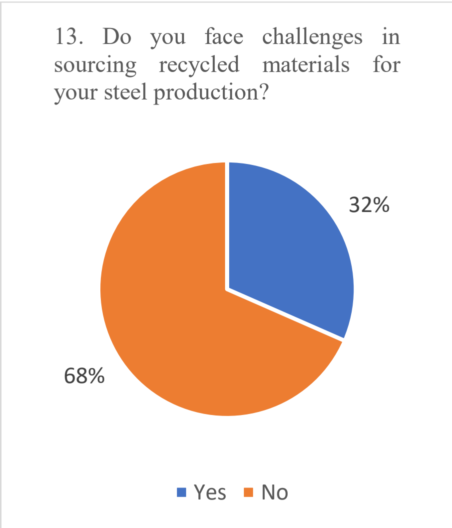

8. Has your company invested in renewable energy sources to reduce carbon emissions?
26%
74%
Yes No

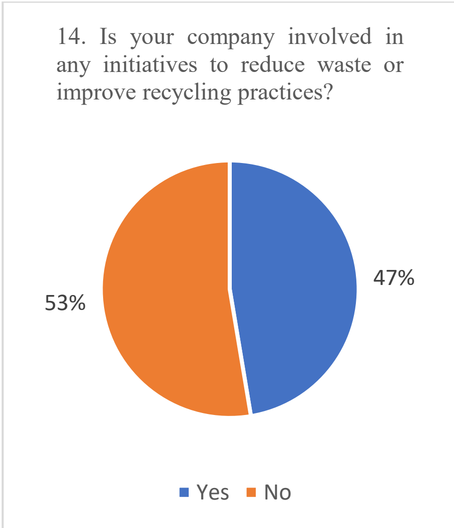

9. Do you believe there is enough government support for the steel industry to transition to greener technologies?
47%
53%
Yes No

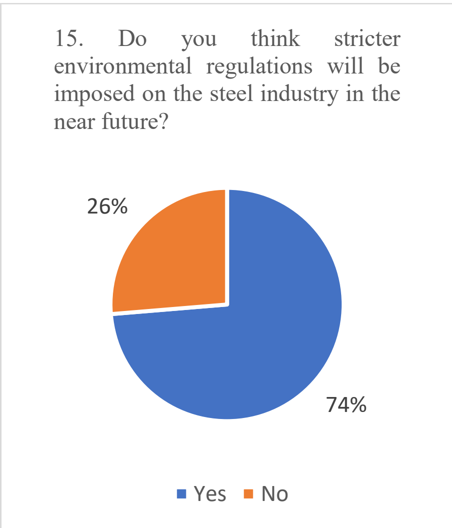

10. Does your company face any challenges in adopting cleaner technologies due to high costs or technical limitations?
21%
79%
Yes No

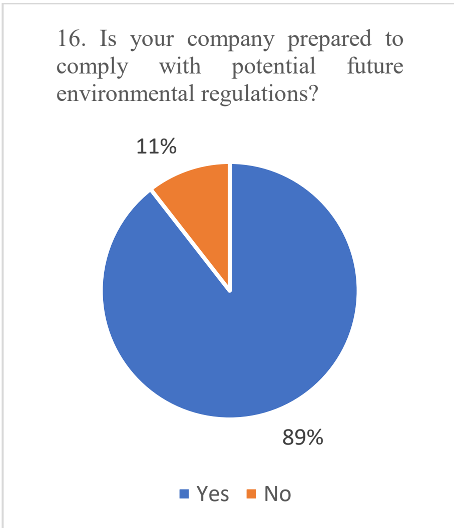

11. Does your company have a waste management strategy in place to minimize industrial waste?
21%
79%
Yes No

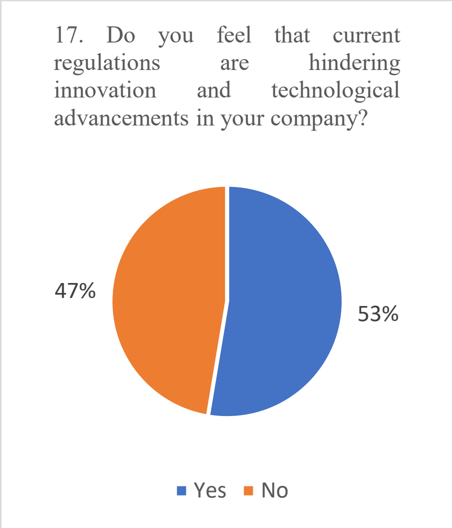

12. Are you currently using recycled steel in the production process?
32%
68%
Yes No

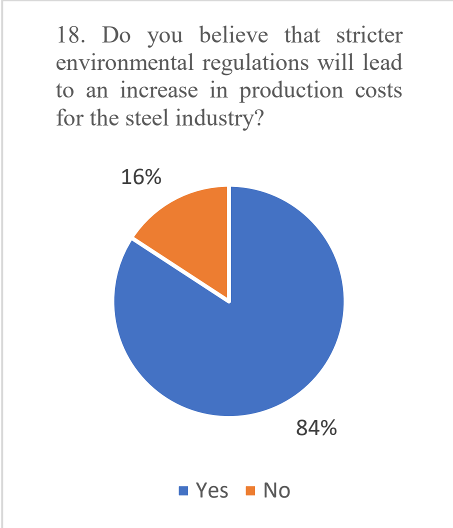

13. Do you face challenges in sourcing recycled materials for your steel production?
32%
68%
Yes No

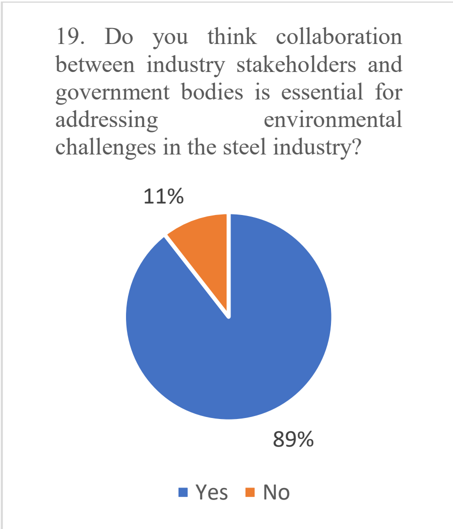

14. Is your company involved in any initiatives to reduce waste or improve recycling practices?
53%
47%
Yes No


15. Do you think stricter environmental regulations will be imposed on the steel industry in the near future?
26%
74%
Yes No


16. Is your company prepared to comply with potential future environmental regulations?
11%
89%
Yes No




Out of 19 respondents, 94.7% reported awareness of environmental regulations, yet only 52.6% said their companies actively reduce environmental impact. 78.9% believe regulations are enforced, but 52.6% face compliance challenges, mainly due to financial constraints and lack of technical support. While 73.7% haven't invested in renewable energy, 63.2% prioritize energy reduction to control costs and meet environmental goals. 68.4% find frequent regulation updates challenging, especially for small and mid-sized firms with limited compliance staff. 89.5% feel prepared for future regulations, but many equate preparedness with awareness, not fully operational readiness. A strong 89.5% emphasized the importance of industry-government collaboration, citing poor consultation and inconsistent inspections as major gaps.

The survey results reveal a promising level of awareness among steel industry stakeholders. However, this awareness does not consistently translate into effective action, as only about half of the respondents report active efforts toward sustainability or face difficulties in compliance due to financial, technical, or regulatory burdens. The high percentage (89.5%) of participants who emphasized the need for collaboration underscores a significant gap between regulation design and practical implementation. While many believe they are prepared for future regulations, the findings suggest that this preparedness is often superficial. Overall, the results indicate that without clearer guidance, stronger institutional support, and inclusive policymaking, the sector's environmental progress will remain limited.

Managers emphasized that many regulations are introduced without sufficient consultation, practical guidance, or transition planning. As a result, companies are often caught off guard and left struggling to implement changes under pressure. Furthermore, after regulations are enacted, inspectors who visit factories are sometimes not fully equipped to interpret the regulations in real-world industrial settings, leading to inconsistent enforcement and confusion. There is a clear demand for two-way communication, proactive engagement, and a stronger partnership model between industry and environmental authorities. Collaboration is not only about joint problem-solving but also about building trust, aligning expectations, and ensuring that regulations are grounded in technical and economic reality.

Manufacturers' Insights: In follow-up discussions with industry managers, two important concerns emerged:

1) Workshops and Meetings Before Regulation Implementation: Managers emphasized the need for early involvement to ensure new regulations are realistic and industry-specific.
2) Training for Regulatory Officers: After implementation, officers inspecting factories often lack the technical expertise to interpret regulations properly, causing confusion or unfair assessments.

This questionnaire-based study gives a good insight into the present levels of environmental awareness, regulatory challenges, and sustainability initiatives in the steel manufacturing industry, which could be used for implementing Vision 2030 that places environmental sustainability at the core of Saudi Arabia's economic transformation. The survey findings reveal both progress and persistent gaps in the steel industry's environmental practices, including challenges in compliance and limited adoption of green technologies. Strengthening collaboration between regulators and industry, highlighted as a major need by respondents, directly supports Vision

2030’s commitment to transparent governance, improved regulation, and fostering innovation in clean technologies across heavy industries.

The study drew on responses from 19 decision makers in the steel industry, gathered through purposive sampling during site visits and in-depth professional discussions at their respective factories. While these insights provide valuable perspectives on current industry practices and the challenges of aligning with environmental objectives, the limited sample size represents a constraint on generalizability. Future research should aim to expand the survey population to include mid-level managers, operational staff, and representatives from smaller firms, to capture a more comprehensive and diverse set of views across the supply chain.

## 4. Conclusion

The steel industry is a major driver of global economic development because it provides an important input for infrastructure, construction, transportation, and manufacturing. One of the major contributions of this study was the creation of a predictive model utilizing linear regression to assess and forecast trends in steel prices based on historical data on GDP growth. This model showed a positive relationship between GDP growth and steel prices, thereby reaffirming the theoretical notion that cyclical demand for steel relates reasonably well with macroeconomic performance measures. In such volatile markets where small margins count, this foresight would typically make the difference between a competitive edge and financial stress. The study also applied an LP model to tackle transportation inefficiency, which is the most expensive aspect in the steel supply chain. The optimization of truck allocation was based on customer demand and vehicle capacity; thus, the LP model not only accounted for total trips but also added load efficiency as an improvement measure. This directly translates into cost savings, reduced emissions, and more sustainable logistics operations. In such heavy goods steeling industries, constant movement can be observed about these models having a high return on implementation that could contribute greatly to financial and environmental performance. Besides the quantitative modeling, a qualitative interview was done with decision makers in the steel sector to get firsthand information on the regulatory and environmental challenges they face. From the interviews, common concerns came out regarding the enforcement of environmental regulations not being consistent, high compliance costs, and a breakdown in communication of clear guidelines by the authorities. These insights are important because they help provide a real context that complements numerical models and shows where there are gaps that numbers alone cannot explain. It also became very clear that more engagement is needed between policymakers and industry stakeholders to develop regulatory frameworks that can be enforced but also should be workable and related to technological and economic realities. The combination of three methods, linear regression for forecasting, linear programming for optimization, and qualitative surveying for getting regulatory insight, makes this research very complete. Instead of looking at these issues separately, the study shows a combined framework that recognizes how economics, logistics, and governance are linked in the steel supply chain.

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