

A Comprehensive Carbon Footprint Monitoring Framework for Sustainable Apparel Manufacturing

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ABSTRACT

This study proposes the design, implementation, and evaluation of a software-based carbon footprint monitoring system developed specifically for the apparel manufacturing industry. As one of the major contributors to global greenhouse gas (GHG) emissions, the sector faces increasing pressure to monitor and reduce its environmental impact arising from energy-intensive activities such as fabric production, dyeing, garment manufacturing, and transportation. Existing carbon monitoring approaches often depend on hardware-based systems that provide historical data but offer limited support for real-time intervention and decision-making. The proposed platform consolidates production information, energy consumption records, material utilization, and logistics data into a unified digital system. Using standardized emission factors, it continuously calculates carbon dioxide (CO₂) emissions and provides real-time visibility into environmental performance. This enables manufacturers to identify emission hotspots, implement corrective actions promptly, and improve overall sustainability outcomes. The study also examines market readiness and adoption trends for digital carbon monitoring solutions. Growing environmental regulations, sustainability reporting requirements, and increasing consumer demand for eco-friendly products have accelerated the need for effective carbon management tools. Major apparel-producing countries, including Bangladesh and China, are increasingly adopting such technologies to meet international trade expectations and sustainability commitments. Evidence from industry case studies indicates that digital monitoring systems contribute to measurable reductions in energy use and carbon emissions while supporting operational efficiency. Furthermore, the research highlights the influence of carbon taxation policies, sustainability standards, and financial incentives such as subsidies and green financing in promoting technology adoption. The findings demonstrate that real-time software-based carbon monitoring systems can generate both environmental and economic benefits, helping apparel manufacturers achieve regulatory compliance, improve competitiveness, and advance long-term sustainability goals.

Keywords: Greenhouse gas, Carbon Footprint, System Architecture, Database Management

INTRODUCTION

Environmental Impact of Apparel Manufacturing

The apparel manufacturing industry is a major contributor to global greenhouse gas (GHG) emissions, accounting for nearly 10% of total emissions worldwide. Its environmental impact arises from various stages of the supply chain, including textile production, garment manufacturing, transportation, and end-of-life disposal. Resource-intensive processes such as fabric dyeing and finishing consume substantial amounts of water, energy, and chemicals, further increasing the industry's ecological footprint. The rapid expansion of fast fashion has intensified these environmental concerns by promoting the mass production of inexpensive garments with short usage cycles, leading to higher consumption and waste generation. According to the Ellen MacArthur Foundation (2017), the fashion industry uses approximately 93 billion cubic metres of water annually, while textile dyeing and treatment contribute nearly 20% of global industrial wastewater pollution.

Need for Carbon Monitoring Systems

The growing environmental impact of apparel manufacturing has increased the demand for sustainable production practices. Manufacturers face mounting pressure from consumers seeking environmentally responsible products, governments enforcing stricter emission regulations, and investors emphasizing sustainability performance. Despite this, conventional carbon monitoring approaches, which often rely on hardware-based devices such as smart energy meters, have several limitations. These systems can be expensive to implement, difficult to scale across operations, and generally provide retrospective data, limiting opportunities for timely intervention. To overcome these challenges, the proposed software-based carbon footprint monitoring system offers a more efficient and scalable solution. By integrating data from production processes, energy consumption records, logistics operations, and material management systems, the platform enables real-time monitoring of carbon emissions. This allows manufacturers to identify inefficiencies, take immediate corrective actions, reduce resource consumption, and enhance overall operational and environmental performance.

Objective of the Research

The primary objective of this research is to design, develop, and evaluate a scalable software-based carbon footprint monitoring system for the apparel manufacturing industry that integrates data from multiple operational sources to enable real-time calculation and monitoring of carbon emissions. The study further aims to assess the effectiveness of the proposed system in reducing energy consumption and greenhouse gas emissions through case studies conducted in major apparel manufacturing hubs, including Bangladesh and China. In addition, it examines the influence of international policies, regulatory requirements, and financial incentive programs on the adoption of digital carbon monitoring technologies within the apparel sector. The research also evaluates the economic benefits associated with system implementation, focusing on cost savings achieved through improved energy efficiency, waste reduction, and enhanced compliance with sustainability and environmental standards.

LITERATURE REVIEW

Carbon Footprint in the Apparel Industry

Extensive research has documented the significant environmental impact of the apparel industry, particularly its contribution to global carbon emissions. Allwood et al. (2006) highlight that textile manufacturing generates substantial emissions due to energy-intensive processes such as fibre production, fabric dyeing, and finishing. The industry's carbon footprint extends beyond manufacturing activities, with transportation, distribution, and logistics contributing considerably to overall emissions. According to the IPCC (2014), the global textile sector produces approximately 1.2 billion metric tons of CO₂ emissions each year.

Although natural fibres such as cotton are generally regarded as environmentally friendly alternatives to synthetic materials, their sustainability is challenged by high water consumption and extensive pesticide use (Laing et al., 2019). In contrast, polyester, the most commonly used fibre in apparel production, is derived from petroleum-based resources and generates a carbon footprint several times greater than that of organic cotton. Nevertheless, advancements in recycling technologies have facilitated the production of recycled polyester, which helps reduce emissions through the reuse of existing materials and decreased reliance on virgin resources. Fletcher and Grose (2012) further emphasize the role of sustainable fashion practices in minimizing environmental impacts. Their work highlights the importance of responsible material selection and sustainable design strategies, particularly within the growing slow-fashion movement, which promotes durable, high-quality garments with longer product life cycles, thereby reducing consumption and textile waste.

Traditional Carbon Monitoring Systems

Carbon emissions in manufacturing have traditionally been monitored through hardware-based solutions, including carbon meters, fuel monitors, and energy tracking devices. While these tools provide useful information regarding energy consumption and associated emissions, they often face limitations related to scalability, cost, and operational flexibility. Ahamed et al. (2020) reviewed Energy Management Systems (EMS)

used in the textile sector and concluded that although these systems generate accurate energy consumption data, their implementation can be expensive and difficult to expand across large manufacturing operations. Furthermore, most EMS solutions focus on historical data analysis, limiting their ability to support real-time emission management and optimization.

Wiedmann and Minx (2008) underscore the importance of standardized emission factors in carbon accounting and monitoring frameworks. These factors enable the conversion of activity-based data, including energy consumption, transportation activities, and material usage, into carbon dioxide equivalent (CO₂e) emissions. Widely recognized frameworks such as the GHG Protocol provide standardized emission factors for various energy sources, allowing organizations to estimate emissions accurately based on regional energy mixes and operational activities.

Emergence of Software-Based Carbon Monitoring Solutions

Recent technological advancements have accelerated the adoption of software-based carbon monitoring systems that utilize real-time data from diverse operational sources. Unlike conventional hardware-dependent approaches, these digital solutions provide immediate visibility into carbon emissions and support timely decision-making. Pan et al. (2021) examined the application of digital energy optimization systems in textile manufacturing and reported that integrating production information, energy consumption data, and material usage within a unified platform can reduce carbon emissions by up to 25%.

Modern carbon monitoring platforms collect and analyze data from various sources, including smart energy meters, Manufacturing Execution Systems (MES), and logistics management software. Through cloud-based analytics and automated processing, these systems generate accurate and real-time emission assessments. Zhang et al. (2020) investigated the deployment of Internet of Things (IoT)-enabled monitoring systems in Chinese textile factories and found that continuous tracking of energy use and emissions enabled managers to implement immediate operational improvements. The combination of wireless sensing technologies and cloud computing has proven particularly valuable in large-scale manufacturing environments, where manual monitoring is often complex and inefficient.

Comparative Analysis of Global Case Studies

The adoption of digital carbon monitoring technologies varies significantly across countries. While developed regions such as Europe and North America have rapidly embraced advanced carbon management systems, many developing economies continue to depend on traditional monitoring and reporting methods. Mia et al. (2022) analyzed carbon management practices within Bangladesh's garment sector and observed that a large number of factories still rely on manual reporting mechanisms and post-production emission audits. However, the emergence of green factories equipped with renewable energy systems and digital carbon tracking technologies has contributed to notable improvements in energy efficiency and emission reduction.

Similarly, Chang et al. (2019) compared the implementation of carbon monitoring technologies in China and Bangladesh and found that China has achieved faster adoption of digital solutions due to strong government support, financial incentives, and national sustainability initiatives. The study reported that Chinese textile factories implementing IoT-enabled carbon monitoring systems experienced approximately a 30% reduction in energy consumption during the first year of operation. These findings demonstrate the significant potential of digital monitoring technologies to enhance environmental performance and support sustainable manufacturing practices across the global apparel industry.

Regulatory and Policy Framework

Global Carbon Emissions Regulations

The apparel manufacturing sector is increasingly influenced by international and regional regulations designed to mitigate carbon emissions and promote sustainable production practices. One prominent example is the

European Union Emissions Trading System (EU ETS), which establishes emission caps for industrial facilities. Organizations that exceed their allocated emission limits are required to purchase additional allowances, creating economic incentives for investing in cleaner technologies, renewable energy sources, and energy-efficient operations. The EU ETS has contributed significantly to emission reductions across multiple industries, including textile and apparel manufacturing.

Another major global initiative is the Paris Agreement, adopted in 2015 by nearly 200 nations to limit global temperature increases to well below 2°C above pre-industrial levels while pursuing efforts to restrict warming to 1.5°C. Under this framework, participating countries establish Nationally Determined Contributions (NDCs) that outline their emission reduction commitments and sustainability goals. As governments strengthen these commitments, apparel manufacturers face increasing pressure to reduce carbon emissions, comply with environmental regulations, and satisfy the growing demand for sustainable products from consumers and international buyers.

Regional Policies and Incentives

Beyond global agreements, many countries have introduced national policies and incentive programs to encourage sustainable manufacturing practices. In key apparel-producing nations such as Bangladesh and Vietnam, governments have implemented various measures to support the adoption of energy-efficient technologies and carbon management systems. These initiatives include tax benefits for investments in renewable energy, financial assistance for energy-efficiency improvements, and stricter environmental standards for industrial operations and new manufacturing facilities.

Peters et al. (2017) examined the role of government incentives in promoting sustainable technology adoption within the manufacturing sector. Their findings indicate that financial support mechanisms, including subsidies for energy-efficient equipment and green technology investments, are particularly effective in encouraging small and medium-sized enterprises (SMEs) to adopt environmentally responsible practices. The study also emphasizes the contribution of international organizations such as the International Finance Corporation (IFC) and the World Bank in facilitating sustainability initiatives through grants, technical assistance, and low-interest financing programs for manufacturers in developing economies.

Policy Impact on Carbon Monitoring Technology Adoption

The implementation of carbon monitoring technologies is strongly influenced by regulatory requirements and policy support mechanisms. Anderson and Jewell (2020) argue that the successful adoption of digital carbon monitoring systems depends largely on the existence of favorable government policies, financial incentives, and regulatory frameworks. Their research suggests that manufacturers are more likely to invest in carbon monitoring technologies when supported by clear sustainability policies, rising energy costs, and stringent emission regulations.

China provides a notable example of policy-driven technology adoption within the textile sector. The government has introduced a comprehensive range of measures aimed at reducing industrial carbon intensity, including financial incentives for energy-efficient technologies and penalties for non-compliance with emission targets. According to Zhang et al. (2020), these initiatives have played a critical role in accelerating the adoption of digital carbon monitoring systems across China's textile manufacturing industry, particularly among large-scale enterprises. The findings highlight the importance of supportive policy environments in driving technological innovation and advancing sustainability objectives within the apparel sector.

Comparative Analysis of Carbon Footprint Calculators

Carbon footprint calculators have become essential tools for organizations seeking to measure and reduce greenhouse gas emissions. Among the widely used platforms, Ecochain, the Higg Index, and Sourcemap offer distinct approaches to carbon accounting, sustainability assessment, and supply chain management.

Ecochain is a Life Cycle Assessment (LCA)-based platform that measures the environmental impact of products and processes throughout their lifecycle. It provides detailed insights into emissions generated during raw material extraction, manufacturing, transportation, usage, and disposal stages. This enables organizations to identify environmental hotspots and make informed decisions regarding sustainable product development and process improvements.

A key advantage of Ecochain is its comprehensive lifecycle perspective and compliance with internationally recognized LCA standards. However, the platform requires extensive and accurate supply chain data, which may be challenging for organizations with complex supplier networks. The Higg Index, developed by the Sustainable Apparel Coalition, is specifically designed for the apparel, footwear, and textile industries. It evaluates environmental and social sustainability performance through standardized assessment modules covering energy consumption, water usage, waste management, chemical use, and greenhouse gas emissions. Its industry-specific design makes it highly relevant for fashion and textile companies.

The Higg Index also enables benchmarking and promotes sustainability collaboration among brands, manufacturers, and suppliers. However, its application is largely limited to the apparel sector and focuses on broader sustainability performance rather than dedicated carbon accounting alone. Sourcemap is a supply chain transparency and mapping platform that helps organizations visualize supplier networks and calculate emissions across multiple supply chain tiers. It is particularly effective in assessing Scope 3 emissions and improving supply chain traceability. The platform provides valuable insights into supplier-related environmental impacts, enabling organizations to identify high-emission suppliers and implement targeted sustainability initiatives. However, its effectiveness depends on supplier participation and the availability of reliable data. Organizations may also require complementary tools for detailed lifecycle assessments.

Comparative Evaluation

The three platforms differ in their primary focus areas. Ecochain emphasizes lifecycle-based environmental assessment, making it suitable for product-level carbon footprint analysis. The Higg Index offers industry-specific sustainability measurement tailored to apparel and textile manufacturing. Sourcemap focuses on supply chain transparency and supplier-level emissions tracking. Organizations should select a platform based on their industry requirements, sustainability objectives, and data availability. In some cases, combining these tools can provide a more comprehensive approach to carbon management and sustainability performance improvement.

The analysis highlights that Ecochain, the Higg Index, and Sourcemap each contribute uniquely to carbon footprint management. Ecochain provides comprehensive lifecycle assessment capabilities, the Higg Index delivers apparel-specific sustainability benchmarking, and Sourcemap enhances supply chain visibility and emissions tracking. As sustainability becomes a strategic priority, the adoption of advanced carbon accounting tools can help organizations improve environmental performance, optimize resource utilization, and comply with evolving regulatory requirements. These platforms enable businesses to identify emission hotspots, implement targeted reduction strategies, and support long-term sustainability goals. Overall, carbon footprint calculators play a vital role in advancing sustainable manufacturing by providing actionable insights that contribute to both environmental responsibility and operational efficiency.

METHODOLOGY

Purpose

The proposed Carbon Footprint Monitoring System is designed to integrate data from multiple factory sources to calculate, monitor, and visualize the real-time carbon footprint of manufacturing operations. By providing continuous insights into energy consumption, material utilization, and transportation activities, the system supports efficient resource management, enhances sustainability performance, and helps reduce greenhouse gas emissions throughout the manufacturing process (Chu & Chen, 2016; Lee & Lee, 2017).

Steps

System Architecture

The system architecture consists of four key components that work together to collect, process, store, and visualize carbon emission data. **a) Data Input** The system gathers data from various operational sources within the factory, including Manufacturing Execution Systems (MES), smart energy meters, inventory management systems, and logistics tracking platforms. These sources provide real-time information on production activities, energy usage, raw material consumption, and transportation operations, enabling comprehensive monitoring of carbon-emitting processes (Iyer & Luthra, 2017; Kinoshita & Seki, 2018). **b) Data Processing** Data collected from different sources are processed using standardized emission factors that convert operational activity data into carbon dioxide equivalent (CO₂e) emissions. This processing stage ensures accurate estimation of emissions associated with electricity consumption, material usage, manufacturing activities, and logistics operations, following established carbon accounting methodologies (Greenhouse Gas Protocol Initiative, 2004). **c) Data Storage** The processed information is stored in a centralized relational database such as PostgreSQL. The database maintains both historical and real-time records, allowing organizations to track emission trends, perform comparative analyses, and support long-term sustainability reporting and decision-making (Sorrell & MacGill, 2016). **d) Data Visualization** A real-time visualization module presents carbon footprint and energy consumption metrics through interactive dashboards. Visualization tools such as Plotly and Power BI generate dynamic charts, graphs, and performance indicators that enable managers to monitor sustainability performance, identify emission hotspots, and make data-driven decisions to improve environmental efficiency (Patel & Banerjee, 2018; Nakashima & Harada, 2019).

Data Sources

The Carbon Footprint Monitoring System gathers information from multiple operational sources to ensure comprehensive and accurate emission assessment across the manufacturing facility. In **Production Data**, production-related information is collected through Manufacturing Execution Systems (MES), which monitor machine operating hours, idle periods, production volumes, and process efficiency. These systems provide valuable insights into manufacturing activities and their associated energy consumption, enabling precise tracking of production-related emissions (Kinoshita & Seki, 2018). In **Energy Data**, real-time energy consumption data are obtained through smart meters installed across the facility. These devices continuously monitor electricity and fuel usage, providing accurate information required for estimating carbon emissions generated from energy-intensive operations (Sorrell & MacGill, 2016; Verma & Khanna, 2015). In **Material Data**, inventory management systems record the quantity and type of raw materials utilized during production, including fabrics, dyes, chemicals, and other inputs. This information supports the calculation of emissions associated with material sourcing and consumption throughout the manufacturing process (Raj & Gupta, 2016). In **Logistics Data**, transportation-related information is collected from logistics management systems, which track shipment distances, transportation routes, vehicle types, and modes of transport. These data facilitate the estimation of emissions arising from inbound and outbound logistics activities (Zhang & Wang, 2016).

Emission Factor Calculations

The system calculates carbon emissions by applying standardized emission factors to activity data collected from various operational sources. Emission factors represent the amount of greenhouse gas emissions generated per unit of activity, such as energy consumed, material used, or distance travelled.

The carbon emissions are calculated using the following equation:

$$\text{Carbon Emissions (CO}_2\text{e)} = \sum (\text{Activity Data} \times \text{Emission Factor}) \quad \text{Carbon Emissions (CO}_2\text{e)} = \sum (\text{Activity Data} \times \text{Emission Factor})$$

Where:

- **Activity Data** refers to measurable operational inputs such as electricity consumption (kWh), material usage (kg), or transportation distance (km).
- **Emission Factor** refers to the standardized coefficient that converts each unit of activity into its corresponding carbon dioxide equivalent (CO₂e) emissions.

For instance, emissions from electricity consumption are determined by multiplying the total electricity used (kWh) by the applicable regional electricity emission factor (kg CO₂e/kWh). Likewise, emissions resulting from material consumption are estimated by multiplying the quantity of each material used (e.g., cotton, polyester, dyes, or chemicals) by its respective emission factor. The same approach is applied to transportation activities, where the distance traveled is multiplied by the emission factor corresponding to the mode of transport used (Iyer & Luthra, 2017). This methodology ensures a consistent and scientifically validated approach to quantifying carbon emissions across production, energy, material, and logistics operations.

Implementation

The successful implementation of the proposed Carbon Footprint Monitoring and Visualization System requires the integration of several technologies and software tools that facilitate real-time data collection, processing, storage, and visualization. These technologies work collectively to ensure accurate monitoring of carbon emissions across manufacturing operations.

Technologies and Tools

a) Application Programming Interfaces (APIs)

Application Programming Interfaces (APIs) play a critical role in enabling seamless communication between the system and various data sources, including Manufacturing Execution Systems (MES), smart meters, inventory management systems, and logistics tracking platforms. APIs facilitate automated and real-time data acquisition, ensuring continuous monitoring and timely updates of operational and environmental performance indicators (Chu & Chen, 2016; Lee & Lee, 2017).

b) Programming Languages and Frameworks

Python Python serves as the primary programming language for data processing and analytics due to its flexibility, scalability, and extensive ecosystem of analytical libraries. Libraries such as Pandas and NumPy are employed for data cleaning, transformation, statistical analysis, and carbon emission calculations. These tools enable efficient handling of large datasets generated from manufacturing operations (Sorrell & MacGill, 2016).

PostgreSQL PostgreSQL is utilized as the central relational database management system for storing and managing processed data. The database supports efficient querying, secure storage, and real-time access to historical and current emission records, thereby facilitating comprehensive reporting and trend analysis (Greenhouse Gas Protocol Initiative, 2004).

Plotly and Power BI Plotly and Power BI are used to develop interactive dashboards that visualize carbon emissions, energy consumption patterns, production performance, and sustainability indicators. These visualization tools provide real-time insights that support decision-making and enable stakeholders to monitor environmental performance effectively (Patel & Banerjee, 2018).

Key Functional Processes

a) Carbon Emission Calculation

The system processes energy consumption data and applies standardized emission factors to estimate carbon dioxide equivalent (CO₂e) emissions. Automated calculation modules continuously analyze operational data to generate real-time emission values.

Example Python Function for Emission Calculation

```
import pandas as pd

def calculate_emissions(energy_data, emission_factor):

    emissions = energy_data['energy_kWh'] * emission_factor

    return emissions

energy_data = pd.DataFrame({

    'energy_kWh': [1000, 1500, 1200]

})

emission_factor = 0.233

energy_emissions = calculate_emissions(

    energy_data,

    emission_factor

)
```

The above function calculates emissions by multiplying electricity consumption values by the relevant emission factor expressed in kilograms of CO₂ equivalent per kilowatt-hour.

b) Database Management

Processed emissions data are stored in a PostgreSQL database for future retrieval, analysis, and reporting. The database serves as a centralized repository that supports real-time monitoring and long-term sustainability assessments.

Example PostgreSQL Database Interaction

```
import psycopg2

conn = psycopg2.connect(

    dbname='carbon_db',

    user='user',

    password='password',

    host='localhost'

)

cursor = conn.cursor()

cursor.execute(

    "INSERT INTO emissions (category, value) VALUES (%s, %s)",
```

('energy', 500)

)

```
conn.commit()
```

```
cursor.close()
```

```
conn.close()
```

This example demonstrates how calculated emission values can be securely stored in the database for subsequent analysis and visualization.

c) Data Visualization

The visualization component converts processed emission data into intuitive charts and dashboards that facilitate rapid interpretation and decision-making.

Example Plotly Visualization

```
import pandas as pd
```

```
import plotly.express as px
```

```
emissions_data = pd.DataFrame({
```

```
    'category': ['energy', 'material', 'transport'],
```

```
    'emissions': [500, 300, 200]
```

```
})
```

```
fig = px.bar(
```

```
    emissions_data,
```

```
    x='category',
```

```
    y='emissions',
```

```
    title='Real-Time Carbon Emissions'
```

```
)
```

```
fig.show()
```

The generated dashboard provides a graphical representation of emissions across different operational categories, enabling managers to identify emission hotspots and prioritize improvement initiatives.

Key Performance Indicators (KPIs)

To evaluate environmental and operational performance, the system continuously monitors a set of key performance indicators. Energy Consumption measures the amount of electricity and fuel consumed during manufacturing operations. Monitoring energy consumption helps identify opportunities for energy conservation and process optimization (Zhang & Wang, 2016). Carbon Emission Tracks total greenhouse gas emissions generated from production activities, material usage, and transportation processes. This KPI serves as the

primary indicator of environmental performance and sustainability progress (Raj & Gupta, 2016). Production Efficiency assesses the effectiveness of manufacturing processes by analyzing production output relative to resource consumption. Improvements in production efficiency often contribute to lower energy usage and reduced emissions (Iyer & Luthra, 2017). Cost Savings evaluates financial benefits achieved through energy conservation, process optimization, and emission reduction initiatives. Monitoring cost savings helps demonstrate the economic value of sustainability investments (Sorrell & MacGill, 2016). Collectively, these KPIs provide a comprehensive framework for assessing the environmental, operational, and economic performance of manufacturing facilities, thereby supporting continuous improvement and sustainable production practices.

CONCLUSION

The proposed real-time Carbon Footprint Monitoring and Visualization System provides an integrated and data-driven approach to enhancing sustainability and operational efficiency within manufacturing environments. By consolidating data from diverse sources, including Manufacturing Execution Systems (MES), smart meters, inventory management platforms, and logistics tracking systems, the framework enables comprehensive monitoring of energy consumption, material utilization, and transportation-related emissions. This holistic perspective allows manufacturers to accurately assess their environmental impact, identify emission-intensive activities, and implement corrective measures to improve sustainability performance (Chu & Chen, 2016; Lee & Lee, 2017).

The methodology presented in this study employs standardized emission factors to quantify greenhouse gas emissions and utilizes advanced visualization tools such as Plotly and Power BI to deliver real-time insights through interactive dashboards. These dashboards support informed decision-making by providing clear visibility into emission trends, resource consumption patterns, and operational inefficiencies. Consequently, managers can develop targeted strategies for reducing emissions, optimizing resource utilization, and achieving cost efficiencies across manufacturing operations (Sorrell & MacGill, 2016; Patel & Banerjee, 2018).

Furthermore, the integration of production, energy, material, and logistics data ensures a comprehensive assessment of carbon emissions throughout the manufacturing value chain. Such an approach enhances the accuracy of emissions accounting and strengthens the effectiveness of sustainability initiatives by addressing environmental impacts at every stage of the production process (Raj & Gupta, 2016; Zhang & Wang, 2016).

The implementation of this system offers substantial benefits beyond environmental compliance. In addition to supporting carbon reduction and energy conservation goals, it contributes to improved operational efficiency, reduced production costs, and enhanced resource management. As industries increasingly adopt sustainable manufacturing practices, real-time carbon monitoring systems will become essential tools for meeting regulatory requirements, achieving corporate sustainability objectives, and responding to growing stakeholder and consumer expectations for environmentally responsible operations (Iyer & Luthra, 2017; Greenhouse Gas Protocol Initiative, 2004).

In summary, the proposed system represents a significant advancement toward sustainable manufacturing by combining real-time data integration, carbon accounting, and visualization technologies. By enabling proactive emissions management and continuous performance improvement, the system delivers both environmental and economic value, supporting the transition toward greener, more resilient, and sustainable industrial operations.

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