

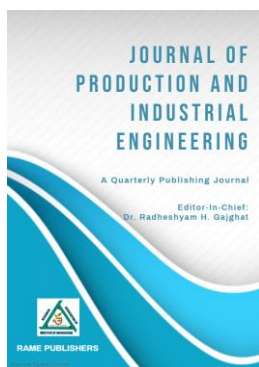
A Review on Sustainable Manufacturing Practices for Energy Efficiency and Waste Reduction

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Abstract: Sustainable manufacturing has emerged as a critical approach to address the growing concerns of energy consumption, environmental degradation, and resource depletion in modern industrial systems. It focuses on minimizing environmental impact while maintaining productivity and economic viability. This review paper aims to provide a comprehensive analysis of sustainable manufacturing practices with a specific emphasis on improving energy efficiency and reducing material waste. The study examines key strategies such as energy-efficient process design, optimization of manufacturing operations, waste minimization techniques, recycling and reuse practices, and the adoption of cleaner production technologies. A systematic review of recent literature has been conducted to evaluate the application of these practices across various manufacturing sectors. The findings indicate that the integration of advanced technologies, including smart monitoring systems, data-driven optimization, and renewable energy sources, significantly enhances energy efficiency and reduces waste generation. Additionally, approaches such as lean manufacturing, life cycle assessment, and circular economy principles play a vital role in achieving sustainable production. However, challenges such as high implementation costs, lack of awareness, and limited technological adoption remain barriers to widespread implementation. This paper contributes by synthesizing existing research, identifying key trends, and highlighting research gaps in sustainable manufacturing. The insights provided can assist researchers and industry practitioners in developing efficient, cost-effective, and environmentally responsible manufacturing systems. The study also emphasizes the need for integrated and scalable solutions to achieve long-term sustainability in manufacturing industries.

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1. Introduction

Sustainable manufacturing has become a critical priority for modern industries due to increasing concerns over energy consumption, environmental degradation, and resource scarcity. The manufacturing sector is one of the largest consumers of energy and a significant contributor to greenhouse gas emissions and industrial waste generation. As global demand for products continues to rise, there is an urgent need to adopt manufacturing practices that not only improve productivity but also minimize environmental impact. The concept of sustainable manufacturing focuses on achieving a balance between economic growth, environmental protection, and social well-being, thereby ensuring long-term industrial sustainability. According to Siddique (2020) [1], the integration of environmental and economic objectives is essential for achieving sustainable development in industrial systems.

Energy efficiency and waste reduction are two of the most important pillars of sustainable manufacturing. Energy consumption in manufacturing processes accounts for a substantial portion of global energy use, particularly in energy-intensive industries such as metal processing, chemical production, and machining operations. Inefficient energy usage not only increases operational costs but also contributes to environmental pollution and climate change. Similarly, waste generation in manufacturing processes, including material waste, scrap, and emissions, poses serious environmental and economic challenges. Renna & Materi (2021) [2] highlighted that improving energy efficiency and reducing waste can significantly lower the environmental footprint of manufacturing systems while enhancing productivity.

In recent years, various sustainable manufacturing practices have been developed to address these challenges. These include energy-efficient process design, lean manufacturing principles, recycling and reuse strategies, and cleaner production techniques. The integration of advanced technologies such as IoT, artificial intelligence, and smart monitoring systems has further enhanced the capability of manufacturing systems to optimize energy usage and minimize waste generation. These technologies enable real-time monitoring, predictive analysis, and intelligent decision-making, leading to more efficient and sustainable operations. According to Jawahir and Cai et al. (2019) [3], the adoption of sustainable practices in manufacturing not only improves environmental performance but also provides economic benefits through cost reduction and resource optimization.

Despite the growing importance of sustainable manufacturing, several challenges hinder its widespread adoption. High initial investment costs, lack of awareness, technological limitations, and insufficient policy support are some of the major barriers faced by industries. Additionally, the implementation of sustainable practices requires a comprehensive understanding of energy consumption patterns and waste generation mechanisms within manufacturing systems.

The primary objective of this review paper is to analyze various sustainable manufacturing practices with a focus on improving energy efficiency and reducing waste. The study aims to examine the concept of sustainable manufacturing, evaluate energy consumption in manufacturing systems, and review key strategies such as energy efficiency improvement, waste reduction, recycling, cleaner production, and the role of advanced technologies. By synthesizing existing literature, this paper provides valuable insights for researchers and industry practitioners to develop efficient, cost-effective, and environmentally sustainable manufacturing systems.

2. Concept of Sustainable Manufacturing

Sustainable manufacturing refers to the creation of manufactured products through economically sound processes that minimize negative environmental impacts while conserving energy and natural resources. It also emphasizes the safety and well-being of employees, communities, and consumers. This concept has gained significant importance in recent years as industries strive to balance productivity with environmental responsibility. According to Meng et al. (2018) [4], sustainable development in industrial systems is achieved by integrating economic performance with environmental and social considerations.

A key foundation of sustainable manufacturing is the Triple Bottom Line (TBL) approach, which focuses on three dimensions: economic viability, environmental protection, and social responsibility. The economic aspect ensures profitability and efficient resource utilization, the environmental aspect emphasizes reduction in emissions, waste, and energy consumption, while the social aspect focuses on worker safety, health, and community well-being. Geng & Evans (2022) [5] highlighted that manufacturing systems must be designed to optimize all three dimensions simultaneously to achieve long-term sustainability.

Another important concept in sustainable manufacturing is Life Cycle Thinking (LCT), which considers the environmental impact of a product throughout its entire life cycle—from raw material extraction and processing to manufacturing, usage, and end-of-life disposal or recycling. This approach enables manufacturers to identify opportunities for reducing energy consumption and waste at each stage of the product life cycle. According to Peter & Mbohwa (2019) [6], life cycle-based approaches are essential for evaluating the overall sustainability of manufacturing processes and products.

Sustainable manufacturing also emphasizes resource efficiency and the reduction of environmental impact through strategies such as cleaner production, eco-design, and circular economy principles. Cleaner production focuses on minimizing waste and emissions at the source, while eco-design aims to develop products that are environmentally friendly throughout their life cycle. Circular economy principles promote the reuse, recycling, and recovery of materials to reduce dependence on virgin resources. These approaches collectively contribute to reducing the environmental footprint of manufacturing systems.

Furthermore, the integration of sustainability into manufacturing systems requires a shift from traditional linear production models to more holistic and closed-loop systems. This transition involves the adoption of advanced

technologies, improved process design, and effective resource management strategies. As highlighted by Abdul-Rashid et al. (2017) [7], sustainable manufacturing not only reduces environmental impact but also enhances competitiveness by improving efficiency and reducing costs.

In summary, sustainable manufacturing is a comprehensive approach that integrates economic, environmental, and social considerations into manufacturing processes. The adoption of concepts such as the Triple Bottom Line and Life Cycle Thinking enables industries to achieve efficient resource utilization, reduced environmental impact, and long-term sustainability. These principles form the foundation for implementing effective strategies for energy efficiency and waste reduction in modern manufacturing systems.

3. Energy Consumption in Manufacturing Systems

Energy consumption is a critical aspect of manufacturing systems, significantly influencing both operational costs and environmental impact. Manufacturing industries are among the largest consumers of energy globally, accounting for a substantial share of total industrial energy use. Energy is required at various stages of manufacturing, including raw material processing, machining, heat treatment, transportation, and auxiliary operations such as lighting and ventilation. According to Ghazilla et al. (2015) [8], inefficient energy utilization in manufacturing processes not only increases production costs but also contributes to greenhouse gas emissions and environmental degradation.

The sources of energy consumption in manufacturing systems can be broadly categorized into direct and indirect energy use. Direct energy consumption includes energy used in core production processes such as machining, casting, forging, and welding. These processes often require high power input and are considered energy-intensive operations. Indirect energy consumption, on the other hand, includes energy used for supporting activities such as material handling, compressed air systems, heating, ventilation, and air conditioning (HVAC), and lighting. Dincer & Acar (2015) [9] highlighted that auxiliary systems can account for a significant portion of total energy consumption in manufacturing facilities, often exceeding the energy used in primary production processes.

Different manufacturing processes exhibit varying levels of energy consumption depending on the nature of the operation. For example, thermal processes such as heat treatment and casting are highly energy-intensive due to the requirement of high temperatures, while machining operations consume energy based on cutting parameters and machine efficiency. Additionally, factors such as machine age, maintenance condition, process optimization, and production planning significantly influence energy consumption levels. Modern manufacturing systems are increasingly focusing on energy-efficient technologies and process optimization to reduce energy usage and improve sustainability.

The environmental impact of energy consumption in manufacturing is primarily associated with carbon emissions and resource depletion. The use of fossil fuels for energy generation leads to increased emissions of carbon dioxide and other pollutants, contributing to climate change. Therefore, improving energy efficiency and adopting renewable energy sources are essential strategies for sustainable manufacturing. According to Nižetić et al. (2019) [10], energy-efficient manufacturing practices not only reduce environmental impact but also enhance economic performance through cost savings.

To better understand energy consumption patterns, Table 1. presents a comparative overview of different manufacturing processes, their energy sources, consumption levels, and environmental impacts.

Table 1 Energy Consumption in Manufacturing Processes[11]

Process	Energy Source	Consumption Level	Environmental Impact	Remarks
Machining	Electricity	Medium	Moderate emissions	Depends on cutting parameters
Casting	Fossil fuel, electricity	High	High emissions	Thermal intensive process
Forging	Electricity, fuel	High	High emissions	Requires high force and heat
Welding	Electricity	Medium	Moderate emissions	Process-dependent
Heat Treatment	Gas, electricity	Very High	High emissions	Continuous heating required
Injection Molding	Electricity	Medium	Moderate emissions	Polymer processing
Grinding	Electricity	Medium	Moderate emissions	High precision operation

CNC Machining	Electricity	Medium to High	Moderate emissions	Machine efficiency dependent
Additive Manufacturing	Electricity	Medium	Low to moderate emissions	Material efficient
Material Handling	Electricity	Low	Low emissions	Auxiliary process
HVAC Systems	Electricity	Medium	Indirect emissions	Facility support
Lighting Systems	Electricity	Low	Low emissions	Can be optimized

4. Sustainable Manufacturing Practices

Sustainable manufacturing practices are essential for reducing energy consumption, minimizing waste generation, and improving overall resource efficiency in industrial systems. These practices focus on optimizing manufacturing operations while maintaining product quality and economic viability. With increasing environmental concerns and regulatory pressures, industries are adopting sustainable approaches to enhance competitiveness and reduce their ecological footprint. According to Carvalho et al. (2018) [12], sustainable manufacturing involves the integration of environmentally conscious strategies into process design, production planning, and resource management.

The implementation of sustainable practices in manufacturing systems encompasses a wide range of strategies, including energy efficiency improvement, waste reduction, recycling and reuse, cleaner production techniques, and the adoption of advanced technologies. These approaches aim to address both energy-related and material-related inefficiencies in manufacturing processes. For instance, energy efficiency techniques focus on optimizing machine performance and reducing unnecessary energy losses, while waste reduction strategies aim to minimize material losses through process optimization and lean manufacturing principles. Javaid et al. (2021) [13] highlighted that the combined application of these practices can significantly reduce the environmental impact of manufacturing systems.

In addition to traditional approaches, modern manufacturing systems are increasingly leveraging advanced technologies such as the Internet of Things (IoT), artificial intelligence, and data analytics to enhance sustainability. These technologies enable real-time monitoring of energy consumption, predictive maintenance, and intelligent decision-making, thereby improving efficiency and reducing waste. The integration of digital technologies with sustainable practices represents a key trend in the evolution of smart and sustainable manufacturing systems.

This section provides a detailed review of major sustainable manufacturing practices, categorized into energy efficiency improvement techniques, waste reduction strategies, recycling and reuse practices, cleaner production methods, and the role of advanced technologies. Each subsection discusses the principles, applications, advantages, and limitations of these practices in achieving energy-efficient and waste-minimized manufacturing systems.

4.1 Energy Efficiency Improvement Techniques

Energy efficiency improvement is a fundamental aspect of sustainable manufacturing, focusing on reducing energy consumption while maintaining or enhancing production output. In manufacturing systems, energy losses often occur due to inefficient machines, poor process design, and lack of real-time monitoring. Therefore, adopting energy-efficient techniques is essential for minimizing operational costs and reducing environmental impact. According to Machado et al. (2020) [14], improving energy efficiency in manufacturing processes can significantly lower energy demand and associated carbon emissions.

One of the primary approaches to improving energy efficiency is the use of energy-efficient machines and equipment. Modern machines are designed with advanced technologies such as variable frequency drives (VFDs), high-efficiency motors, and optimized control systems that reduce energy consumption during operation. Replacing outdated machinery with energy-efficient alternatives can lead to substantial energy savings. Additionally, proper maintenance of equipment ensures optimal performance and prevents energy losses due to wear and inefficiencies.

Process optimization is another key strategy for enhancing energy efficiency. By optimizing process parameters such as cutting speed, feed rate, temperature, and cycle time, manufacturers can reduce unnecessary energy consumption. Techniques such as lean manufacturing and process integration help eliminate wasteful operations and improve overall efficiency. According to Baah et al. (2021) [15] optimizing machining parameters can significantly reduce energy usage without compromising product quality.

Energy monitoring and management systems also play a crucial role in improving efficiency. The implementation of smart energy monitoring systems enables real-time tracking of energy consumption across different processes and equipment. These systems use sensors and data analytics to identify energy-intensive operations and detect inefficiencies. The integration of advanced technologies such as IoT and artificial intelligence further enhances energy management by enabling predictive analysis and automated control of energy usage.

Another important approach is the adoption of renewable energy sources such as solar, wind, and biomass in manufacturing operations. The use of renewable energy reduces dependence on fossil fuels and lowers greenhouse gas emissions. Many industries are integrating renewable energy systems into their operations to achieve sustainability goals and comply with environmental regulations.

Despite the benefits, the implementation of energy efficiency techniques faces challenges such as high initial investment costs, lack of technical expertise, and resistance to change. However, the long-term benefits in terms of cost savings and environmental impact make these techniques highly valuable for sustainable manufacturing.

In summary, energy efficiency improvement techniques are essential for reducing energy consumption and enhancing sustainability in manufacturing systems. The use of advanced machinery, process optimization, energy monitoring systems, and renewable energy sources can significantly improve efficiency and reduce environmental impact, contributing to more sustainable industrial operations.

4.2 Waste Reduction Strategies

Waste reduction is a key component of sustainable manufacturing, aimed at minimizing material losses, reducing environmental impact, and improving resource efficiency. In manufacturing systems, waste can take various forms, including scrap materials, defective products, excess inventory, energy losses, and emissions. Effective waste reduction strategies focus on eliminating inefficiencies at every stage of the production process while maintaining product quality and operational performance. According to Agyekum et al. (2022) [16], the elimination of waste is a fundamental principle of lean manufacturing and plays a crucial role in improving productivity and sustainability.

One of the most widely adopted approaches for waste reduction is lean manufacturing, which emphasizes the identification and elimination of non-value-added activities. Lean principles categorize waste into different types, such as overproduction, waiting, transportation, overprocessing, inventory, motion, and defects. By systematically addressing these wastes, manufacturers can streamline operations and reduce material and time losses. Lean tools such as value stream mapping, 5S, and continuous improvement (Kaizen) are commonly used to identify inefficiencies and implement corrective actions.

Material optimization is another important strategy for reducing waste in manufacturing systems. This involves efficient utilization of raw materials through improved design, process control, and cutting techniques. For example, optimizing cutting patterns in machining or sheet metal operations can significantly reduce scrap generation. Additionally, the use of advanced manufacturing techniques such as additive manufacturing allows for precise material usage, minimizing excess waste. Ghavam et al. (2021) [17] highlighted that material efficiency is a critical factor in reducing the environmental footprint of manufacturing processes.

Process redesign also plays a significant role in waste reduction. By reengineering production processes, manufacturers can eliminate unnecessary steps, reduce defects, and improve overall efficiency. The implementation of quality control systems and process standardization helps in minimizing variations and reducing the likelihood of defects. Furthermore, the adoption of automation and advanced control systems enhances precision and consistency, leading to reduced waste generation.

In addition to these strategies, waste segregation and proper management are essential for effective waste reduction. Separating recyclable and non-recyclable materials enables better utilization of resources and reduces the burden on disposal systems. The integration of waste management practices with production processes ensures that waste is minimized at the source rather than treated as an afterthought.

Despite its importance, waste reduction faces challenges such as lack of awareness, resistance to process changes, and initial implementation costs. However, the long-term benefits in terms of cost savings, improved efficiency, and environmental sustainability make waste reduction strategies indispensable for modern manufacturing systems.

In summary, waste reduction strategies such as lean manufacturing, material optimization, process redesign, and effective waste management play a vital role in achieving sustainable manufacturing. These approaches not only reduce environmental impact but also enhance productivity and resource efficiency, contributing to overall industrial sustainability.

4.3 Recycling and Reuse Practices

Recycling and reuse practices are essential components of sustainable manufacturing, aimed at minimizing waste generation and promoting efficient utilization of resources. These practices focus on extending the lifecycle of materials by reintroducing them into the production cycle, thereby reducing the need for virgin raw materials and lowering environmental impact. In manufacturing systems, recycling involves processing waste materials into reusable forms, while reuse refers to the direct use of materials or components without significant reprocessing. According to Jamwal et al. (2021) [18], recycling and reuse strategies are fundamental to achieving resource efficiency and reducing the ecological footprint of industrial activities.

One of the key approaches in this area is the implementation of closed-loop manufacturing systems, where waste materials generated during production are collected, processed, and reintegrated into the manufacturing process. This approach significantly reduces material losses and enhances sustainability by minimizing dependence on external resources. For example, metal scrap generated in machining operations can be recycled and reused in casting or forming processes. Similarly, plastic waste from manufacturing can be reprocessed and utilized in new product development.

The concept of the circular economy plays a vital role in promoting recycling and reuse practices. Unlike traditional linear models of production (take–make–dispose), the circular economy emphasizes the continuous use of resources through recycling, remanufacturing, and refurbishment. This approach not only reduces waste but also creates economic value by extending the usability of materials. According to Peng et al. (2018) [19], the adoption of circular economy principles in manufacturing systems enhances sustainability by improving resource efficiency and reducing environmental impact.

Another important aspect of recycling and reuse is remanufacturing, where used products or components are restored to their original or improved condition. Remanufacturing extends product life, reduces material consumption, and lowers energy requirements compared to producing new components. This practice is widely used in industries such as automotive and electronics, where components can be refurbished and reused effectively.

Despite the advantages, recycling and reuse practices face several challenges. These include the need for efficient collection and segregation systems, additional processing costs, and potential degradation of material properties during recycling. Furthermore, the lack of standardized processes and infrastructure can hinder the effective implementation of these practices. However, advancements in recycling technologies and increasing awareness of sustainability are driving the adoption of these strategies in modern manufacturing systems.

In summary, recycling and reuse practices are critical for reducing waste and promoting sustainable resource utilization in manufacturing. The implementation of closed-loop systems, circular economy principles, and remanufacturing strategies significantly contributes to environmental sustainability and cost efficiency. These practices play a vital role in transforming manufacturing systems towards more sustainable and resource-efficient operations.

4.4 Cleaner Production Techniques

Cleaner production techniques are a proactive approach to sustainable manufacturing that focus on minimizing environmental impact by reducing waste and emissions at the source rather than treating them after generation. These techniques emphasize the efficient use of resources, including energy, water, and raw materials, while maintaining product quality and economic viability. According to United Nations Environment Programme (UNEP) [20], cleaner production is defined as the continuous application of integrated preventive environmental strategies to processes, products, and services to increase efficiency and reduce risks to humans and the environment.

One of the primary strategies in cleaner production is process optimization, which involves modifying manufacturing processes to reduce resource consumption and waste generation. This includes improving process parameters, adopting energy-efficient technologies, and eliminating non-value-added activities. For example, optimizing cutting conditions in machining or improving thermal efficiency in heat treatment processes can significantly reduce energy usage and emissions. Arshad et al. (2017) [21] highlighted that process-level improvements are among the most effective ways to achieve sustainability in manufacturing systems.

Another important aspect of cleaner production is the use of environmentally friendly or “green” materials. Substituting hazardous or non-renewable materials with eco-friendly alternatives reduces environmental risks and improves sustainability. For instance, the use of biodegradable materials, low-toxicity chemicals, and recyclable components contributes to reducing pollution and enhancing product lifecycle sustainability. Additionally, cleaner production promotes the reduction of emissions such as greenhouse gases, particulate matter, and wastewater through improved process control and pollution prevention techniques.

Energy efficiency is also closely linked to cleaner production. The adoption of cleaner energy sources and efficient energy utilization practices helps in reducing carbon emissions and environmental impact. Techniques such as waste heat recovery, energy recycling, and the use of renewable energy sources are commonly implemented to improve energy performance. Furthermore, cleaner production encourages the integration of environmental management systems (EMS) to monitor and control environmental performance in manufacturing operations.

Despite its benefits, the implementation of cleaner production techniques faces challenges such as high initial investment, lack of technical knowledge, and resistance to process changes. Small and medium enterprises, in particular, may face difficulties in adopting these techniques due to limited resources. However, the long-term benefits in terms of cost savings, regulatory compliance, and environmental protection make cleaner production an essential strategy for sustainable manufacturing.

In summary, cleaner production techniques provide an effective approach for reducing waste, emissions, and resource consumption in manufacturing systems. By focusing on prevention rather than treatment, these techniques enhance both environmental and economic performance, contributing significantly to sustainable industrial development.

4.5 Role of Advanced Technologies

Advanced technologies play a pivotal role in enabling sustainable manufacturing by improving energy efficiency, minimizing waste, and enhancing overall process optimization. The integration of digital technologies with manufacturing systems has led to the development of smart and intelligent production environments capable of real-time monitoring, analysis, and decision-making. Technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and cyber-physical systems are transforming traditional manufacturing into more efficient and sustainable systems. According to Schulze et al. (2016) [22], the adoption of smart manufacturing technologies significantly enhances operational efficiency and sustainability.

The Internet of Things (IoT) is widely used in manufacturing systems for real-time monitoring of energy consumption and process parameters. IoT-enabled sensors collect data from machines and production lines, which can be analyzed to identify inefficiencies and optimize performance. This enables manufacturers to monitor energy usage, detect anomalies, and implement corrective actions in real time. Similarly, artificial intelligence and machine learning techniques are used for predictive analysis and optimization of manufacturing processes. These technologies can predict equipment failures, optimize process parameters, and reduce energy consumption and waste generation.

Big data analytics is another critical technology that supports sustainable manufacturing by analyzing large volumes of data generated from manufacturing systems. By identifying patterns and trends, data analytics helps in improving decision-making and optimizing resource utilization. For instance, analyzing production data can help identify energy-intensive processes and suggest improvements to reduce consumption. Additionally, advanced simulation and modeling tools, such as digital twins, enable virtual representation of manufacturing systems, allowing engineers to evaluate and optimize processes before implementation.

Automation and robotics also contribute to sustainability by improving precision, reducing material waste, and enhancing productivity. Automated systems ensure consistent quality and minimize defects, which in turn reduces rework and scrap. Furthermore, advanced technologies facilitate the integration of renewable energy systems and energy management platforms, enabling more efficient use of energy resources.

Despite the numerous advantages, the adoption of advanced technologies in manufacturing faces challenges such as high implementation costs, complexity, and the need for skilled workforce. Data security and system integration are also critical concerns that need to be addressed. However, the benefits of improved efficiency, reduced environmental impact, and enhanced competitiveness make these technologies essential for achieving sustainable manufacturing.

In summary, advanced technologies play a crucial role in transforming manufacturing systems into intelligent, efficient, and sustainable operations. Their ability to enable real-time monitoring, predictive analysis, and process optimization significantly contributes to energy efficiency and waste reduction in modern manufacturing systems.

5. Comparative Analysis of Sustainable Practices

A comparative evaluation of sustainable manufacturing practices is essential to understand their effectiveness in improving energy efficiency and reducing waste across different industrial contexts. The practices discussed in Section 5 energy efficiency improvement, waste reduction strategies, recycling and reuse, cleaner production, and advanced technologies offer distinct benefits and limitations depending on the nature of manufacturing processes, resource

availability, and technological maturity. This section presents a structured comparison of these practices based on key performance indicators such as energy savings, waste minimization, implementation complexity, and economic feasibility.

Energy efficiency improvement techniques primarily focus on reducing energy consumption through process optimization, efficient machinery, and energy monitoring systems. These practices provide immediate economic benefits by lowering operational costs and reducing emissions. However, their effectiveness depends on the level of technological adoption and initial investment. Waste reduction strategies, particularly lean manufacturing, emphasize eliminating non-value-added activities and optimizing material usage. These approaches are relatively easy to implement and offer quick improvements in productivity and resource efficiency.

Recycling and reuse practices contribute significantly to resource conservation by reducing dependence on raw materials and minimizing waste generation. These practices align with circular economy principles and are highly effective in industries dealing with recyclable materials such as metals and plastics. However, they may require additional processing infrastructure and may be limited by material degradation. Cleaner production techniques focus on preventing waste and emissions at the source, offering long-term environmental benefits. These methods often involve process redesign and the use of eco-friendly materials, which may require higher initial investment but result in sustainable outcomes.

The role of advanced technologies is particularly significant in modern manufacturing systems. Technologies such as IoT, AI, and data analytics enable real-time monitoring and intelligent decision-making, enhancing the effectiveness of all other sustainable practices. While these technologies offer high potential for optimization and automation, their implementation involves higher costs and requires technical expertise.

Table 2. Comparison of Sustainable Manufacturing Practices [23]

Practice	Energy Efficiency	Waste Reduction	Implementation Complexity	Cost	Key Benefits	Limitations
Energy Efficiency Techniques	High	Moderate	Medium	High	Reduced energy cost	Initial investment
Waste Reduction (Lean)	Moderate	High	Low	Low	Improved productivity	Requires cultural change
Recycling & Reuse	Moderate	High	Medium	Medium	Resource conservation	Material degradation
Cleaner Production	High	High	Medium to High	High	Reduced emissions	Process redesign needed
Advanced Technologies	Very High	High	High	Very High	Smart optimization	Skilled workforce needed
Process Optimization	High	Moderate	Medium	Medium	Improved efficiency	Requires analysis
Renewable Energy Use	Very High	Low	High	High	Reduced emissions	Infrastructure needed
Material Optimization	Moderate	High	Medium	Medium	Reduced scrap	Design dependency
Automation & Robotics	High	High	High	High	Precision, reduced waste	High cost
Circular Economy	Moderate	Very High	High	Medium	Sustainable resource use	Complex implementation

Table 3. Literature-Based Comparative Analysis

Author(s)	Practice	Focus Area	Key Findings
Kamble et al., 2020 [24]	Energy Efficiency	Machining	Reduced energy consumption
Mhatre et al., 2021 [25]	Lean Manufacturing	Waste reduction	Improved productivity
Ford & Despeisse, 2016 [26]	Recycling	Resource efficiency	Reduced material usage
Megía et al., 2021 [27]	Sustainable Manufacturing	Overall systems	Integrated approach needed
Mehrpuoya et al., 2019 [28]	Cleaner Production	Emission control	Preventive strategy effective
Zhao et al., 2020 [29]	Smart Manufacturing	IoT/AI	Improved efficiency
Golewski, 2020 [30]	Process Optimization	Machining	Energy savings possible
Worrell et al., 2018 [31]	Circular Economy	Sustainability	Resource loop efficiency
Pan et al., 2015 [32]	Energy Use	Industrial systems	High auxiliary consumption
Thanki et al., 2016 [33]	Advanced Tech	Smart systems	Real-time optimization

Despite the wide range of sustainable manufacturing practices available, several research gaps still exist. Most studies focus on individual practices rather than integrated approaches that combine multiple strategies for maximum impact. There is limited research on the real-time implementation of sustainable practices using advanced technologies, particularly in small and medium enterprises. Additionally, the economic feasibility and scalability of these practices are not sufficiently explored in diverse industrial contexts. The integration of renewable energy with manufacturing processes and the development of intelligent systems for dynamic optimization remain underexplored areas. Future research should focus on developing holistic, data-driven, and cost-effective sustainable manufacturing frameworks that can be widely adopted across different industries[34].

6. Conclusion

Through this research, it was clarified how to use the Analytic Hierarchical Process (AHP) to determine the weights of the relative importance of criteria and alternatives on the one hand, and the application of a mathematical model (ILP) that helped in the process of determining and diagnosing the impact of those alternatives on the company's products without resorting to methods of estimation and estimation on the other hand. The model was very effective after being tested in the company under study, thus knowing the priorities of those alternatives for the decision maker in order to choose the optimal decision and achieve the maximum benefit. This model can also be applied in many other fields.

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