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"A REVIEW ON INTEGRATING ENVIRONMENTAL, SOCIAL, AND ECONOMIC DIMENSIONS FOR SUSTAINABLE MANUFACTURING ACROSS PRODUCT LIFE CYCLE"

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ABSTRACT

Sustainability in manufacturing has evolved from reducing material and energy consumption towards a holistic approach that encompasses environmental quality, social equity, and economic prosperity, often referred to as the triple bottom line. This study presents an extensive literature synthesis on sustainability factors within manufacturing, focusing on their integration across the entire product life cycle—from raw material acquisition to disposal or remanufacturing. The environmental dimension addresses resource optimization, emissions reduction, waste minimization, and energy efficiency. The social dimension emphasizes occupational health and safety, equitable working conditions, stakeholder engagement, and community development. The economic dimension focuses on life cycle costing, operational efficiency, market presence, and long-term value creation. Various methodologies, including Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA), and Life Cycle Costing (LCC), are reviewed to evaluate sustainability performance quantitatively and qualitatively. The findings highlight that while environmental and economic factors have been widely explored, the social dimension remains comparatively underrepresented in both research and industrial application. The integration of all three dimensions is essential for achieving genuine sustainable manufacturing, enabling industries to comply with regulatory requirements, enhance competitiveness, and contribute to long-term socio-environmental well-being. This paper provides a structured framework for aligning sustainability principles with manufacturing strategies, offering insights for policymakers, practitioners, and researchers to drive systemic improvements in industrial sustainability.

Key Words: *Sustainable manufacturing, Triple bottom line; Life Cycle Assessment (LCA); Social sustainability; Life Cycle Costing (LCC); Environmental performance; Product life cycle.*

I. INTRODUCTION

Initially, companies used to implement activities related to sustainability to decrease material and energy consumption throughout manufacturing. From the beginning, manufacturing organizations shifted from achieving manufacturing sustainability towards the sustainability of products (Seliger *et al*., 2008). The concept of sustainability and sustainable development describes the development of society considering the financial concern using respect for the environment and interaction among the processes (Galvic & Lukman, 2007). It has now become an important factor for companies. Due to this, companies have started integrating sustainability into their business and developmental activities (Haaneas *et al*., 2011; Dyllick & Hockerts, 2002; Jones, 2003; Bielak *et al*., 2007; Bonini *et al*., 2006). Sustainability from a business perspective is defined as the "Triple Bottom line" (Harris *et al*., 2001) (Dyllick & Hockerts, 2002) (Pava, 2007) (Goel, 2010). It is a sustainability construct that includes three significant dimensions: environmental quality,

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social equity, and economic prosperity (Elkington & Rowlands, 1999). Due to sustainability, companies can gain a competitive advantage (Campbel, 2007). In general, very few known industries are there as huge, varied, and dominant compared to the automotive industry. Specifically, it is the largest manufacturing sector worldwide, covering different management practices, various forms of organizational levels, and mainly how it captures the environmental pressures during production (Orsato & Wells, 2007). Companies aim to satisfy user needs by attaining the principle, thereby reducing the environmental and communal influence of products to provide economic value to the company considering the complete life cycle of a product, which is the main aim of sustainable development (Hseuh, 2011). In line with sustainability principles, Gupta *et al*. in 2018 adapted from Barbie in 2014, integrating sustainability in manufacturing lead to sustainable manufacturing by simultaneously considering environmental, social, and economic aspects. These days' manufacturers are becoming more dynamic in improving environmental performance by reducing the cost of materials and energy, which has increased drastically over the period due to the decrease infinite resources (Despeisse *et al*., 2012). Regarding sustainability issues, organizations are concerned with manufacturing products, considering the complete manufacturing stage (Ghadimi *et al*., 2012). Companies aim to satisfy user needs by attaining the principle, thereby reducing the environmental and communal influence of products with the motive of providing economic value to the company considering the complete life cycle of a product which is the main aim of sustainable development (Hseuh, 2011). Sustainability from the total product life cycle perspective in manufacturing was conducted by Jawahir *et al.* in 2006, wherein the design stage plays a crucial role in leaving the manufacturing and user stage of the product life cycle. Each product has a life cycle. Nowadays, manufacturers are enhancing themselves by managing the benefits and inheriting those life cycles (Sendler, 2009). Significantly little research was conducted wherein sustainability, and product life cycle concepts are considered the area of study with few exceptions (e.g. sustainable consumption, green manufacturing, and sustainable manufacturing) (Maxwell & Vander Vorst, 2003). Warther and Rebitzer in 2010 focused on addressing the complete product life cycle following the relative sustainability of a product. Sundin and Bras, in 2005, explained the product life cycle starting from raw material acquisition, parts manufacturing, product assembly/ remanufacturing, product use, reuse, recycling and final disposal. The essential environmental factors considered during the study (covering manufacturing and user end) were raw material usage, energy consumption and water consumption, and air emissions. According to Jawahir *et al.* in 2006, manufacturing techniques must be developed to address the product life cycle issues simultaneously. Reduction of material use/weight reduction, energy consumption, hazardous wastes, energy efficiency, and minimum toxic emissions at all levels of the product life cycle are some of the main drivers from an environmental perspective to be paid attention to. There is a positive relationship between sustainability and manufacturing (Song & Moon, 2016). The environment, social aspects, energy, and economic aspects are among the most important factors that need to minister while manufacturing a product during the product life cycle (Linke & Dornfeld, 2012). The research conducted so far in sustainable production considers only the economic aspect of the supply chain, ignoring the excessive use of energy, material required, water consumption, hazardous waste etc., from a product manufacturing point of view (Amrina & Yusof, 2011). The social dimension of sustainability consists of s*ocial responsibility, health and safety* issues *and reporting concerns to the respective business stakeholders.* Social sustainability refers to safety, indistinguishable human development, and promoting humanity and the environment. Authors have conducted much research on product sustainability's environmental and economic dimensions. Less has been contributed towards the social dimension of sustainability and has focused on the social impact caused by the manufacturing industries on the stakeholders either directly or indirectly (Sutherland *et al*., 2016). When manufacturing a product is considered, deciding the cost is the most prominent factor. Still, environmental performance must be taken care of during the complete life cycle. The product's use and end-of-the-life phase costs (EOL) are considered (Witik *et al.,* 2011). Due to stringent environmental regulations imposed by the government, manufacturing companies face many issues in operating both green and economical businesses. To meet this challenge remanufacturing, reusing, and recycling are gaining interest in sustainability (Kwak & Kim, 2015). The foremost aim of the *manufacturing industry is to manufacture products that gratify the client's* demand. Hence, it becomes important for the manufacturing organization to incorporate sustainability into their production processes and policies. Suppose the manufacturing company's objective is to encompass the sustainability concept comprehensively. In that case, the organization has to consider all the essential assets for designing, manufacturing and delivering the products to the customers (Sangwan *et al*., 2018).

Numerous methodologies exist to conduct the performance and assess the sustainability factors of industries (Ramachandran, 2000) and product assessment levels (He *et al*., 2019). There are tools in the Literature that address the

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environmental dimension of sustainability along the product life cycle as life cycle assessment (LCA). The economic dimension is life cycle costing (LCC). The social dimension is the social life cycle assessment. It is a procedural framework that helps measure and calculates the environmental impact considering the life cycle (Rebitzer *et al*., 2004). In totality, life cycle assessment offers to analyze the product's complete life cycle, which covers the broad range of impacts to perform the quantitative assessment. Assessing the life cycle or life cycle assessment (LCA) is extensively utilized in making conclusions and supporting decisions (Dreyer *et al*., 2006). *Life cycle assessment* is a method that helps in quantifying and evaluating the environmental impacts of products and their related services. This implies the application of LCA to any product and helps in decision-making where the environmental impact of the complete or part of the life cycle is the area of interest. LCA covers only the environmental dimension of sustainability and environmental life cycle assessment (Finkbeiner *et al*., 2010). It defines a strategy to direct "*the potential environmental impact caused throughout the product life cycle stages starting from raw material acquisition to manufacturing, use, end of the product life cycle, recycling, remanufacturing and final disposal*" (Hannouf & Assefa, 2017). "Social life cycle assessment" is a way through which whatever influence on products and services can be measured concerning the social impact, which is further used to evaluate and make out the comparison between the products or identify the hotspots covering all of its stakeholders during the life cycle of a product (Benoit & Mazijn, 2009). The main aim of the S-LCA is to upgrade a product's social and socio-economic conditions throughout its life cycle for all stakeholders. The economic dimension of sustainability consists of cost and performance; approaches like life cycle costing are one of the methods performed by businesses to measure the manufacturing cost (business perspective) and life cycle cost (from a customer perspective) (Finkbeiner *et al*., 2010). The main objective of the manufactured product's life cycle cost analysis (LCCA) is to anticipate the total cost involved starting from the product's development, production, use, and disposal. Besides deciding the total cost of the manufactured product, the ultimate objective is to reduce the overheads of the manufactured product (Durairaj *et al*., 2002). The main stage of the product life cycle consists of production, usage and disposal or remanufacturing. With this viewpoint, cost reduction is achieved at different product life cycle stages by adopting the life cycle costing approach (Durairaj *et al*., 2002). As cited by Alejandrino *et al*. in 2021, in most of the conducted research, the economic analysis considered only the cost during product manufacturing and at the consumer end.

II. LITERATURE ON SUSTAINABILITY AND SUSTAINABILITY FACTORS

Sustainability is defined in ample ways in various works of literature. In actuality, it is not defined as a new concept; it has a comprehensive history and has gained attention over a while (Kidd, 1992). The most important thing to look into this is that the sustainability attention that has been achieved over time is being pretentious by diverse "intellectual and political streams of thought that have molded concepts of sustainability" (Kidd, 1992). There is unprecedented attention gained by the topic "sustainability" by the practitioner and researcher in recent years. Referred by the World Commission on Environment and Development, (i.e. Brundtland's Commission, WECD 1987) defined "Development that meets the needs of the present without compromising the future needs" (Adams, 2006) (Dresner, 2002). In Figure 1, Adams in 2006 explained the 3D concept of sustainability called three supports.

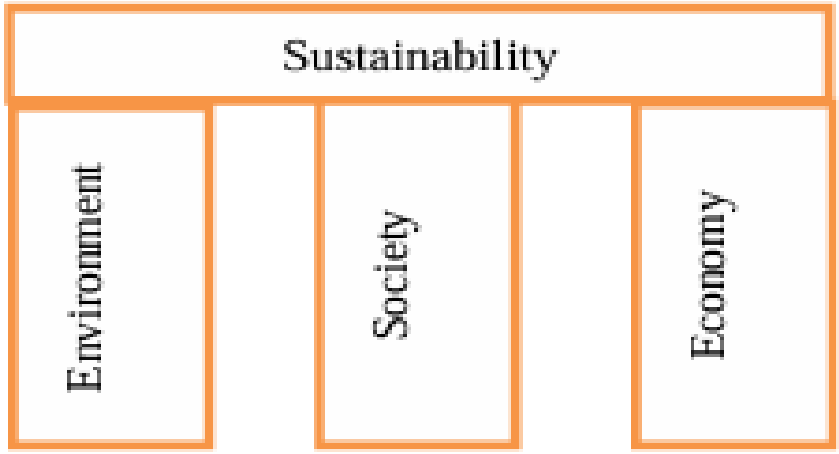

Figure 1 Sustainability – Three Pillars adapted from Adams

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Sustainability from a business perspective is defined as "Triple Bottom line" (Harris *et al*., 2001) (Dyllick & Hockerts, 2002) (Pava, 2007) (Goel, 2010). It is a sustainability construct that includes three significant dimensions: environmental quality, social equity, economic prosperity (Elkington and Rowlands, 1999). The basic thought of the triple bottom line (People, Planet, and Profit) is mostly used concerning business (Elkington, 1998). Sustainability with the well-built environmental concept explains the "ability to reduce the long-term risk associated with the resource depletion, fluctuation in energy cost, product liabilities, and pollution and waste management" (Shrivastava, 1995). The concept of sustainability and sustainable development describes the development of the society considering the financial concern using respect to the environment and interaction among the processes (Galvic & Lukman, 2007). It has now become an important factor for companies. Due to the fact companies have started integrating the concept of sustainability into their business and developmental activities (Haaneas *et al.*, 2011; Dyllick & Hockerts, 2002; Jones, 2003, Bielak *et al.* 2007; Bonini *et al*. 2006). Due to sustainability, companies can gain a competitive advantage (Campbel, 2007). Companies aim to satisfy user needs by attaining the principle, thereby reducing the environmental and communal influence of products to provide the economic value to the company considering the complete life cycle of a product, which is the main aim of sustainable development (Hseuh, 2011). Though sustainability term is new to the addition to the popular world, which is commonly used every day, the term "sustainability" holds ancient and universal roots (Alexis *et al.*, 2011). The dimension has been significantly accepted over the period with the inception of the term "Sustainable development" (Alhaddi, 2015). As cited by Alexis *et al.* in 2011, sustainability in itself refers to the idea of sustainable development. In the last couple of decades, sustainability and sustainable development have grown steadily among people with the notion of the threat of global warming. Many authors have quoted different terms and definitions for the word "sustain" (Alexis *et al*., 2011). The term "sustain" indicates which can be "supported" or "maintained" over time. According to John in 2008, sustainable development is defined as "the idea that future should be better healthier place than the present". Various authors have reviewed and inconsistently used the sustainability terms (Alhaddi, 2015). Adams, in 2006 explained the concept of three dimensions of sustainability. The study conducted by Yan *et al.* in 2009 primarily focused on the environmental dimension. Dyllick & Hockerts in 2002 explained the social dimension of sustainability, while (Marcus & Fremeth, 2009) considered all the proportions of sustainability i.e. environmental, economicand social). Galvis & Lukman in 2007 described environmental dimensions are those factors that explain the environmental performance to reduce hazardous materials, resources and energy. These factors are resource minimization, renewable resources, source reduction, recycling, reuse, remanufacturing etc. From the last few decades, the research in sustainability is focused mainly on the environmental dimension covering the refinement in the level of processes of the businesses (e.g. eco-efficient production, occupational health and safety) (Hansen & Grosse-Dunker, 2012). Incorporation of sustainability in creating core value activities and from the products and services point of view has been lately prioritized (Maxwell & Vander Vorst) in 2003. Sustainability from the total product life cycle perspective in manufacturing was conducted by Jawahir *et al.* in 2006, wherein the design stage plays a crucial role in leaving the manufacturing and user stage of the product life cycle. Each product has a life cycle. These days' manufacturers are enhancing themselves in managing the benefits and inheriting those life cycles (Sendler, 2009). Significantly little research was conducted wherein sustainability and product life cycle concepts are considered the area of study with few exceptions (e.g. sustainable consumption, green manufacturing, and sustainable manufacturing) (Maxwell & Vander Vorst, 2003). Sangwan and Mittal in 2015 mentioned the environmental factors to improve manufacturing performance, resulting in less pollution, minimizing waste, and less material and energy consumption during production. This would consider the environmental and social gains and lead to economic gains and, if collectively considered sustainable manufacturing. Sustainability in manufacturing mainly focuses on conservation of resources (Tsiliyannis, 2015), product sustainability (Mani *et al*., 2013; Rodrigues *et al*., 2016) and process sustainability (Shin *et al*., 2017). In a similar context, Barreto *et al.* in 2010 explained why a company practices green manufacturing and how product life cycle supports environmentally friendly initiatives. Energy efficiency, emissions to the environment, and waste minimization are the study's main factors. Warther and Rebitzer in 2010 focused on addressing the complete product life cycle following the relative sustainability of a product. The essential environmental factors considered during the study (covering manufacturing and user end) were raw material usage, energy consumption and water consumption, and air emissions. According to Jawahir *et al.* in 2006, manufacturing techniques must be developed to simultaneous address the product life cycle issues. Reduction of material use/weight reduction, energy consumption, hazardous wastes, energy efficiency, minimum toxic emissions at all levels of the product life cycle is some of the main drivers from an environmental perspective to be paid attention to.

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Arena *et al*. in 2009 mentioned the nine sub-dimensions of environmental factors covering materials selection, energy, water consumed, emissions, hazardous waste generated, transport, compliance, product and services. Many authors have investigated the environmental factors in terms of water, materials used, energy consumption, emissions to the air and waste minimization. Amrina and Yusof in 2011 explained the environmental performance of sustainable manufacturing by considering air emissions, waste minimization, water consumption and energy utilization main environmental factors of the conducted study. Vila *et al*. in 2015 explained the importance of environmental factors from a manufacturing activities perspective. Greenhouse gas emissions and hazardous waste are the factors that need to be paid attention to that are not enough controlled also, the optimal use of resources is to minimize the impact on the environment. The research conducted so far in sustainable production considers only the economic aspect of the supply chain, ignoring the excessive use of energy, material required, water consumption, hazardous waste etc., from a product manufacturing point of view. Gupta *et al*. in 2018 highlighted the environmental factors considered by the Indian manufacturing firms to improve their environmental performance by focusing on emissions, hazardous waste and energy as sub-dimensions of the environmental factor. Dubey and Bag in 2018 explained the area of focus in green manufacturing by taking energy consumption, carbon emissions, water consumption and waste reduction factors to measure the environmental performance. It is one of the significant manufacturing objectives by taking care of the overall requirement of the product quality and economy. Kumar and Mani in 2019 explained environmental factors as an efficiency measure during manufacturing operations. Energy consumption, water consumption, and GHG's emissions are the major factors considered to determine the embodied impact caused during manufacturing a product.

In line with sustainability principles, Gupta *et al*. in 2018 adapted the concept of sustainability in manufacturing from Garbie (2014), which led to the sustainable manufacturing, by considering the environmental, social and economic aspects simultaneously. These days' manufacturers are becoming more dynamic to improve the environmental performance by reducing the cost of material and energy, which has increased drastically over the period due to the decrease infinite resources Despeisse *et al.* in 2012. Sustainability has always been an essential aspect of all divisions of the economy. Most of the manufacturing companies have to work according to a wide-ranging set of directions plus policies that is concerned about the CO2 emission, polluting the environment and emissions product from noise, safety aspect in context to product and components, reusability of the products, recyclability, and recoverability (Petrescu *et al*., 2015). (Duflou *et al*., 2009; Witik *et al*., 2011) explained the weight reduction factor of automobile manufacturing by carrying out the environmental impact assessment. Brockhaus *et al*. in 2016 mentioned the air emissions and waste reduction factors like ecological issues of sustainability. Zarte and Nunes in a 2019 review, considered the environmental factors like material used, energy consumption, waste and effluent, greenhouse gases emissions and other pollutants during different stages of the product life cycle phase in manufacturing processes. Hernandez *et al.* in a 2019 review, considered the essential environmental elements of sustainability such as energy consumption, waste management and resource utilization considered during manufacturing. He *et al.* in the 2019 review consider environmental factors like energy; exhaust gas emissions, waste and water emissions using the product sustainability assessment approach to evaluate the ecological impact of the product by covering the entire product life cycle. Taddese *et al*. in 2020 explained the sustainability dimensions considered for the product life cycle, which further helps in the managerial decision-making process. Linke and Dornfeld in 2012 highlighted the environment, social aspects, energy, and economic aspects are one of the most critical factors that need to be ministered to while manufacturing a product.

III. SOCIAL SUSTAINABILITY

The social dimension of sustainability consists of s*ocial responsibility, health and safety* issues *and reporting the concerns to the respective business stakeholders.* Social sustainability refers to safety, indistinguishable human development, promoting humanity and the environment. Authors have conducted much research on product sustainability's environmental and economic dimensions. Less has been contributed towards the social dimension of sustainability and has focused on the social impact caused by the manufacturing industries on the stakeholders either directly or indirectly (Sutherland *et al*., 2016). Social factors like safety, human health, labour rights, equity, and diversity are explained. Gauthier in 2005 mentioned the quality, health and safety at work in the conducted research. Arena *et al*. in 2009 said about the nine sub-dimensions of social factors covering occupational health and safety, work practices and working conditions, equal opportunity and diversity, policies related to social compliance and human rights. 'Adequate working condition' is the most critical sub-dimension of the social factors followed by the industries in sustainability. Warther and Rebitzer in 2010 explained the social factors considered during the physical product life

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cycle covering safety or health issues (injuries or incidents, exposure to hazardous substances) both at the manufacturing and user end. Authors have conducted much research in the area of environment, and an economic dimension of the product sustainability with less has been contributed towards the social dimension of sustainability. Judge *et al*. in 2010 considered the social factors like better working environment for workers, employee development, health and safety aspect, supplier development, customer engagement in the conducted study. As cited by Jasiulewicz and Drozyner in 2011, workers and stakeholders are leading social factors in the industrial environment. The social impact of human health and safety, unhealthy working conditions, and accident factors lead to unsafe working conditions and low-quality manufactured products. Zarte and Nunes in a 2019 review, considered the social factors by the manufacturing industries (employee health and safety, employee development, customer health and safety, customer satisfaction, community development). Jovane *et al.* in 1993 discussed related to the working conditions and occupational health and safety factors during the usage phase must be considered in the design stage of the product life cycle. Accordingly, it is not easy to evaluate these factors during every step of the product life cycle, but they can be adequately addressed to provide a solution. Kocmanova and Nemecek in 2009 discussed the health and safety at work, training and development of workers, benefits for consumers as the social factors with their impact during the product life cycle stages. Vinyes *et al*. in 2013 classified workers level of education as a social
factor and job training aspect by (Geyhan *et al*., 2019). Wang *et al.* in 2018 covered consumer education factor, which includes training and development.

IV. Economic Sustainability

Fabrycky and Blanchard, 1991 categorized the total product cost during the various phases of a PLC, starting research & development, production cost, operations and maintenance cost, retirement and disposal cost. Asiedu and Gu in 1998 considered different costs as an economic factor used during the different stages of the product life cycle, which includes various types of company, user and society costs. Jovane *et al*. in 1993 addressed energy, material and maintenance costs during the usage phase of the product life cycle. Seliger *et al*. in 1994 review considered maintenance cost, material cost and energy cost as economic factors during the usage phase of the product life cycle. Durairaj *et al*. in 2002 regarded as environmental work cost, operational and employment cost during product development. The cost is further bifurcated into recruitment, production, training and development, wages, and overhead costs. Arena *et al*. in 2009 considered the economic factors and have been classified into three main issues; financial performance, market presence and indirect economic impact. Zang *et al*. in 2012 review considered the labour cost, cost of material, disposal cost, manufacturing cost, maintenance cost during the sustainability evaluation of product life cycle stages. Toktay and Wei in 2011 explained that costing strategies for manufacturing and remanufacturing differs. Witik *et al.* in 2011 demonstrated the assessment of economic factors and environmental performance of the automobile applications with the help of the case study method. As far as manufacturing a product is considered, deciding the cost is the most prominent factor. Still, environmental performance must be taken care of during the complete life cycle of a product. The product's use and end of the life phase costs (EOL) are considered. As cited by Shi *et al*. in 2020, the product life cycle consists of manufacturing cost, procurement cost, usage cost, maintenance cost, waste disposal cost.

V. Conclusion

The review establishes that sustainable manufacturing must be approached as an integrated framework combining environmental, social, and economic dimensions throughout the product life cycle. The environmental dimension requires strategic actions such as minimizing raw material usage, improving energy efficiency, reducing hazardous emissions, and promoting recycling and remanufacturing. The social dimension, though less addressed in literature and practice, plays an equally vital role by ensuring worker safety, fostering equitable work environments, safeguarding human rights, and enhancing community well-being. Economic sustainability is achieved by applying life cycle costing strategies that optimize expenses from product development to end-of-life management, ensuring cost-effectiveness without compromising quality or environmental integrity.

Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA), and Life Cycle Costing (LCC) emerge as essential tools for evaluating sustainability performance in a quantifiable manner, supporting evidence-based decision-making. The study reveals that while environmental and economic aspects have received significant research attention,

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the social dimension requires further empirical exploration and industrial adoption. To achieve genuine sustainable manufacturing, industries must embed these three pillars into their operational and strategic frameworks, ensuring balanced growth that aligns economic viability with environmental stewardship and social responsibility.

Ultimately, integrating sustainability into manufacturing processes not only enhances compliance with stringent environmental regulations but also fosters competitive advantage and long-term resilience in global markets. The adoption of such a holistic approach can transform manufacturing into a driver of sustainable development, benefiting businesses, society, and the environment alike.

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