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Sustainable Manufacturing Practices in Saudi Arabia: Considering the Moderating Role of Circular Economy and Cleaner Production

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Abstract

This study investigates the moderating role of circular economy and cleaner production in shaping the relationship between green practices (renewable energy adoption, waste reduction, and resource efficiency) and sustainable development outcomes in manufacturing industries. The theoretical framework of this study is based on the integration of resource-based theory, industrial ecology, and systems thinking theory. The methodology is quantitative and employs a Likert scale questionnaire for data collection. The sample size is 242 managers from the manufacturing industry of Saudi Arabia. Partial least squared-structural equation modeling was used for the analysis of the data. The findings show that green practices, including resource efficiency, waste reduction and renewable energy adoption, have a positive and significant relationship with sustainability in manufacturing. The findings also reveal that cleaner production and circular economy have moderating roles in the relationship of resource efficiency, waste reduction and renewable energy adoption and sustainable development. This study has implications for policymakers, managers and industrialists to bring sustainability into the manufacturing industry. The findings also advance sustainable development goals (SDG-7, SDG-9, SDG-12, and SDG-13).

Keywords: resource efficiency; renewable energy adoption; waste reduction; cleaner production; circular economy; sustainable development

1. Introduction

Environmental issues and challenges are increasing exponentially, and the world is facing severe challenges due to climate change and global warming [1]. Industries are one of the main sources of these challenges through the emission of Greenhouse Gases (GHGs), production of hazardous wastewater, depletion of natural resources and fossil fuels, plastics pollution and other non-degradable waste formation. According to the Development Aid Report on global waste, nearly 2 billion tons of Municipal Solid Waste (MSW) is generated, with a 70% increase until 2053, as shown in Figure 1 [2].

Similarly, according to the World Meteorological Organization, the percentages of methane, carbon dioxide and nitrous oxide have increased exponentially in the past 10 years [3]. Similarly, consumption of fossil fuels per capita increased from 15,355 kilowatt-hours in 2000 to 17,449 kilowatt-hours worldwide in 2024 [4]. These statistics show that the consumption of resources is increasing rapidly, increasing the negative impact on the environment. Furthermore, manufacturing industries use resources as raw materials, producing products and waste and intensifying the environmental issues. New markets and industries further intensify these issues. It is also important to highlight that the

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manufacturing sector contributes to economic growth, yet reforms are needed to reduce its challenges and make it sustainable.

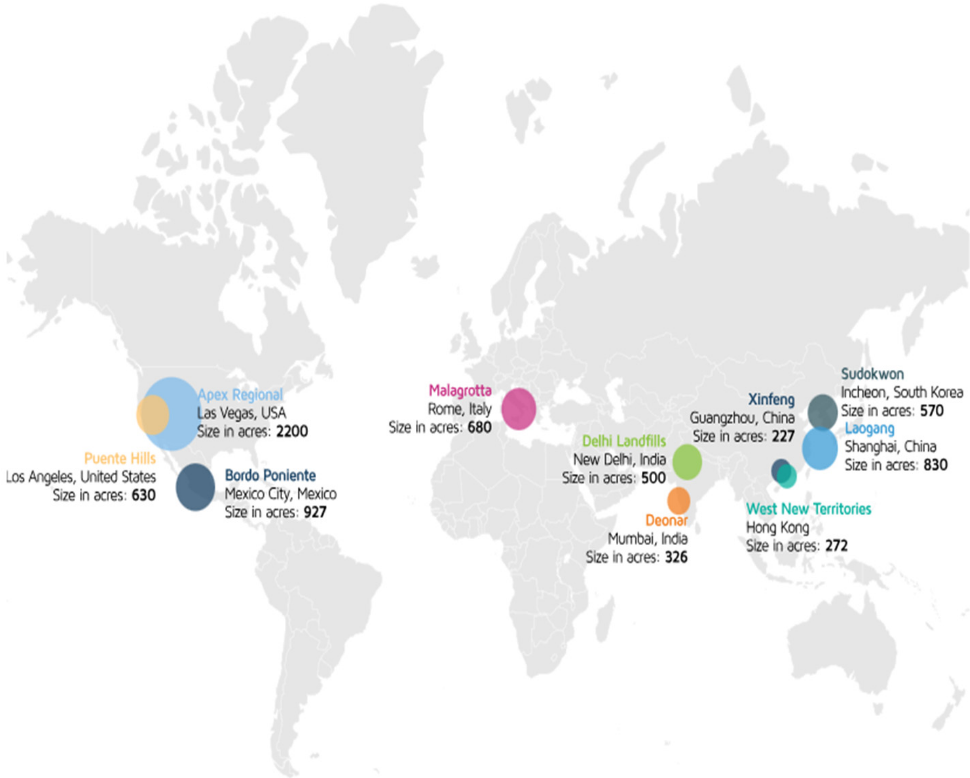
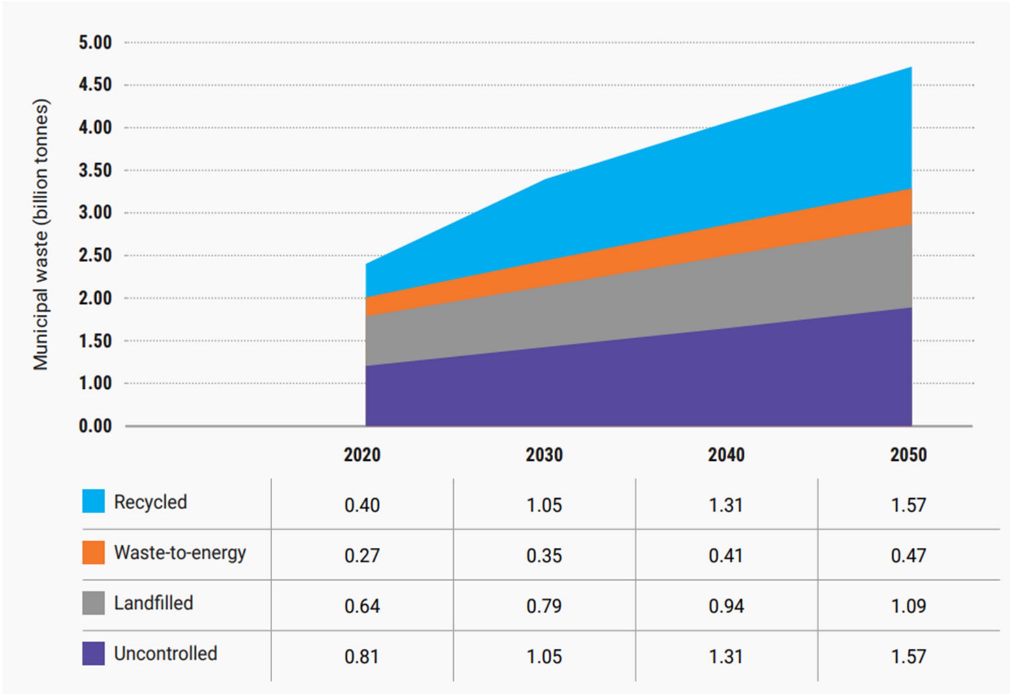


Figure 1. Global Municipal Solid Waste (MSW) in billion tons per year.

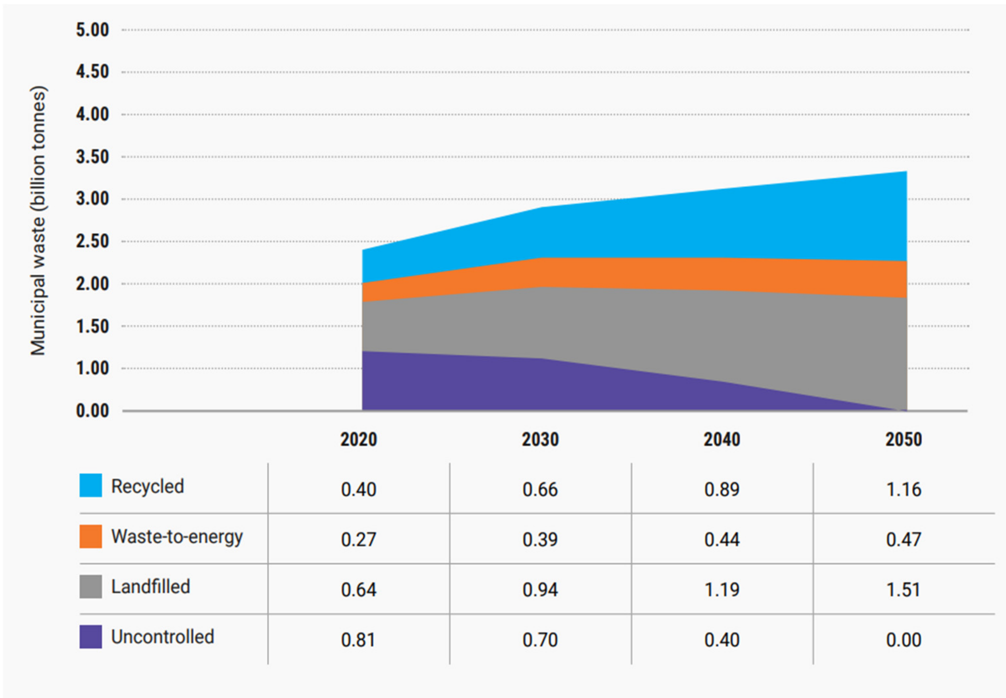
To address these issues, Green Practices (GPs) have been the new norm in the world [5]. Similarly, Circular Economy (CE) has emerged as a critical paradigm for enhancing sustainability in the manufacturing sector by integrating resource efficiency, waste reduction, and regenerative production systems by introducing new perspectives on industrial development through reducing environmental impact and maximizing resource value [6]. Furthermore, recent studies also underscore the significant role of improving efficiency in manufacturing industries for sustainable and efficient industrial processes, advancing CP in manufacturing environments [7]. Similar findings were also observed in the context of Saudi Arabia [8].

Manufacturing industries are adopting GPs in their manufacturing units to reduce the environmental impacts [9]. Resource Efficiency (RE), Waste Reduction (WR) and Renewable Energy Adoption (REA) are the most important GPs in the context of manufacturing [10]. Similarly, waste management strategies are employed using lean manufacturing systems [11]. Usage of Renewable Energy (RE) has become popular in industries as a replacement for natural resources. Waste reduction is another important factor. The Global Waste Management Outlook 2024 creates three scenarios based on recycled, waste-to-energy, landfilled and uncontrolled Municipal Solid Waste (MSW) [2]. The first scenario shows that, if waste management is the same as it is now, the landfills and uncontrolled MSW will further increase until 2050, as shown in Figure 2. In the second scenario, if Cleaner Production (CP) strategies are being used, including better waste management, recycling, and continuous improvement, in the production system to generate less waste, then the landfilled and uncontrolled MSW will be controlled by 2050 but keep threatening our environment, as shown in Figure 3. In the third scenario, if Circular Economy (CE) principles are adopted to control waste, it will end uncontrolled waste until 2050, as shown in Figure 4.



	2020	2030	2040	2050
Recycled	0.40	1.05	1.31	1.57
Waste-to-energy	0.27	0.35	0.41	0.47
Landfilled	0.64	0.79	0.94	1.09
Uncontrolled	0.81	1.05	1.31	1.57

Figure 2. Scenario 1—Waste management as usual.



	2020	2030	2040	2050
Recycled	0.40	0.66	0.89	1.16
Waste-to-energy	0.27	0.39	0.44	0.47
Landfilled	0.64	0.94	1.19	1.51
Uncontrolled	0.81	0.70	0.40	0.00

Figure 3. Scenario 2—Waste under control.

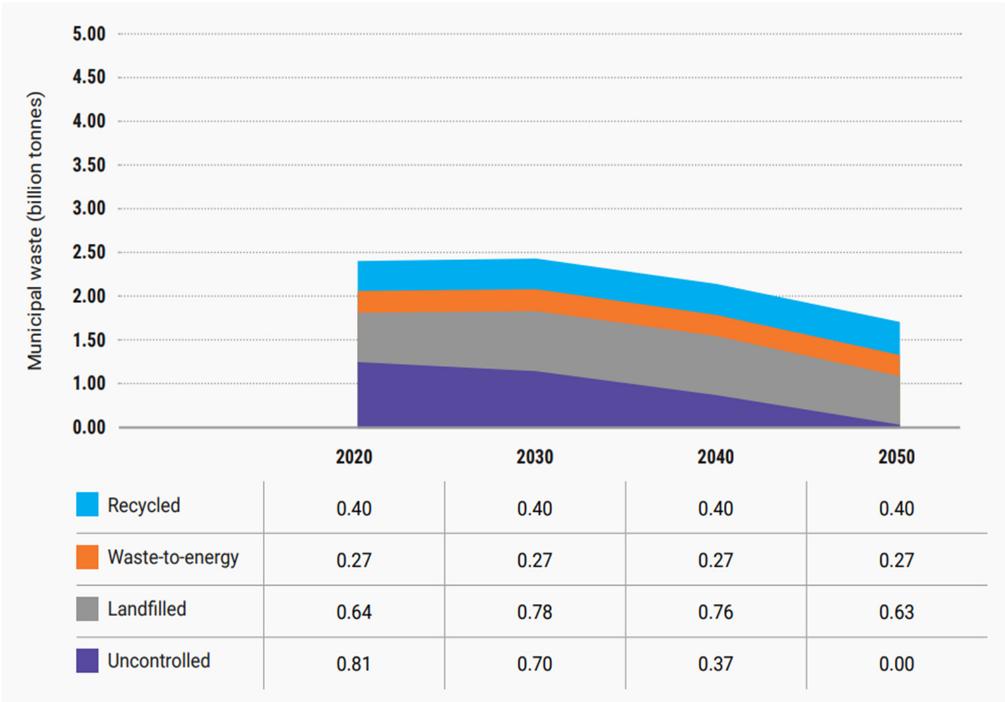


Figure 4. Scenario 3—Circular economy.

This shows that CP practices and CE principles can help manufacturing units achieve Sustainable Development (SD). Using the above-mentioned GPs combined with CP and CE principles, Saudi Arabia's industries can advance SD in their manufacturing industries. This study fills this gap by integrating GPs, CE, and CP with sustainability in a single framework. Resource-Based Theory (RBT), System Thinking Theory (STT) and Industrial Ecological Theory (IET) were used for understanding the relationships among the variables and the development of the theoretical framework. This study has the following objectives.

1. To find out the relationships between GPs and sustainable development in the manufacturing industry.
2. To explore the moderating role of circular economy and cleaner production principles on the relationships of GPs and sustainable development in the manufacturing industry.

This study provides significant insights for reducing environmental challenges by focusing on green industrial processes. The investigation among RE, WR, and REA, with the moderating role of CP, CE and SD, is pivotal. By focusing on GPs combined with CP and CE principles, manufacturing units can improve their environmental performance. Sustainable Development Goals (SDGs) can be advanced by examining the relationships between GPs, CE, and CP. This research fills the gap by developing its own theoretical framework by integrating multiple theories. This research has several theoretical, practical, and managerial implications as well, which assist policymakers, lawmakers, industrialists, and researchers to advance sustainability in manufacturing industries.

2. Development of Hypotheses

2.1. The Green Practices

GPs have gained popularity in the industrial sector around the globe due to rising environmental issues and challenges in the last few decades. Industries all around the world are looking for different ways to make their processes sustainable and are shifting towards the adoption of practices that have less impact on the environment. The need to tackle climate change and rapidly increasing global warming has been the key motivator among industrialists to shift towards GPs in their manufacturing facilities [12]. The evolution of GPs started in the 20th century, when environmental movements started around the globe. The increase in the different types of pollution was leading to many environmental issues. As a result, a need was felt to develop laws to control the toxic emissions from industries and waste disposal in landfills and oceans [13]. The rapid depletion of natural resources has caused deterioration in the environment and necessitates the adoption of GPs in the manufacturing sector. Since the industrial sector is the prime contributor to environmental-related issues, its role in addressing and resolving these environmental issues is also crucial. RE, WR, and REA are popular and widely used GPs in manufacturing units to achieve sustainability. The implementation of GPs can help reduce the environmental footprints by controlling toxic emissions, waste generation, and resource depletion [14]. The adoption of GPs in manufacturing units can be cost-effective for the industrialist in the long run, as it can improve their operational performance by managing waste generation and using alternative resources. It can also help them build a strong brand image in the market, as stakeholders, investors, and customers are more inclined towards companies that focus on sustainability in their manufacturing processes [15]. Organizations are shifting towards green technology and renewable resources by incorporating GPs into their industrial processes. This helps organizations address market demands, consumers' changing perspectives, and legal legislations to minimize environmental issues and achieve sustainability in the process. Efficient resource management, waste-to-recycle systems, and REA can help manufacturers tackle uncertainties caused by environmental disruptions [16].

2.2. Resource Efficiency

The rapid economic expansion in the 20th century due to the industrial revolution has caused resource exploitation and environmental degradation. Industries started to ignore sustainability for mass production, but soon, the depletion of natural resources caused availability and cost issues. This led to the RE concept in manufacturing units [17]. RE is an effective strategy used in the manufacturing sector to achieve sustainability. The depletion of natural resources and increasing environmental concerns have increased the significance of optimizing resource usage in manufacturing units. The rising global environmental issues forced manufacturing companies to reevaluate the usage of natural resources in their manufacturing processes. As a result, sustainable production and consumption strategies were developed to reduce or mitigate such issues [18]. RE helps manufacturers achieve productivity and profitability in their processes at the expense of minimal resources. RE helps protect natural resources and decrease resource depletion by managing processes efficiently and switching to green resources. This helps achieve environmental sustainability in the long run. By increasing RE, industries can add their efforts to tackle climate change and global warming caused by the depletion of natural resources around the world [19]. Industries can also control resource scarcity, price inflation, and legal compliance-related issues by using RE in their manufacturing processes. Resource-efficient organizations can quickly adjust to customer demand change, market demand change, and legal legislation requirements, giving them a long-term competitive advantage in the market [20].

2.3. Waste Reduction

Waste generation by industries is one of the most significant concerns on the path towards sustainable development. It is a major source of pollution and a key contributor to the environmental footprint, leading to global climate change and other environmental concerns. To control the excessive production of waste, WR is necessary [21]. The concept of WR became popular in the middle of the 20th century as environmental issues and

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challenges were getting out of control. Different environmental-related initiatives were started to reduce waste in many countries. One among them was the United States' Clean Air Act and Clean Water Act. This initiative led to the foundation of WR in production units. Excessive waste production causes many environmental issues, such as soil, water, air, and land pollution. WR is essential to reduce the environmental footprints and to protect the ecosystem for future generations [22]. In manufacturing industries, WR strategies include waste recycling, which converts it into useful products and effectively uses resources. WR initiatives also save expenses by reusing waste and by reducing waste disposal [23]. WR is one of the effective practices to be used in the manufacturing industry. As the depletion of resources and environmental issues increase, the need for and importance of WR also increase. As the manufacturing sector is one of the prime sectors responsible for these issues, it must adopt WR practices to ensure sustainable development.

2.4. Renewable Energy Adoption

REA has gained significant popularity in the manufacturing sector to tackle environmental concerns. The integration of RE into manufacturing units has become essential to mitigate climate change and global warming. The depletion of energy resources and increased GHGs have led to the evolution of RE resources in the manufacturing sector [24]. Conventional energy resources, such as oil, gas, etc., started to diminish at a rapid rate due to industrialization and mass production. Not only the depletion of these resources but its negative environmental impact was another issue. To reduce such issues, the adoption of renewable energy is an effective option. Some of the most common renewable energy resources are solar, wind, hydro, etc. They not only reduce the consumption of resources but also reduce the environmental footprint [25]. These RE resources are used in parallel with conventional energy resources to minimize their usage. REA can cause a significant decrease in GHG emissions, and these resources are environmentally friendly. Also, organizations reduce their carbon footprints through REA, moving towards a low-carbon economy. This helps to reduce the environmental impact of the manufacturing industry [26]. Industries in developed countries are shifting towards RE infrastructure to reduce their expenses, dependency on conventional energy resources, and environmental impact. Industries that have invested in RE get market competitiveness, as investors, stakeholders, and customers are more inclined towards REA in the manufacturing sector [27].

2.5. Sustainable Development

Sustainability means to fulfill the current generation's needs without compromising the requirements of future generations by maintaining an equilibrium between economic growth and social well-being. Due to the rise in environmental issues and challenges, the concept of sustainability is being widely used in manufacturing industries to tackle these issues. Sustainability is not against economic development and industrialization; instead, it focuses on strategies and practices to reduce the effects of environmental changes [28]. SD plans were first framed during the United Nations Conference on the Human Environment in Stockholm, 1972, to debate environmental issues. Environmental degradation, social injustice, and economic instability were the reasons that raised the concept of SD in the industrial sector. According to the Brundtland Commission Report in 1987, named as "Our Common Future", "SD is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [29]. Major environmental degradation and biodiversity loss caused by industrial activities, including pollution and resource depletion, have challenged SD. It advances social fairness and reduces economic disparity and carbon footprints by guaranteeing inclusive economic growth, fair benefit distribution, and significant involvement of society [30]. Unsustainable

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practices increase the risks to long-term economic stability and prosperity by excessive use of natural resources and dependency on fossil fuels. Industries can lessen their environmental impact and support international efforts to address climate change and biodiversity loss by implementing WR programs, investing in renewable energy sources, and adopting cleaner industrial techniques [31].

2.6. Green Practices and Sustainable Development

Green practices refer to tactics and methods for making better use of resources during manufacturing while reducing waste production and negative environmental effects. To make sure resources are used wisely and sustainably, they focus on optimizing resource extraction, production procedures, distribution networks, and consumption patterns. Furthermore, they maximize efficiency while reducing the negative impact on the environment, society, and economy [32]. However, sustainability is a more comprehensive term that includes social, economic, and environmental factors and guarantees the long-term survival of human societies and the planet, economic success, social well-being, and environmental conservation [33]. Reducing waste is key to advancing environmental sustainability because it reduces pollution, preserves natural resources, and safeguards ecosystems. Industries may help preserve biodiversity and ecosystem resilience while minimizing their environmental impact by minimizing waste output and encouraging reuse and recycling. Reducing waste helps to promote SD by preserving natural resources and reducing their depletion. Industries can optimize resource use, lessen dependency on natural resources, and encourage sustainable consumption and production by reducing waste generation and promoting resource-efficient methods. Reducing waste results in financial savings, increased effectiveness, and strengthened economic stability, all of which are critical components of SD [34]. Industries can lower production costs and enhance productivity and competitiveness by reducing waste generation and optimizing resource utilization. This promotes economic growth and prosperity. WR improves community quality of life, public health, and employment opportunities, all of which contribute to social fairness [35,36]. In addition, another factor of GP is the adoption of renewable energy. It helps in the reduction of carbon footprints, minimizes operational expenses, and supports sustainable growth [37]. REA helps to improve the living standards of people and control the energy load shedding by providing energy access and equity. They will help in achieving the SDGs related to REA [24,38].

2.7. Cleaner Production

Cleaner production means an environmentally friendly production. Its objective is to produce goods at the lowest cost with the least impact on the environment and sustainability. It is one of the essential prerequisites for obtaining sustainability. The adoption of CP processes has become imperative due to growing issues and challenges regarding resource depletion, climate change, and environmental damage [39]. The manufacturing industry is primarily responsible for the depletion of natural resources and the production of waste, which is a challenge for sustainable development. To reduce these challenges, manufacturing industries use CP strategies [40]. The implementation of cleaner manufacturing methods can safeguard the ecosystem and minimize the environmental impact [41]. Through CP, manufacturing firms can make their processes more efficient, reduce waste, consume less energy, adopt renewable energy, and enhance productivity [42]. It reduces the risk of resource shortages and environmental deterioration and increases regulatory compliance through the adoption of CP practices. CP practices help firms build a reputation among investors and stakeholders by focusing on sustainability. Firms can also get a competitive edge in this era of sustainability challenges through their dedication to sustainable practices, which enhances their brand value, etc. [42].

Cleaner production plays a key role in the relationship between GPs and SD. The connection between RE and SD is helpful in reducing resource consumption to minimize the environmental impact and attain economic prosperity. CP has a pivotal moderating role in shaping the relationship between RE and SD because CP enhances RE by promoting the usage of green resources and raw materials that will have less impact on the environment. SDGs can be achieved by using RE in the manufacturing processes with the help of CP strategies [43]. Similarly, the relationship between WR and SD is moderated by CP practices. Reducing waste, carbon footprints, and environmental impact is the objective of CP. CP helps in implementing waste management strategies to achieve sustainability. CP also supports a recycling culture to reduce waste formed during the manufacturing process into useful products. In addition, CP uses green technology to develop sustainable processes in which waste generation is minimal. These CP strategies help organizations reduce waste, which leads to environmental sustainability [44]. Similarly, CP also moderates the relationship between REA and SD. CP helps lower GHG emissions, which contributes to SD. CP also helps increase the efficient use of energy and decrease energy use without compromising production by enhancing the optimization of manufacturing units. Industries can implement CP practices to reduce environmental footprints and accomplish environmental sustainability [45].

2.8. Circular Economy

"It is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible." [46]. Due to growing sustainability issues like resource scarcity, environmental deterioration, and waste generation, industries are adopting the concept of CE [47]. CE helps improve sustainable development by controlling waste generation, promoting recycling culture and reducing toxic chemicals from manufacturing units [48,49]. CE focuses on sustainable resource management methods to save natural resources from depletion. CE also uses continuous improvement techniques to reuse, recycle, and remanufacture materials to control waste production during manufacturing processes. CE promotes sustainability by reducing waste, conserving natural resources and minimizing carbon emissions [50].

The relationship between GPs and SD is moderated by CE practices and principles. To achieve SD in the manufacturing industry, RE is pivotal, as the optimization of resources can reduce the impact on the environment by controlling the depletion of natural resources. CE helps form this relationship by recycling the resources used in manufacturing units and reusing them for better efficiency. In this way, the consumption of resources is minimized in the production process. CE, through the concept of product remanufacturing and regeneration, also enhances RE in the manufacturing facility by using faulty and recycled items. Similarly, the relationship between WR and SD is also moderated by the principles and practices of CE. CE focuses on the recycling culture in production to reduce generated waste. This helps organizations convert waste into useful products rather than dispose them into lands and oceans [51,52]. Industries can enhance their environmental sustainability by using the concepts of CE by controlling and eliminating waste from their industrial processes. CE also helps control corban emissions, hazardous substances, and wastewater. The concept of CE helps organizations form products with durability, repairability, and recyclability in mind [53,54]. The relationship between REA and SD is moderated by CE practices, as CE emphasizes the substitution of resources with greener materials to achieve sustainability [55,56]. These CE practices can help protect the environment to achieve SD in manufacturing units [57,58].

2.9. Theoretical Framework and Hypothesis

The theoretical mechanism of this study, "the relationship of GPs with SD through the moderating role of CP and CE in the manufacturing firms", is based on insights from RBT, industrial ecology and system thinking theories. These theories are used to explore the integration of variables like green practices, sustainable development, circular economy, and cleaner production in the manufacturing industry.

RBT focuses on the management and use of natural resources in such a way as to obtain a competitive advantage and do less harm to the environment [59]. According to this theory, firms should recognize the importance and value of natural resources and use them in a sustainable manner to get economic, social, and environmental sustainability [60]. In the context of this research, this framework provides insights regarding the use of natural resources during manufacturing processes. It promotes GPs, such as WR, REA and RE, to achieve sustainable development manufacturing by focusing on the usage of renewable energy resources, effective waste management strategies and efficient use of natural resources. Similarly, by using RBT, firms can enhance RE and reduce their reliance on natural resources, which reduces expenses and sustainability risks. RBT also supports the practices of CP by optimizing resource consumption and waste minimization in manufacturing facilities, leading to a competitive advantage and reputation [61]. In addition, it also supports the principles of CE and remanufacturing and provides solid arguments in favor of the adoption of CE principles in manufacturing processes [32].

Similarly, IET draws its theme from the natural ecosystem and provides insight for industries to follow this inspiration by emphasizing WR, RE, and sustainability [62]. In the context of the manufacturing industry, it provides an understanding of how to use resources and reduce environmental consequences [63]. It focuses on the conservation of energy, recycling of materials and resources, waste management and pollution control. One of the key elements of industrial ecology is CP, which focuses on waste management strategies and waste control [64,65], improves efficiency and reduces the cost of production in manufacturing processes. Industrial ecology also deals with process optimization, material substitution and REA, which are essential for sustainability. Industrial ecology is also linked with the principles and practices of CE, by promoting recycling, reusing, and remanufacturing, and provides solid arguments in favor of the adoption of CE principles in manufacturing processes [66].

Furthermore, STT uses a systematic approach to address the environmental issues and challenges associated with different complex systems to promote sustainability [67]. In the context of this study, it stresses the environmental, social, and economic factors using GP principles and practices. Using this theory, manufacturing firms can more effectively implement sustainable GPs that can address the root causes of sustainability challenges and can take actions accordingly [68]. It also clarifies the importance and significant role of CE and CP to influence the relationship of GPs, like WR, REA, and RE, with sustainable development in the manufacturing industry [69,70].

The shift towards sustainable production models has been widely examined from the perspective of CE, focusing on a balanced interaction between economic and environmental systems. For example, it reduces resource consumption and waste, advancing sustainable manufacturing processes [71]. This was enforced by RBT theory, which provides insights regarding the RE concept and stresses the use of resources in a manner that has a minimal impact on the environment [72]. It also focuses on REA in manufacturing units to control and conserve energy resources to reduce their cost and reliance on natural energy resources. RBT supports the role of REA and RE as the key GP practices that support the sustainable use of natural resources. These factors are the main pillars of industrial sustainability. The product-service systems are critical tools for reducing resource consumption and advancing toward circular economy models, enabling more sustainable production [73].

Industrial ecology theory emphasizes WR practices, which include the minimization of pollution, wastewater, toxic emissions, and other types of waste during industrial activities. CE practices also align with industrial ecology, as they emphasize the waste recycling culture. It also uses the concept of CP, which implements a reuse, recycle and remanufacturing strategy to achieve SD. Similarly, system thinking theory focuses on the integration of the different CP and CE practices and principles to adopt GPs in manufacturing units to achieve SD. It emphasizes the usage of green materials, renewable energy resources and waste management strategies by making a complex integrated system that interconnects these practices to achieve SD in the manufacturing industry. The adoption of GPs, CE principles and CP strategies is driven by factors like regulatory pressures, competitive advantages, social expectations, etc. And firms adopt environmental strategies in response to these dynamics [74]. Furthermore, CP strategies are increasingly focused on increasing environmentally friendly industrial processes. For example, a study provides evidence that the use of environmentally friendly fluids significantly reduces waste and resource consumption, strengthening the key role of CP in sustainable manufacturing [75]. Moreover, CE principles rely on closing material loops, optimizing resource use, and minimizing environmental impacts, establishing it as a critical factor for SD in the manufacturing sector [76]. Furthermore, sustainability in the manufacturing sector is linked with sustainable supply chain practices, which is highlighted by many studies [77]. These insights clarify the positive role of GPs for sustainable manufacturing processes. For instance, if an industry implements waste reduction strategies and reduces waste, it will maximize resource utilization, ensure the responsible use of resources and advance sustainability in manufacturing. Similarly, by maximizing resource efficiency use, manufacturing industries can reduce waste, resource exploitation, etc., leading to sustainability in manufacturing. Furthermore, by adopting renewable energy, the manufacturing sector can not only reduce power expenses but also reduce pollution, extraction of coal, etc., that are necessary for power generation. These three GPs positively impact sustainability in manufacturing, and their implementation can reduce the environmental impact, increase economic growth and positively impact society. The positive relationship of GPs and sustainable development in the manufacturing industry is further intensified by integrating CP strategies and CE principles. Manufacturing industries need to adopt CP and CE principles to increase the benefits of GPs. For example, both CP and CE principles stress waste reduction, material recycling, reusing, repairing, etc., with the objective to increase the efficiency of resource use during processes, reduce waste, and minimize expenditure while ensuring sustainable development. This study integrates these theories and designs the following hypotheses and theoretical framework, as shown in Figure 5. Figure 6 shows the mapping of theories and variables for better understanding and clarity.

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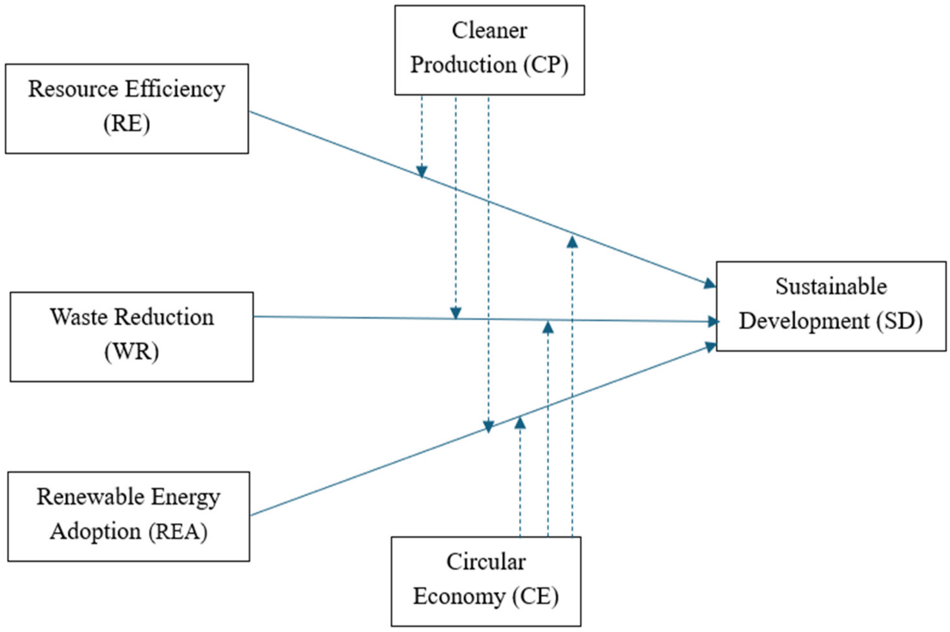

Figure 5. Theoretical framework for Sustainable Manufacturing Practices in Saudi Arabia.

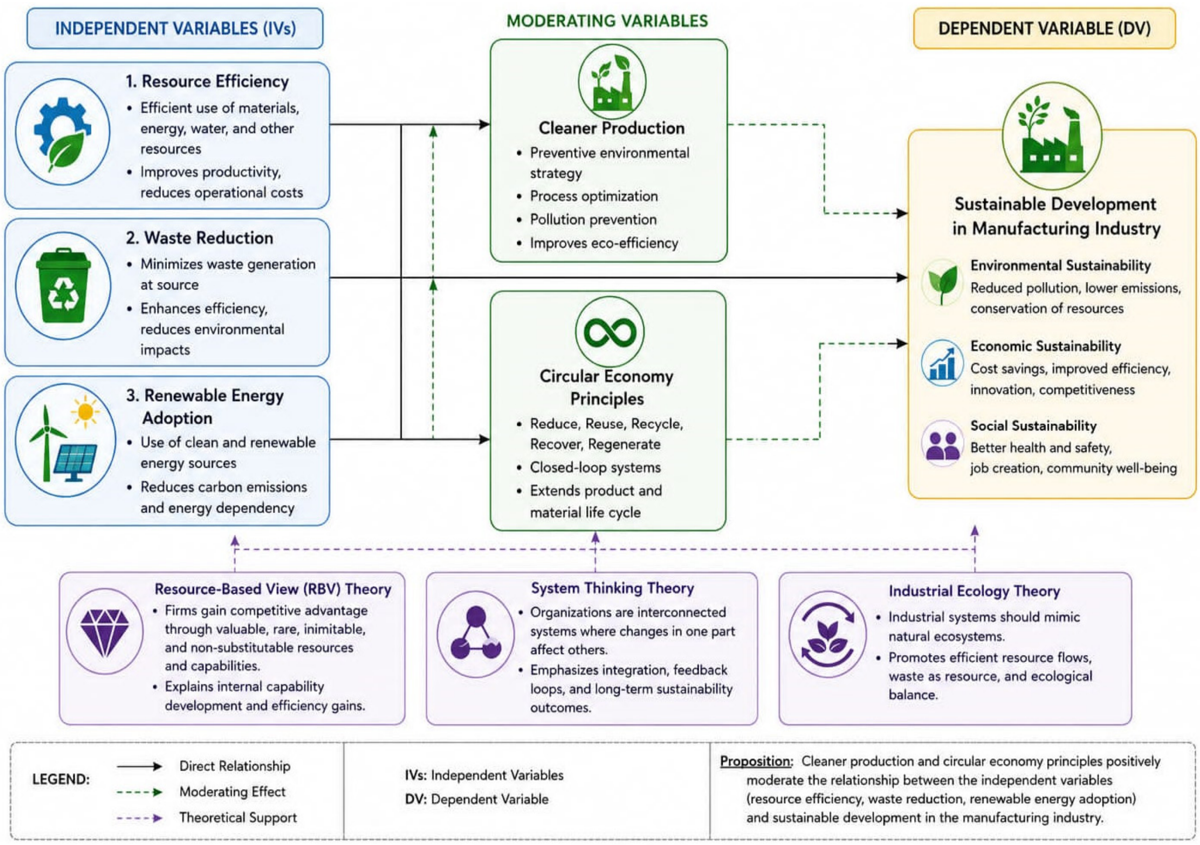

Figure 6. Mapping theories and relationships among variables.

Based on the above discussion, this study assumes the following hypotheses to be true.

H1. *RE has a positive relationship with SD in the manufacturing industry.*

H2. *WR has a positive relationship with SD in the manufacturing industry.*

H3. *REA has a positive relationship with SD in the manufacturing industry.*

H4. *CP moderates the relationship between RE and SD in the manufacturing industry.*

H5. *CP moderates the relationship between WR and SD in the manufacturing industry.*

H6. *CP moderates the relationship between REA and SD in the manufacturing industry.*

H7. *CE moderates the relationship between RE and SD in the manufacturing industry.*

H8. *CE moderates the relationship between WR and SD in the manufacturing industry.*

H9. *CE moderates the relationship between REA and SD in the manufacturing industry.*

3. Methodology and Results

3.1. Philosophical Foundation

As this is quantitative research, its philosophical foundation is rooted in positivism, which emphasizes the use of scientific methods and empirical evidence for understanding the situation at hand. It emphasizes the importance of objectivity and empirical evidence for gaining knowledge. By using a quantitative research approach, the authors aim to reduce subjectivity and bias in the selection of respondents and data collection. By employing Likert scale questionnaires, this study tries to quantify the attitudes and perceptions regarding the relationships of green practices with sustainable development, which provides an understanding of multiple stakeholders' perspectives. The approach provides an evidence-based framework aimed at understanding the relationship of GPs with SD and the moderating roles of cleaner production and circular economy on those relationships. This helps in reducing the environmental challenges and promoting sustainable development and the effective use of resources in manufacturing industries.

3.2. Sample Selection and Data Collection

As this study aims to target the manufacturing industry, a purposive sampling technique was used for sample selection. The data was collected from the engineers and managers of Saudi Arabia's manufacturing industries through a closed-ended Likert scale-based questionnaire. The questionnaires were distributed personally from 1 April 2026 to 10 April 2026 among 400 respondents. Out of 400 respondents, 242 responses were found suitable for data analysis. The response rate was 60.5. Only the completed responses were used; incomplete responses or those having missing values were discarded. Although the ideal sample size is 384, a smaller size like 242 is also acceptable while using PLS-SEM. Furthermore, the population of engineers and managers working in the manufacturing sector is small, and therefore, it is hard to collect a large sample size. A sample size between 150 and 300 is considered acceptable [78].

3.3. Measurement Instrument and Statistical Tool

All the measurement instruments used in this research were adopted from previous research. The measurement instruments of resource efficiency were taken from [36]. Similarly, the measurement instruments for waste reduction were adopted from [35,36], for renewable energy were adopted from [79], for cleaner production were adopted from [80], for circular economy were adopted from [81,82], and for sustainable development were adopted from [80,83]. Before conducting the complete survey, a pilot survey was conducted to validate the questionnaires for this study. All the items were found valid and reliable.

PLS-SEM-4 software was used to analyze the primary data via the partial least squares-structural equation modeling technique. Comprehensive validation tests, including item reliability, consistency reliability, convergent and discriminant validity, and multicollinearity, were examined to ensure the robustness of the measurement model. Bootstrapping was used to further enhance the result's credibility. These measures ensure the reliability, replicability and transparency of the results.

3.4. General Sample Characteristics

The general sample characteristics of the respondents are given in Table 1. It shows that a total of 242 employees across Saudi Arabia's manufacturing industries participated in the research questionnaire survey. The age group statistics show that 45 respondents were from the age group of 26–30 years, 51 were from the age group of 31–35 years, 109 were from the age group of 36–40 years, 33 were from the age group of 41–45 years, and 4 were from the age group of more than 45 years.

Table 1. Demographics.

Age Group (Years)	Number	Percentage
26–30	45	18%
31–35	51	21%
36–40	109	45%
40–45	33	13%
46 and above	4	1%
Total	242	100%

3.5. Scale Reliability

Reliability refers to the completeness and accuracy of data as a measure of consistency of measures. Construct and item reliability are two commonly used reliability methods in structural equation modeling. The reliability of the item is measured by outer loading values, whereas the reliability of the construct is measured by Cronbach's alpha and composite reliability. For both measures, 0.7 is the threshold value. Table 2 demonstrates that the values are higher than the threshold values, indicating the item's reliability. The findings show that the items are reliable for the study in the context of this study. In other words, the data collected by using these items are reliable for making a judgment or for examining the relationships between the intended variables.

Table 2. Item reliability and multicollinearity.

Construct	Items	Outer Loadings	VIF	Chronbach Alpha
Circular Economy	CE1	0.845	2.353	0.911
	CE2	0.876	2.897	
	CE3	0.922	2.853	
	CE4	0.914	2.567	
	CE5	0.931	2.068	
	CE6	0.924	2.457	
Cleaner Production	CP1	0.757	1.882	0.810
	CP2	0.768	2.147	
	CP3	0.852	2.714	
	CP4	0.812	2.21	
	CP5	0.823	2.699	
	CP6	0.802	2.549	

Table 2. *Cont.*

Construct	Items	Outer Loadings	VIF	Chronbach Alpha
Renewable Energy Adoption	RE1	0.770	1.698	0.821
	RE2	0.809	1.899	
	RE3	0.828	2.178	
	RE4	0.835	2.465	
	RE5	0.835	2.29	
Resource Efficiency	REA1	0.846	2.645	0.860
	REA2	0.872	2.382	
	REA3	0.883	2.574	
	REA4	0.864	2.997	
	REA5	0.889	2.447	
	REA6	0.860	2.99	
Sustainable Development	SD1	0.838	2.459	0.877
	SD2	0.847	2.633	
	SD3	0.902	2.577	
	SD4	0.916	4.44	
	SD5	0.861	2.019	
Waste Reduction	WR1	0.757	1.948	0.853
	WR2	0.853	2.732	
	WR3	0.845	2.047	
	WR4	0.835	2.526	
	WR5	0.869	2.544	
	WR6	0.872	2.348	

3.6. Convergent and Discriminant Validity

Validity measures the extent to which the scores from a measure represent the variable they are intended to. Convergent and discriminant validity are two types of common validity measures in PLS-SEM. Convergent validity is measured by AVE, having a threshold value of 0.5 and higher. Table 3 shows that every AVE value is higher than the threshold value, indicating its convergent validity. In other words, the scales represent the constructs to the acceptable values. And the use of these scales is suitable for measuring the corresponding constructs or variables.

Table 3. Convergent validity.

Construct	Average Variance Extracted (AVE)
Circular Economy	0.815
Cleaner Production	0.745
Renewable Energy Adoption	0.756
Resource Efficiency	0.723
Sustainable Development	0.763
Waste Reduction	0.705

Discriminant validity measures how it varies from other constructs. It can be assessed by the Heterotrait–Monotrait Ratio (HTMT) and Fornell–Larcker criteria. All diagonal values must exceed the values of the corresponding columns and rows to meet the Fornell–Larcker criteria's threshold value. Table 4 establishes the convergent validity of the data by demonstrating that all the diagonal values are greater than the corresponding column and row values. The HTMT has a threshold value of 0.85 or lower. Table 5 shows that the HTMT value is less than the threshold value, ensuring the discriminant validity among the constructs.

Table 4. Fornel–Larcker criteria.

	CE	CP	REA	RE	SD	WR
CE	0.903					
CP	0.652	0.803				
REA	0.624	0.799	0.869			
RE	0.67	0.71	0.678	0.816		
SD	0.564	0.661	0.691	0.664	0.873	
WR	0.632	0.793	0.816	0.673	0.712	0.839

Table 5. HTMT ratios.

	CE	CP	REA	RE	SD
CP	0.709				
REA	0.657	0.876			
RE	0.73	0.803	0.746		
SD	0.597	0.729	0.739	0.733	
WR	0.673	0.879	0.875	0.75	0.77

3.7. Model Fitness

Standardized Root Mean Square Residual (SRMR) is used for examining model fitness. When using PLS-SEM, a result of less than 0.08 is typically regarded as a satisfactory value. Table 6 demonstrates that the SRMR value is 0.055, which is less than the 0.08 threshold value, indicating that the model is fit. The findings suggest that the model adequately reproduces the observed data and shows an acceptable level of predictive accuracy.

Table 6. Model fitness.

	Saturated Model	Estimated Model
SRMR	0.055	0.055

3.8. Hypothesis Testing

Hypothesis testing was used to examine the relationships between the variables of interests. Beta value, t-statistics, and *p*-values are used for examining the relationships. For t-statistics, the threshold value is 1.96 and higher, and for *p*-value, it is 0.05 or lower. The statistics show that all hypotheses were accepted by the data, as shown in Table 7. The strength of each relationship is indicated by the beta value. Figures 7 and 8 display the tested framework by showing the t-statistics and beta values for each hypothesis respectively. The findings show that WR has the most effective relationship with SD, followed by REA and RE respectively. A detailed discussion of the hypotheses is done in the Discussion section.

Table 7. Hypothesis testing.

Hypothesis	Beta	T Statistics	*p*-Values
H1: Resource Efficiency -> Sustainable Development	0.142	5.341	0.008
H2: Waste Reduction -> Sustainable Development	0.318	2.640	0.009
H3: Renewable Energy Adoption -> Sustainable Development	0.241	11.893	0.000
H4: RE/CP -> Sustainable Development	0.309	5.064	0.000
H5: WR/CP -> Sustainable Development	0.216	7.193	0.000
H6: REA/CP -> Sustainable Development	0.261	10.374	0.000
H7: RE/CE -> Sustainable Development	0.110	6.791	0.000
H8: WR/CE -> Sustainable Development	0.286	1.964	0.050
H9: REA/CE -> Sustainable Development	0.362	11.839	0.000

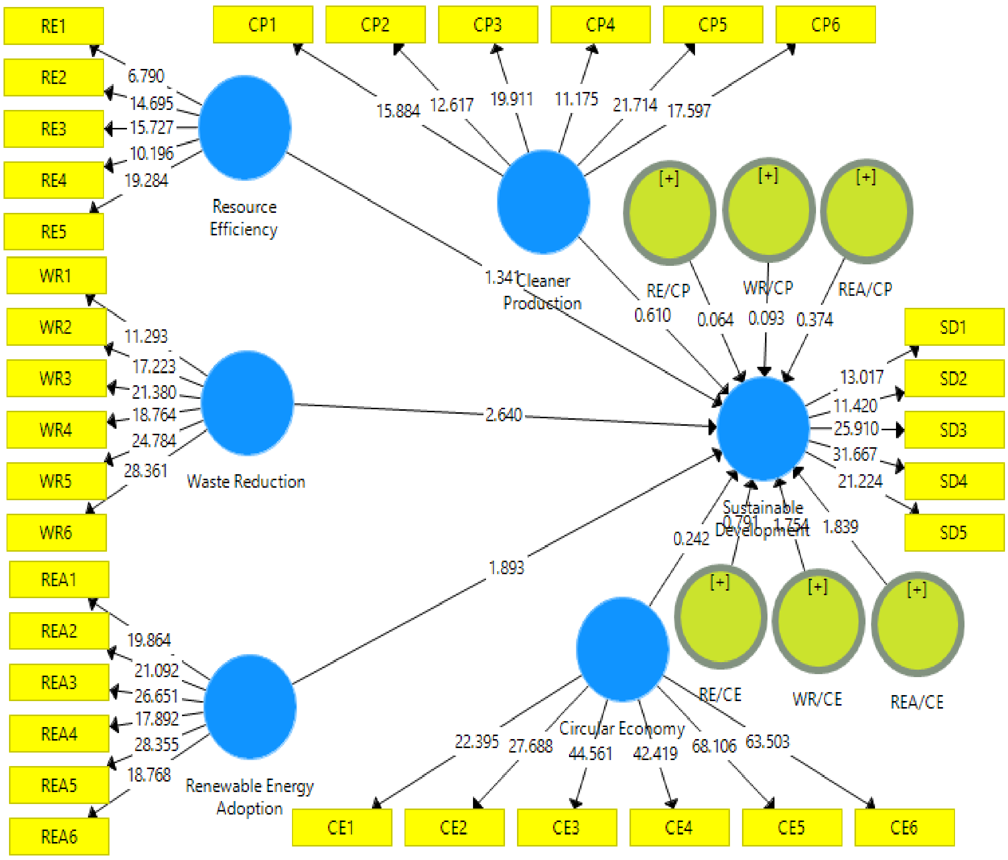

Figure 7. Hypothesis testing (t-statistics).

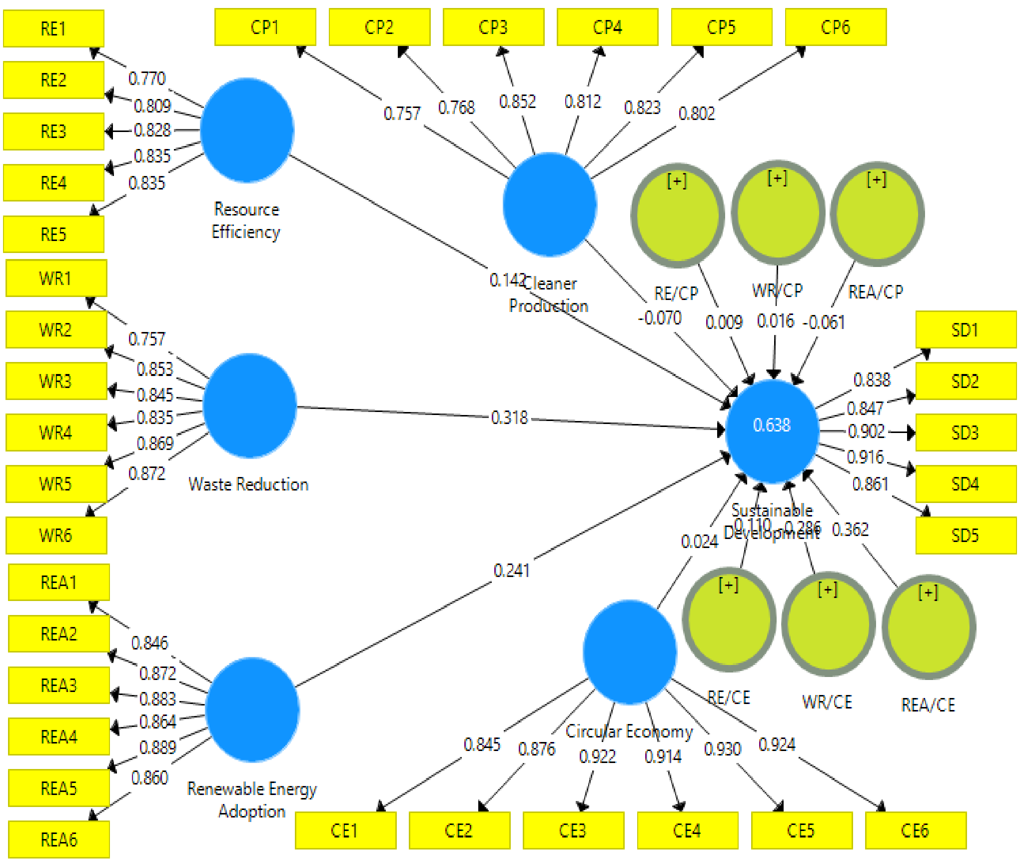

Figure 8. Hypothesis testing (beta statistics).

3.9. Coefficient of Determination

The cumulative influence of the variables on the dependent variable is explained by the coefficient of determination. With an R-square value of 0.585 in Table 8, the independent variables in the model account for 58.5% of the sustainability variation in the given scenario. The findings show that the independent variables (GPs) have moderate explanatory power for sustainable development of the manufacturing industry.

Table 8. Coefficient of determination.

	R Square	R Square Adjusted
Sustainable Development	0.585	0.571

3.10. Importance of Performance Matrix Analysis

The Importance of Performance Matrix Analysis (IMPA) is a tool used in PLS-SEM to predict the significance and performance of the independent variables with the dependent variables of the research model. According to the IMPA shown in Table 9, WR is the most important variable, having a value of 30.7%, and RE is the most performed variable, with a value of 89.991%. The findings highlight the importance of waste reduction in manufacturing industries for obtaining sustainability, while the performance of the variables is relatively similar.

Table 9. IPMA analysis.

Sustainable Development	Importance	Performances
Circular Economy	0.015	84.217
Cleaner Production	0.079	88.031
Renewable Energy Adoption	0.219	88.922
Resource Efficiency	0.158	89.991
Waste Reduction	0.307	89.071

3.11. Predictive Relevance of the Model

Predictive relevance calculates a model's prediction potential based on how well it performs in other testing scenarios. It is measured by Q-square. The statistics in Table 10 show a Q-square value of 0.439, indicating that the model has a 43.9% prediction power. The results show a moderate predicting power of the study model.

Table 10. Predictive relevance of the model.

	SSO	SSE	Q^2 (=1 − SSE/SSO)
Circular Economy	948	948	
Cleaner Production	948	948	
Renewable Energy Adoption	948	948	
Resource Efficiency	790	790	
Sustainable Development	790	443.01	0.439
Waste Reduction	948	948	

4. Discussion

The manufacturing sector is one of the major contributors to environmental issues and global warming [84] due to its reliance on the consumption of resources, waste production, and pollution. To reduce the negative impact on sustainability, investigating the role of manufacturing industries in minimizing environmental issues is essential [85]. This research investigates the relationship of GPs with sustainability in manufacturing industries by considering CP and CE as moderators. This study consists of nine hypotheses, including three direct and six moderating hypotheses.

The first hypothesis claims that there is a positive relationship between RE and SD in the manufacturing industry. The results show that there is a positive and significant relationship between RE and SD, with a beta of 0.14, t-statistics of 5.34, and *p*-value of 0.008. The results are aligned with previous studies that explored the practice of RE in manufacturing processes to achieve SD [86–88]. In the context of Saudi Arabia, it validates that industries can minimize the depletion rate of natural resources by applying RE in their manufacturing processes. This highlights the importance of RE for SD. If manufacturing industries ensure efficient use of resources, they can obtain SD, not only by consuming less resources but also by reducing waste, pollution, resource extraction, etc., contributing to the sustainable use of resources and environmental protection. The second hypothesis claims that there is a positive relationship between WR and SD in the manufacturing industry. The findings also show that there is a positive and significant relationship between WR and SD, with a beta of 0.318, t-statistics of 2.64, and *p*-value of 0.009. The findings validate prior studies that emphasized WR strategies to control waste during industrial processes [89,90]. In the context of Saudi Arabia, the findings highlight the importance of recycling for advancing the sustainable use of resources. Reducing waste can significantly minimize pollution, cost of operations and resource extraction and increase economic growth and operational efficiency. Its role further intensifies SD in manufacturing, where waste has a significant cost and severe effect. The third hypothesis claims that there is a positive relationship between REA and SD in the manufacturing industry. The results also validate this, with a beta of 0.241, t-statistics of 11.89, and *p*-value of 0.000. Past studies also have similar findings, indicating that firms should optimize energy resources and adopt alternate and cost-efficient options in the form of renewable resources to reduce the negative impact on sustainability and ensure SD [90–92]. In the context of Saudi Arabia, the manufacturing industry can advance sustainability by REA that reduces carbon footprints [93]. Many industries are shifting to renewable energy sources like solar energy, etc., due to high energy costs and its negative environmental impact. Many countries also encourage the adoption of renewable energy sources and provide various incentives. Specifically in Saudi Arabia, where fossil fuels are the major source of energy production, the adoption of renewable energy sources in the manufacturing industry is very necessary for manufacturing process sustainability.

The fourth hypothesis claims that CP moderates the relationship between RE and SD in the manufacturing industry. The results also show that a positive and significant moderating role of CP exists between WR and SD, with a beta of 0.309, t-statistics of 5.06, and *p*-value of 0.000. The findings are similar to previous studies [94]. In the context of Saudi Arabia, CP increases the effectiveness of RE initiatives and encourages sustainable resource usage in production processes, which leads to SD. CP stresses the use of environmentally friendly materials and technologies in industries, thereby reducing the environmental impact and advancing SD in manufacturing. Manufacturing industries in Saudi Arabia should implement CP strategies to enhance the relationship of RE and SD in manufacturing. The fifth hypothesis claims that CP moderates the relationship between WR and SD in the manufacturing industry. The findings also show that a positive and significant moderating role of CP exists between WR and SD, with a beta of 0.21, t-statistics of 7.19, and *p*-value of 0.000. In the context of Saudi Arabia, the respondents believe that CP helps reduce waste by producing fewer pollutants, toxic materials, and non-recyclable items. CP initiatives are significant for the implementation of WR strategies during manufacturing, reducing the concerns of sustainability and leading to SD [44]. CP stresses the use of environmentally friendly materials and technologies in industries, thereby reducing waste production during manufacturing processes. Manufacturing industries in Saudi Arabia should use resources that are environmentally friendly to reduce waste. Furthermore, environmentally friendly technology should be used for reducing waste. This clarifies the need to implement CP strategies that increase the relationship between WR and SD in manufacturing. The sixth hypothesis of this study claims that CP moderates the relationship between REA and SD in the manufacturing industry. The results also validate a positive and significant moderating role of CP exists between REA and SD, with a beta of 0.261, t-statistics of 10.37, and *p*-value of 0.000. In the context of Saudi Arabia, the respondents believe that CP techniques improve REA and energy conservation in production processes. CP initiatives are essential for promoting the use of renewable energy sources to maximize energy utilization and minimize dependency on fossil fuels [10], which leads to sustainable development. CP stresses the use of environmentally friendly materials and technologies in industries, thereby reducing waste production during manufacturing processes. Energy, as the key element of manufacturing industries, is produced by burning fossil fuels, which negatively impact the environment, and depends heavily on resource extraction. If manufacturing industries in Saudi Arabia use renewable resources for energy production that are environmentally friendly, they can further intensify the relationship among REA and SD. The seventh hypothesis claims that CE moderates the relationship between RE and SD in the manufacturing industry. The results validate this, with a beta of 0.110, t-statistics of 6.79, and *p*-value of 0.000. CE principles focus on recycling, reusing, remanufacturing, etc., which reduces the use of resources and increases the efficiency of manufacturing processes. The moderating role of CE helps to achieve RE, and SDGs align with it by controlling the depletion of natural resources and having a diverse impact on the environment [95]. CE stresses the reuse, repair, recycle, etc., of materials and products, thereby increasing the efficient use of resources. And if CE principles are implemented, the benefits of RE can be further increased towards sustainable development. It is the responsibility of the government to implement CE principles across manufacturing processes, especially where resources are rare and expensive, to advance SD across manufacturing. The eighth hypothesis claims that CE moderates the relationship between WR and SD in the manufacturing industry. The results also show that a positive and significant moderating role of CE exists between WR and SD, with a beta of 0.286, t-statistics of 1.96, and *p*-value of 0.05. CE principles focus on a reduction in waste by implementing waste reduction strategies and help manufacturing industries control waste and reduce pollution levels in the environment [57,96]. CE principles emphasize the reuse, repair, recycle, etc., of materials and products, thereby increasing the efficient use of resources. The implementation of CE principles reduces waste and increases the benefits of WR towards sustainable development. It is the responsibility of the government to implement CE principles across manufacturing processes, especially where waste production is high, to advance SD across manufacturing. The ninth hypothesis claims that CE moderates the relationship between REA and SD in the manufacturing industry. The results also show that a positive and significant moderating role of CE exists between REA and SD, with a beta of 0.362, t-statistics of 11.83, and *p*-value of 0.00. By encouraging energy efficiency, conservation, and optimization, CE principles make it easier to integrate renewable energy sources into manufacturing, leading to SD. Through a reduction in greenhouse gas emissions, climate change, and promotion of energy security and resilience, this moderation guarantees a contribution to the attainment of SDGs [69]. In the context of Saudi Arabian manufacturing industries, the implementation of CE principles is necessary to adopt renewable energy sources for energy production, which is not only necessary for reducing the carbon footprints but also for ensuring sustainability in manufacturing. A renewable energy source can be reused for energy generation, with no or low environmental impact and huge sustainability benefits. The assessment of the moderating roles of CP and CE principle is a significant contribution of this study, while there are many studies on CP and CE principles and their role in sustainable manufacturing.

In summary, the findings of this study clarify the importance of WR, RE, and REA for achieving SD in manufacturing practices, which brings many benefits across economic, social, environmental, and regulatory domains in the context of Saudi Arabia. Through the implementation of WR strategies and by embracing RE sources, the manufacturing sector can reduce its carbon footprint, increase production efficiency, promote social responsibility, and follow regulations. Furthermore, by playing a critical regulatory role, CP and CE principles further strengthen the relationships of WR, RE, and REA with SD by ensuring a closed-loop manufacturing system that has an improved capability to reduce waste, reuse, and conserve resources. Similarly, CP and CE principles also focus on system optimization and digitalization [97] and waste minimization, which reduces the ecological impact throughout the lifecycle of products. Both CE and CP enhance WR, REA, and RE and reinforce the shift towards sustainable manufacturing. Thus, in the context of Saudi Arabia, CE and CP principles regulate manufacturing activities to reduce their ecological footprints and open doors for innovation, resource efficiency, and value creation. The following lines discuss the contribution of findings for advancing SDGs and implications.

4.1. Contribution to the Attainment of the United Nations' Sustainable Development Goals

The findings have the following contribution to the advancement of SDGs.

1. Affordable and Clean Energy (SDG-7): GPs help societies provide modern, affordable, and sustainable energy by using REA and CP technologies. CE concepts also help in energy efficiency to control ecological footprints linked with the usage of energy resources.
2. Industry, Innovation, and Infrastructure (SDG-9): GP initiatives, including CP and CE practices, help organizations achieve sustainable industrialization and innovation in their industrial processes. Using these GPs, organizations can control environmental issues, such as pollution and waste, to build a sustainable infrastructure and industrialization.
3. Responsible Consumption and Production (SDG-12): Through the help of CP and CE, GPs can help to achieve sustainable consumption and production in manufacturing units. The impact of consumption during production can be controlled by implementing RE, WR, and REA practices in the organization.
4. Climate Action (SDG-13): The adoption of GPs, in particular REA, can help reduce the impact of climate change and global warming in the world. GPs help to reduce GHG emissions and depletion of resources to reduce climate-related concerns and achieve sustainability.

4.2. Implications of the Findings

Theoretical Implication:

1. This study integrates NRBT, industrial ecology, and system thinking in a single framework and shows how these theories help achieve SD by implementing GPs in manufacturing units. The findings validate the importance of these theories in attaining sustainability in manufacturing industries.
2. The moderating role of CP and CE is another key contribution of the theoretical framework, which shows that SD can be achieved by using CPs and CE principles in manufacturing units.

Practical Implication:

- The findings of this study show that, by using GPs in manufacturing units, organizations can reduce environmental issues related to industrial processes and can achieve SD. So, to reduce the environmental impact of manufacturing processes and increase the efficient use of resources, manufacturing firms should adopt this framework and design their production accordingly.
- The research also shows that CP and CE practices can help implement GPs in manufacturing units by using WR, RE, and REA in their production systems.
- Manufacturing firms can increase their profits by increasing the efficient use of resources.
- Environmental footprints can be reduced by producing less waste and consumption of resources.

Managerial Implication:

1. Managers can use the framework to implement GPs, such as RE, WR, and REA, in manufacturing units to achieve sustainability in their production systems.
2. Managers can also train their subordinates and staff regarding the effective use of resources, waste management strategies, recycling, and REA in manufacturing units to achieve SD.
3. The findings can also be used to minimize the production cost and reliance on resources.
4. Successful implementation of the framework can be beneficial to enhance reputation and earn carbon credits.

Policy Implications:

1. The findings have many policy implications and provide enough evidence for policymakers to regulate the manufacturing sector in the context of green practices, clean production, and circular economy.
2. A strict policy is needed for the implementation of GPs in manufacturing to ensure SD.
3. This research also provides evidence to regulate resource consumption, to use less and produce more.
4. A strict policy is needed to ensure the regulatory role of CE and CP in the manufacturing industry.

5. Conclusions

This study examined the relationship between green practices and sustainable development in the manufacturing industries of Saudi Arabia by considering the moderating role of circular economy and cleaner production. This study integrates resource-based theory, system thinking and industrial ecological theories to develop its own model. This study underscores the critical role of GPs in advancing sustainability in manufacturing industries by reducing waste and using renewable resources by enhancing efficient resource use. This study also reveals the significant moderating role of CP and CE on the relationship between GPs and SD, validating their significance for enhancing manufacturing practices towards sustainability. Although this study integrates GPs, CP and CE principles in a novel way and assesses them in Saudi Arabia for the first time, the assessment of the moderating roles of CP and CE principles in the Saudi Arabian context is a novel contribution of this study. This study offers a significant contribution to the adoption of green technologies in manufacturing industries and advances Saudi Arabia Vision 2030. This study also provides insights for policymakers, engineers and institutions to design environmentally friendly strategies along with the advancement of the manufacturing sector in Saudi Arabia and abroad. This study also advances the SDGs.

Limitations and Future Work

This study was conducted in Saudi Arabia, limiting its generalizability. The theoretical framework of this study can be tested in other nations to make it more generalizable. Furthermore, this study is limited to the manufacturing sector; the framework can also be examined in other industrial sectors to enhance its generalizability in other sectors. Similarly, due to its scope and time, this study may have overlooked other variables that can be added in future studies. The sample size is limited to 242. It can be increased in future studies to strengthen the validity of the results. The adoption of GPs is very complex, and considering only CP and CE as moderators is not sufficient. All these limitations open doors for future researchers to conduct research on this topic and address the limitations.

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Institutional Review Board Statement: This study was conducted in accordance with the ethical principles of the Declaration of Helsinki and Research Center for Humanities and Sciences, King Saud University (protocol code 2026/14GP and 5 April 2026).

Informed Consent Statement: All participants were informed about the purpose of the study, and informed consent was obtained prior to their participation. Participant confidentiality and anonymity were maintained throughout the research process.

Data Availability Statement: The data file is available and can be obtained from the author on request.

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References

1. Singh, V. Global Warming and Climate Change. In *Textbook of Environment and Ecology*; Springer: Berlin/Heidelberg, Germany, 2024; pp. 283–295.
2. Beyond an Age of Waste Turning Rubbish into a Resource. 2024. Available online: https://wedocs.unep.org/20.500.11822/44939 (accessed on 12 March 2026).
3. WMO Greenhouse Gas Bulletin. 2025. Available online: https://wmo.int/resources/publication-series/greenhouse-gas-bulletin/wmo-greenhouse-gas-bulletin-no-21 (accessed on 12 March 2026).
4. Statista Fossil Fuel Consumption per Capita Worldwide from 1965 to 2024. Statista. Available online: www.statista.com (accessed on 29 May 2026).
5. Boopathi, S. Implementation of Green Manufacturing Practices in Automobile Fields. In *Sustainable Machining and Green Manufacturing*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2024; pp. 221–248. [CrossRef]
6. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.P.; Hultink, E.J. The circular economy—A new sustainability paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [CrossRef]
7. Gómez-Merino, A.I.; Jiménez-Galea, J.J.; Rubio-Hernández, F.J.; Arjona-Escudero, J.L.; Santos-Ráez, I.M. Heat transfer and rheological behavior of fumed silica nanofluids. *Processes* **2020**, *8*, 1535. [CrossRef]
8. Islam, M.S.; Islam, M.M.; Rehman, A.U.; Biswas, H.A. Performance of renewable energy technology and environmental safety in the Hail region of Saudi Arabia: Moderating effect of regulatory governance and public awareness. *Asia-Pac. J. Reg. Sci.* **2026**, *10*, 11. [CrossRef]
9. Hossain, M.I.; San, O.T.; Ling, S.M.; Said, R.M. The role of environmental awareness and green technological usage to foster sustainable green practices in Bangladeshi manufacturing SMEs. *Int. J. Adv. Sci. Technol.* **2020**, *29*, 3115–3124.
10. Geldermann, J.; Kolbe, L.M.; Krause, A.; Mai, C.; Militz, H.; Osburg, V.S.; Schöbel, A.; Schumann, M.; Toporowski, W.; Westphal, S. Improved resource efficiency and cascading utilisation of renewable materials. *J. Clean. Prod.* **2016**, *110*, 1–8. [CrossRef]
11. Leksic, I.; Stefanic, N.; Veza, I. The impact of using different lean manufacturing tools on waste reduction. *Adv. Prod. Eng. Manag.* **2020**, *15*, 81–92. [CrossRef]

12. Borah, P.S.; Dogbe, C.S.K.; Marwa, N. Green dynamic capability and green product innovation for sustainable development: Role of green operations, green transaction, and green technology development capabilities. *Corp. Soc. Responsib. Environ. Manag.* **2025**, *32*, 911–926. [CrossRef]
13. Praskievicz, S. From Hetch Hetchy to the Cuyahoga: How rivers shaped the American environmental movement. *Prof. Geogr.* **2021**, *73*, 26–37. [CrossRef]
14. Mulvaney, D. *Green Technology: An A-to-Z Guide*; Sage: Newcastle upon Tyne, UK, 2011; Volume 10.
15. Song, A.; Rasool, Z.; Nazar, R.; Anser, M.K. Towards a greener future: How green technology innovation and energy efficiency are transforming sustainability. *Energy* **2024**, *290*, 129891. [CrossRef]
16. Zhang, H.; Yu, Z.; Zhu, C.; Yang, R.; Yan, B.; Jiang, G. Green or not? Environmental challenges from photovoltaic technology. *Environ. Pollut.* **2023**, *320*, 121066. [CrossRef]
17. Xiong, Y.; Guo, H.; Nor, D.D.M.M.; Song, A.; Dai, L. Mineral resources depletion, environmental degradation, and exploitation of natural resources: COVID-19 aftereffects. *Resour. Policy* **2023**, *85*, 103907. [CrossRef]
18. Cheng, X.; Yan, C.; Ye, K.; Chen, K. Enhancing resource efficiency through the utilization of the green bond market: An empirical analysis of Asian economies. *Resour. Policy* **2024**, *89*, 104623. [CrossRef]
19. Thiede, S.; Bogdanski, G.; Herrmann, C. A systematic method for increasing the energy and resource efficiency in manufacturing companies. *Procedia CIRP* **2012**, *2*, 28–33. [CrossRef]
20. Wang, Z.; Huang, Y.; Ankrah, V.; Dai, J. Greening the knowledge-based economies: Harnessing natural resources and innovation in information and communication technologies for green growth. *Resour. Policy* **2023**, *86*, 104181. [CrossRef]
21. Sharma, S.; Basu, S.; Shetti, N.P.; Kamali, M.; Walvekar, P.; Aminabhavi, T.M. Waste-to-energy nexus: A sustainable development. *Environ. Pollut.* **2020**, *267*, 115501. [CrossRef] [PubMed]
22. Boopathi, S. Minimization of Manufacturing Industry Wastes Through the Green Lean Sigma Principle. In *Sustainable Machining and Green Manufacturing*; John Wiley & Sons: Hoboken, NJ, USA, 2024; pp. 249–270.
23. Wang, Y.P.; Smith, R. Wastewater minimisation. *Chem. Eng. Sci.* **1994**, *49*, 981–1006. [CrossRef]
24. Hassan, Q.; Viktor, P.; Al-Musawi, T.J.; Ali, B.M.; Algburi, S.; Alzoubi, H.M.; Al-Jiboory, A.K.; Sameen, A.Z.; Salman, H.M.; Jaszczur, M. The renewable energy role in the global energy Transformations. *Renew. Energy Focus* **2024**, *48*, 100545. [CrossRef]
25. Mentel, G.; Lewandowska, A.; Berniak-Woźny, J.; Tarczyński, W. Green and renewable energy innovations: A comprehensive bibliometric analysis. *Energies* **2023**, *16*, 1428. [CrossRef]
26. Holechek, J.L.; Geli, H.M.E.; Sawalhah, M.N.; Valdez, R. A global assessment: Can renewable energy replace fossil fuels by 2050? *Sustainability* **2022**, *14*, 4792. [CrossRef]
27. Klemeš, J.J.; Varbanov, P.S.; Pierucci, S.; Huisingh, D. Minimising emissions and energy wastage by improved industrial processes and integration of renewable energy. *J. Clean. Prod.* **2010**, *18*, 843–847. [CrossRef]
28. Kuhlman, T.; Farrington, J. What is sustainability? *Sustainability* **2010**, *2*, 3436–3448.
29. Harsanto, B.; Kumar, N.; Michaelides, R. Sustainability-oriented innovation in manufacturing firms: Implementation and evaluation framework. *Bus. Strategy Environ.* **2024**, *33*, 5086–5108.
30. Kucharska, W.; Kowalczyk, R. How to achieve sustainability?—Employee's point of view on company's culture and CSR practice. *Corp. Soc. Responsib. Environ. Manag.* **2019**, *26*, 453–467. [CrossRef]
31. Arora, N.K.; Fatima, T.; Mishra, I.; Verma, M.; Mishra, J.; Mishra, V. Environmental sustainability: Challenges and viable solutions. *Environ. Sustain.* **2018**, *1*, 309–340. [CrossRef]
32. Paauwe, J. Resource based theory. In *A Guide to Key Theories for Human Resource Management Research*; Edward Elgar Publishing: Cheltenham, UK, 2024; pp. 231–237.
33. Beatson, A.; Gottlieb, U.; Pleming, K. Green consumption practices for sustainability: An exploration through social practice theory. *J. Soc. Mark.* **2020**, *10*, 197–213. [CrossRef]
34. Ahmad, A.; Ikram, A.; Rehan, M.F.; Ahmad, A. Going green: Impact of green supply chain management practices on sustainability performance. *Front. Psychol.* **2022**, *13*, 973676. [CrossRef]
35. Ni, L.; Ahmad, S.F.; Alshammari, T.O.; Liang, H.; Alsanie, G.; Irshad, M.; Alyafi-AlZahri, R.; BinSaeed, R.H.; Al-Abyadh, M.H.A.; Bakir, S.M.D.M.A.; et al. The role of environmental regulation and green human capital towards sustainable development: The mediating role of green innovation and industry upgradation. *J. Clean. Prod.* **2023**, *421*, 138497. [CrossRef]
36. Habiba, U.M.M.E.; Xinbang, C.; Anwar, A. Do green technology innovations, financial development, and renewable energy use help to curb carbon emissions? *Renew. Energy* **2022**, *193*, 1082–1093. [CrossRef]
37. Mathews, J.A.; Reinert, E.S. Renewables, manufacturing and green growth: Energy strategies based on capturing increasing returns. *Futures* **2014**, *61*, 13–22. [CrossRef]
38. Ellabban, O.; Abu-Rub, H.; Blaabjerg, F. Renewable energy resources: Current status, future prospects and their enabling technology. *Renew. Sustain. Energy Rev.* **2014**, *39*, 748–764. [CrossRef]
39. Fresner, J. Cleaner production as a means for effective environmental management. *J. Clean. Prod.* **1998**, *6*, 171–179. [CrossRef]

40. Nilsson, L. *Cleaner Production: Technologies and Tools for Resource Efficient Production*; Baltic University Press: Uppsala, Sweden, 2007; Volume 2.
41. Ali, H.; Chen, T.; Hao, Y. Sustainable manufacturing practices, competitive capabilities, and sustainable performance: Moderating role of environmental regulations. *Sustainability* **2021**, *13*, 10051. [CrossRef]
42. Zeng, S.X.; Meng, X.H.; Yin, H.T.; Tam, C.M.; Sun, L. Impact of cleaner production on business performance. *J. Clean. Prod.* **2010**, *18*, 975–983. [CrossRef]
43. Giannetti, B.F.; Agostinho, F.; Eras, J.J.C.; Yang, Z.; Almeida, C. Cleaner production for achieving the sustainable development goals. *J. Clean. Prod.* **2020**, *271*, 122127. [CrossRef]
44. Mostaghimi, K.; Behnamian, J. Waste minimization towards waste management and cleaner production strategies: A literature review. *Environ. Dev. Sustain.* **2023**, *25*, 12119–12166. [CrossRef]
45. Ikram, M.; Ferasso, M.; Sroufe, R.; Zhang, Q. Assessing green technology indicators for cleaner production and sustainable investments in a developing country context. *J. Clean. Prod.* **2021**, *322*, 129090. [CrossRef]
46. Available online: https://www.europarl.europa.eu/topics/en/article/20151201STO05603/circular-economy-definition-importance-and-benefits (accessed on 23 March 2026).
47. Corvellec, H.; Stowell, A.F.; Johansson, N. Critiques of the circular economy. *J. Ind. Ecol.* **2022**, *26*, 421–432. [CrossRef]
48. Jaeger, B.; Upadhyay, A. Understanding barriers to circular economy: Cases from the manufacturing industry. *J. Enterp. Inf. Manag.* **2020**, *33*, 729–745. [CrossRef]
49. Gheewala, S.H. Material recycling in a circular economy—A systems view. *Wiley Interdiscip. Rev. Energy Environ.* **2024**, *13*, e503. [CrossRef]
50. Velenturf, A.P.M.; Purnell, P. Principles for a sustainable circular economy. *Sustain. Prod. Consum.* **2021**, *27*, 1437–1457. [CrossRef]
51. Chen, X.; Memon, H.A.; Wang, Y.; Marriam, I.; Tebyetekerwa, M. Circular Economy and sustainability of the clothing and textile Industry. *Mater. Circ. Econ.* **2021**, *3*, 12. [CrossRef]
52. Dolci, V.; Bigliardi, B.; Petroni, A.; Pini, B.; Filippelli, S.; Tagliente, L. Integrating Industry 4.0 and Circular Economy: A Conceptual Framework for Sustainable Manufacturing. *Procedia Comput. Sci.* **2024**, *232*, 1711–1720. [CrossRef]
53. Sanguino, R.; Barroso, A.; Fernández-Rodríguez, S.; Sánchez-Hernández, M.I. Current trends in economy, sustainable development, and energy: A circular economy view. *Environ. Sci. Pollut. Res.* **2020**, *27*, 1–7. [CrossRef]
54. Barreiro-Gen, M.; Lozano, R. How circular is the circular economy? Analysing the implementation of circular economy in organisations. *Bus. Strategy Environ.* **2020**, *29*, 3484–3494. [CrossRef]
55. Raluca, B. Circular Economy and Recycling in the Textile Industry. *Ann. Univ. Oradea. Fascicle Text. Leatherwork* **2023**, *24*, 17–26.
56. Nikolaou, I.E.; Jones, N.; Stefanakis, A. Circular economy and sustainability: The past, the present and the future directions. *Circ. Econ. Sustain.* **2021**, *1*, 1–20. [CrossRef]
57. Hailemariam, A.; Erdiaw-Kwasie, M.O. Towards a circular economy: Implications for emission reduction and environmental sustainability. *Bus. Strategy Environ.* **2023**, *32*, 1951–1965. [CrossRef]
58. Gómez-Prado, R.; Alvarez-Risco, A.; Sánchez-Palomino, J.; de las Mercedes Anderson-Seminario, M.; Del-Aguila-Arcentales, S. Circular Economy for Waste Reduction and Carbon Footprint. In *Circular Economy: Impact on Carbon and Water Footprint*; Alvarez-Risco, A., Muthu, S.S., Del-Aguila-Arcentales, S., Eds.; Springer: Singapore, 2022; pp. 139–159. [CrossRef]
59. Barney, J. Firm resources and sustained competitive advantage. *J. Manag.* **1991**, *17*, 99–120. [CrossRef]
60. Mills, J.; Platts, K.; Bourne, M. Applying resource-based theory: Methods, outcomes and utility for managers. *Int. J. Oper. Prod. Manag.* **2003**, *23*, 148–166. [CrossRef]
61. Sharp, L.; Macrorie, R.; Turner, A. Resource efficiency and the imagined public: Insights from cultural theory. *Glob. Environ. Change* **2015**, *34*, 196–206. [CrossRef]
62. Allenby, B. The ontologies of industrial ecology? *Prog. Ind. Ecol. Int. J.* **2006**, *3*, 28–40. [CrossRef]
63. Graedel, T.E. On the Concept of Industrial Ecology. 1996. Available online: www.annualreviews.org (accessed on 25 March 2026).
64. Van Berkel, R.; Willems, E.; Lafleur, M. The relationship between cleaner production and industrial ecology. *J. Ind. Ecol.* **1997**, *1*, 51–66. [CrossRef]
65. Ehrenfeld, J.R. Eco-Efficiency and Industrial Ecology Eco-Efficiency Philosophy, Theory, and Tools. *J. Ind. Ecol.* **2005**, *9*, 6–8.
66. Takiguchi, H.; Takemoto, K. Japanese 3R policies based on material flow analysis. *J. Ind. Ecol.* **2008**, *12*, 792–798. [CrossRef]
67. Williams, A.; Kennedy, S.; Philipp, F.; Whiteman, G. Systems thinking: A review of sustainability management research. *J. Clean. Prod.* **2017**, *148*, 866–881. [CrossRef]
68. Bigdeloo, M.; Teymourian, T.; Kowsari, E.; Ramakrishna, S.; Ehsani, A. Sustainability and circular economy of food wastes: Waste reduction strategies, higher recycling methods, and improved valorization. *Mater. Circ. Econ.* **2021**, *3*, 3–9. [CrossRef]
69. Mutezo, G.; Mulopo, J. A review of Africa's transition from fossil fuels to renewable energy using circular economy principles. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110609. [CrossRef]
70. Iacovidou, E.; Hahladakis, J.N.; Purnell, P. A systems thinking approach to understanding the challenges of achieving the circular economy. *Environ. Sci. Pollut. Res.* **2021**, *28*, 24785–24806. [CrossRef]

71. Ghisellini, P.; Cialani, C.; Ulgiati, S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* **2016**, *114*, 11–32. [CrossRef]
72. Hart, S.L. A natural-resource-based view of the firm. *Acad. Manag. Rev.* **1995**, *20*, 986–1014. [CrossRef]
73. Tukker, A. Product services for a resource-efficient and circular economy—A review. *J. Clean. Prod.* **2015**, *97*, 76–91. [CrossRef]
74. Bansal, P.; Roth, K. Why companies go green: A model of ecological responsiveness. *Acad. Manag. J.* **2000**, *43*, 717–736. [CrossRef]
75. Gómez-Merino, A.I.; Jiménez-Galea, J.J.; Rubio-Hernández, F.J.; Santos-Ráez, I.M. Experimental assessment of thermal and rheological properties of coconut oil-silica as green additives in drilling performance based on minimum quantity of cutting fluids. *J. Clean. Prod.* **2022**, *368*, 133104. [CrossRef]
76. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [CrossRef]
77. Seuring, S.; Müller, M. From a literature review to a conceptual framework for sustainable supply chain management. *J. Clean. Prod.* **2008**, *16*, 1699–1710. [CrossRef]
78. Kline, R.B. *Principles and Practice of Structural Equation Modeling*, 4th ed.; Guilford Press: New York, NY, USA, 2016.
79. Khalid, B.; Urbański, M.; Kowalska-Sudyka, M.; Wysłocka, E.; Piontek, B. Evaluating consumers' adoption of renewable energy. *Energies* **2021**, *14*, 7138. [CrossRef]
80. de Oliveira Neto, G.C.; Tucci, H.N.P.; Correia, J.M.F.; da Silva, P.C.; da Silva, V.H.C.; Ganga, G.M.D. Assessing the implementation of Cleaner Production and company sizes: Survey in textile companies. *J. Eng. Fibers Fabr.* **2020**, *15*, 1558925020915585. [CrossRef]
81. Gusmerotti, N.M.; Testa, F.; Corsini, F.; Pretner, G.; Iraldo, F. Drivers and approaches to the circular economy in manufacturing firms. *J. Clean. Prod.* **2019**, *230*, 314–327. [CrossRef]
82. Rodríguez-Espíndola, O.; Cuevas-Romo, A.; Chowdhury, S.; Díaz-Acevedo, N.; Albores, P.; Despoudi, S.; Malesios, C.; Dey, P. The role of circular economy principles and sustainable-oriented innovation to enhance social, economic and environmental performance: Evidence from Mexican SMEs. *Int. J. Prod. Econ.* **2022**, *248*, 108495. [CrossRef]
83. Bressler, R.D. Science and Challenges of Sustainability. In *Sustainability: Business and Investment Implications*; World Scientific Publishing: Singapore, 2024; pp. 9–38. [CrossRef]
84. Davim, J.P. Sustainable and Intelligent Manufacturing: Perceptions in line with 2030 Agenda of Sustainable Development. *Bioresources* **2024**, *19*, 4.
85. Friant, M.C.; Vermeulen, W.J.V.; Salomone, R. Transition to a sustainable circular society: More than just resource efficiency. *Circ. Econ. Sustain.* **2024**, *4*, 23–42. [CrossRef]
86. Gao, J.Q.; Li, D.; Qiao, G.H.; Jia, Q.R.; Li, S.R.; Gao, H.L. Circular economy strategies in supply chains, enhancing resource efficiency and sustainable development goals. *Environ. Sci. Pollut. Res.* **2024**, *31*, 8751–8767. [CrossRef]
87. Feng, C.-Y.; Yang, X.; Afshan, S.; Irfan, M. Can renewable energy technology innovation promote mineral resources' green utilization efficiency? Novel insights from regional development inequality. *Resour. Policy* **2023**, *82*, 103449. [CrossRef]
88. Fatimah, Y.A.; Govindan, K.; Murniningsih, R.; Setiawan, A. Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia. *J. Clean. Prod.* **2020**, *269*, 122263. [CrossRef]
89. Hannan, M.A.; Begum, R.A.; Al-Shetwi, A.Q.; Ker, P.J.; Al Mamun, M.A.; Hussain, A.; Basri, H.; Mahlia, T.M.I. Waste collection route optimisation model for linking cost saving and emission reduction to achieve sustainable development goals. *Sustain. Cities Soc.* **2020**, *62*, 102393. [CrossRef]
90. Debnath, B.; Taha, M.R.; Siraj, M.T.; Jahin, M.F.; Ovi, S.I.; Bari, A.M.; Islam, A.R.M.T.; Raihan, A. A grey approach to assess the challenges to adopting sustainable production practices in the apparel manufacturing industry: Implications for sustainability. *Results Eng.* **2024**, *22*, 102006. [CrossRef]
91. Bilal, M.J.; Shaheen, W.A. Towards sustainable development: Investigating the effect of green financial indicators on renewable energy via the mediating variable. *Renew. Energy* **2024**, *221*, 119819. [CrossRef]
92. Shahzad, M.; Qu, Y.; Rehman, S.U.; Zafar, A.U. Adoption of green innovation technology to accelerate sustainable development among manufacturing industry. *J. Innov. Knowl.* **2022**, *7*, 100231. [CrossRef]
93. Candra, O.; Chammam, A.; Alvarez, J.R.N.; Muda, I.; Aybar, H.Ş. The impact of renewable energy sources on the sustainable development of the economy and greenhouse gas emissions. *Sustainability* **2023**, *15*, 2104. [CrossRef]
94. Fang, X.; Liu, M.; Li, G. Resource curse or sustainable development: The green technology innovation effect of resource-based city transformation. *Clean. Technol. Environ. Policy* **2026**, *28*, 41. [CrossRef]
95. Dantas, T.E.T.; de-Souza, E.D.; Destro, I.R.; Hammes, G.; Rodriguez, C.M.T.; Soares, S.R. How the combination of Circular Economy and Industry 4.0 can contribute towards achieving the Sustainable Development Goals. *Sustain. Prod. Consum.* **2021**, *26*, 213–227. [CrossRef]

96. Salmenperä, H.; Pitkänen, K.; Kautto, P.; Saikku, L. Critical factors for enhancing the circular economy in waste management. *J. Clean. Prod.* **2021**, *280*, 124339. [CrossRef]
97. Jiménez-Galea, J.J.; Martín-Martín, M.Á.; Martín-Béjar, S. Digitalization of Legacy Machining Tools: A Case Study of a Manual Drill Press. *Heritage* **2026**, *9*, 73. [CrossRef]

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