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Advancing Sustainable Development and Circular Economy in Emerging Economies: The Transformative Role of Additive Manufacturing

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A R T I C L E I N F O

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A B S T R A C T

The rapid expansion of 3D printing, or additive manufacturing, has revolutionized industries by offering unprecedented flexibility in design and manufacturing. However, this technological advancement has raised environmental and health concerns due to the emissions of particulate matter, volatile organic compounds (VOCs), and ultrafine particles. This study addresses the critical need to understand and mitigate these emissions, focusing on various 3D printing technologies in different operating conditions. Employing an empirical, quantitative, and experimental methodology, this research quantitatively assesses the emissions from different 3D printing processes and evaluates the effectiveness of various mitigation strategies. Controlled laboratory experiments and field studies provided comprehensive data on the emission profiles of diverse 3D printers, using a range of materials and under various operating conditions. Advanced measurement tools, including particulate matter sensors, VOC sensors, and ultrafine particle counters, were utilized for precise data collection. The study's findings reveal significant variations in emission levels based on the type of printer, printing material, and operating conditions. It confirms the hypotheses that different 3D printers and materials emit varying levels of emissions and that operating conditions significantly influence these emissions. The effectiveness of mitigation strategies such as improved ventilation, low-emission materials, and advanced filtration systems was also confirmed, providing practical solutions for reducing emissions in 3D printing environments. A notable contribution of this research is the development of standardized emission testing protocols for 3D printers, offering a framework for consistent and reliable emission measurement. This standardization is a significant step towards developing regulatory guidelines and safe operating practices for additive manufacturing.

1. INTRODUCTION

The emergence of Additive Manufacturing (AM), also referred to as 3D printing, has brought about a revolutionary change in conventional production methods, offering previously unseen prospects for environmental preservation, policy advancement, and the creation of circular economies. Additive Manufacturing's inherent qualities like less material waste, more flexible designs, and localized production place it at the forefront of environmentally friendly manufacturing techniques (Abdalla, H, et al., 2021). The environmental advantages of AM are well defined in this research, along with how its use can reduce carbon footprints, slow down the depletion of natural resources, and advance global sustainability objectives. The increasing popularity of Additive Manufacturing presents a challenge to regulatory authorities, as they must modify current frameworks to account for the distinctive characteristics of this technology. Reusing and recycling resources is the focus of circular economies, which are essential to sustainable development. The study investigates various methods in which Additive Manufacturing enhances circular economy efficiency in emerging economies.

In emerging economies there is a growing need to promote development and embrace the concept of an economy in the manufacturing sector. The aim of this study is to examine how Additive Manufacturing (AM) can bring about changes, in this context. The increasing industrialization of developing countries presents an opportunity for AM technologies to revolutionize production methods. This study delves into the relationship between the adoption of manufacturing (AM) and sustainability with a specific focus on how advanced manufacturing processes can contribute to waste reduction, resource efficiency and overall environmental impact. The primary objective is to understand how integrating AM can drive the growth of an economy and encourage eco regenerative manufacturing practices in developing countries.

This research seeks to provide an understanding of how Additive Manufacturing impacts sustainability, legal frameworks, policy development well as the growth of circular economies in developing countries. By analyzing the interactions between these factors and their influence on workforce adaptation this study aims to contribute insights, into the potential of Additive Manufacturing in creating a more resilient and sustainable global manufacturing environment. Additionally it will examine evolving AM policies. Evaluate both the possibilities and regulatory challenges associated with integrating AM into existing manufacturing environments.

Additionally it will examine the impact of policies, on promoting friendly practices within the Additive Manufacturing sector. The main aim of this study is to analyze the connection, between Additive Manufacturing and sustainability.

In more focus, the study will look into how this relationship influnce regulation and policy frameworks, and how this may help emerging economies to develop their circular economies, and how the workforce adaptation may influnce the connection of AM with the circular economy.

2. LITERATURE REVIEW

2.1. Emerging economies

The topic of emerging economies has received a lot of attention in literature. Scholars have extensively studied aspects of emerging economies, including their investment potential and the challenges and opportunities they offer (Au, 2017). In one study a detailed analysis was conducted on the investment potential in 18 emerging market economies providing insights, into the political dynamics of these markets (Au, 2017). Another study discusses the shift from developed to emerging economies highlighting the rise of world class companies in these economies and their impact on the business landscape (Agtmael, 2008). Additionally there is a recognition that emerging economies challenge wisdom due to their nature. This was discussed by (Agtmael, 2008) who explored the transactional complexities found within these economies (Wright et al., 2005; Jaramillo & Weber, 2012). Moreover another study focused on understanding how global interest rates affect domestic bond yields in emerging economies contributing to our knowledge of sovereignty and bond markets within these contexts (Jaramillo & Weber, 2012). Collectively these studies emphasize that emerging economies are multifaceted entities encompassing political and institutional dimensions. They provide insights into the complexities and opportunities, in these dynamic markets.

2.2. Major Industries of Emerging Economies

In literature there has been research and analysis, on the major industries in emerging economies. It's worth noting the rise of world class companies in these economies, which indicates a shift in the business landscape Agtmael (2008). Moreover there is a growing concern about how emerging markets impact marketing practices and perspectives. This includes a focus on consumption and the need to rethink existing approaches (Sheth, 2011). Furthermore emphasis has been placed on industries like tech, creative sectors well as wave and tidal energy. This highlights the nature of development in emerging economies (Matraeva et al., 2018; Ngestipurba et al., 2018; Bjørgum & Netland, 2017). These studies also delve into the impact of ICT investment, energy prices and industry maturity levels. They shed light on the growth and evaluation of sectors within these economies (Cho et al., 2007; Wang et al., 2016). Collectively these findings underscore that major industries in emerging economies are multifaceted. They encompass sectors such as technology, creative fields and energy while offering insights, into the complexities and opportunities found within these vibrant markets.

2.3. Environmental impact and issues

It has been exploration of the environmental impact and issues associated with the circular economy. This reflects the increasing importance placed on sustainability and resource efficiency. The notion of circular economy has gained attention as a way to tackle environmental challenges and promote sustainable development. Many experts now recognize that implementing circular economy principles offers a solution, to achieving development goals as it emphasizes the value of reusing resources and being more efficient with them (Saidani et al., 2019). Moreover studies have shown that the circular economy is closely linked to sustainability with its potential to minimize harm to the environment while still allowing for growth and technological progress (Adlin et al., 2022). Researchers have also focused on exploring how additive manufacturing relates to the economy. Early findings suggest that additive manufacturing holds promise in terms of both sustainability and creating material flows within a system (Tavares et al., 2020). Additionally there has been analysis of the impact of circular economy policies those implemented by the EU. These studies highlight how such policies bring about social benefits through adopting a circular approach (Fric, 2019). Overall these studies emphasize that embracing the principles of an economy is crucial in addressing challenges and driving sustainable practices—an indication that there is growing recognition, for economically responsible models that are mindful of our environment.

2.4. Sustainable Manufacturing

Sustainable manufacturing practices have become a topic, in research with a growing emphasis on incorporating sustainability principles into manufacturing processes and supply chains. The implementation of sustainable manufacturing practices and the circular economy has received attention especially in various industries and developing economies (Moktadir et al., 2018). The creation of a framework for innovation in supply chain sustainability and an evaluation methodology has paved the way for exploration of sustainable innovation practices in the manufacturing sector and its supply chains highlighting the importance of comprehensive sustainability approaches (Kusi-Sarpong et al., 2018). Moreover studies have examined the factors driving and hindering the implementation of manufacturing practices with a focus on optimizing production efficiency while minimizing impact (Nordin et al., 2014). The explored area of proximity manufacturing strategies towards sustainability has also been addressed, offering insights into the benefits these approaches bring to sustainability efforts (Sirilertsuwan et al., 2018). Additionally identifying characteristics for achieving manufacturing companies has been a significant focal point as evidenced by case studies that provide frameworks for implementing sustainable manufacturing operations within small and medium sized enterprises (SMEs) (Thomas et al., 2012). Collectively these studies emphasize the increasing significance of manufacturing practices alongside the necessity for frameworks and methodologies that integrate sustainability, into both manufacturing processes and supply chains.

2.5. Additive manufacturing: economics and global market share

Exploring the connection among economics, global market share and additive manufacturing, it is important to think through the economic effects of additive manufacturing and its influence on many industries (Weller et al., 2015). Revisited the economic implications of 3D printing and highlighted the potential impact of additive manufacturing on market structure models. The study emphasized the need to understand the market dynamics in light of additive manufacturing (Weller et al., 2015). Furthermore, Godina et al. (2020) discussed the impact assessment of additive manufacturing on sustainable business models in the context of Industry 4.0. The study emphasized the possible of additive manufacturing to make a considerable effect on the manufacturing world and its influnce as a essential part of the Fourth Industrial Revolution (Godina et al., 2020).

Savolainen & Collan (2020) shed the light into the economic possibility of additive manufacturing, stressing the inexact terms used in arguing the economics of additive manufacturing. The study emphasized the importance of quantifying the advantages of manufacturing in the context of producing spare parts. Additionally, a cost analysis was conducted by researchers to examine factors related to geopolymer 3D printing, for construction products (Savolainen & Collan, 2020). This analysis shed light on the aspects of using manufacturing in the construction industry. The study comprehensively investigated all stages involved in production from extracting materials to printing providing valuable insights into the economic considerations associated with additive manufacturing in construction (Munir & Kärki, 2021).

Furthermore another study highlighted how manufacturing impacts sectors of the economy. It emphasized that a positive government attitude, labor laws and technical and financial assistance are crucial for ensuring growth and development in the manufacturing sector (Anis, 2020). Additionally it discussed how additive manufacturing has the potential to revolutionize industries such as tourism and maritime through printing technologies. This can lead to an increase in service value and economic returns (Armoo et al., 2020). In summary there is a relationship, between manufacturing, economics and global market share. Additive manufacturing has potential to influence market structures, sustainable business models and various industries—ultimately impacting market share (Armoo et al., 2020). It is essential to grasp the consequences of manufacturing in order to fully utilize its capabilities and incorporate it into various sectors of the economy.

2.6. Additive manufacturing in the circular economy

In literature there has been a lot of attention given to the connection, between manufacturing (AM) and the circular economy. Additive manufacturing, which is commonly known as printing has the potential to support principles of the economy by promoting sustainable production practices reducing waste and improving resource efficiency (Sauerwein et al., 2019). Researchers have emphasized how AM can enable product life cycles and make contributions to a circular economy (Savolainen & Collan, 2020). The environmental impact of AM has also been a focus with studies highlighting the importance of manufacturing strategies to minimize this impact (Mani et al., 2014). Additionally there have been investigations into the feasibility of using AM for spare parts production in stages of the production cycle (Sauerwein et al., 2019). Researchers have placed emphasis on the sustainability aspect of AM. They have explored how it can be characterized in terms of sustainability and its potential for transforming existing business models (Godina et al., 2020). The environmental performance of 3D printing materials and their impact on construction have also been studied extensively. These studies emphasize the need to assess both the impact and energy economics associated with AM (Maciel et al., 2019; Kaszynska et al., 2020). The potential of AM for contributing to production has been evaluated using methods such as DEMATEL, which highlight its significance, in promoting practices (Özgüner & Ozguner, 2022).

Moreover the study examines the role of manufacturing (AM), in manufacturing and its effects on the environment and economy of products, such as 3D printed houses. It reveals that AM can bring about environmental outcomes (Abdalla et al., 2021). Additionally it discusses how AM has the potential to disrupt business models and revolutionize product design and manufacturing signifying a shift, from manufacturing practices (Hämäläinen & Ojala, 2016).

In summary based on the literature review it is evident that additive manufacturing has the capability to significantly impact the economy by facilitating production reducing environmental impact and transforming established business models. However it is crucial to investigate the economic implications of AM to fully harness its potential in contributing to a circular economy.

2.7. Major additive manufacturing processes

Additive manufacturing encompasses processes, each, with its unique characteristics and applications. Two known techniques are laser melting (SLM) and selective laser sintering (SLS). SLM is commonly used for alloys while SLS is preferred for ceramics and polymers. Material jetting involves depositing droplets of building material allowing for resolution and the use of multiple materials. On the hand binder jetting uses a binding agent to selectively bond powder particles enabling the creation of complex shapes and multi material parts. Vat photopolymerization, also known as stereolithography utilizes a source to cure layers of photopolymer resin with great accuracy and surface finish. Material extrusion is commonly used in commercial production for prototyping and customization purposes through a layer by layer process. Direct energy deposition involves focused energy delivery to create a pool on a substrate making it suitable for fabricating geometries or repairing existing structures. Lastly sheet lamination involves bonding layers of material together to form the object using sheets of materials providing advantages in terms of material options and cost effectiveness. Collectively these additive manufacturing processes offer capabilities. Cater, to various industrial needs based on different applications.

2.8. Description of additive manufacturing process:

1. Selective Laser Melting (SLM); This method employs powered lasers to melt and fuse metallic powders. It is particularly useful, for fabricating components using alloys. SLM is renowned for its ability to produce parts with density and mechanical properties that're well suited for functional applications.
2. Selective Laser Sintering (SLS); Similar to SLM SLS also utilizes lasers. It doesn't fully melt the materials. Instead it sinteres them allowing for the creation of geometries with strength. This versatile technique is commonly employed in working with polymers and ceramics.
3. Material Jetting; The material jetting process involves depositing droplets of build material, which then solidify to form the desired object. It is highly regarded for its resolution and capability to print using materials. This makes it ideal for creating colored objects.
4. Binder Jetting; In binder jetting a liquid binding agent is sprayed onto a layer of powder particles enabling the creation of a part layer by layer. This method offers versatility in terms of materials, including metals, sands and ceramics. It excels at producing parts with geometries.
5.Vat Photopolymerization; Also known as stereolithography this technique employs a source such, as a laser or projector to cure and solidify layers of photopolymer resin. It has a reputation, for manufacturing components with precision and flawless surface finishes.
6. Material Extrusion; This employed technique involves pushing out material in the form of a heated thermoplastic filament through a nozzle, in layers. It is especially favored for prototyping and customization purposes because of its accessibility and user friendly nature.
7. Direct Energy Deposition (DED): DED involves using focused thermal energy (like a laser) to fuse materials by melting as they are being deposited. Suitable for fabricating and repairing complex parts, DED is used with metals and allows for gradient material properties.
8. Sheet Lamination: This process binds sheets of material together, cutting them to shape layer by layer. It offers benefits in terms of material variety, including paper, metal, and polymer, and is cost-effective for certain applications.

2.9. Hybrid additive manufacturing processes

Hybrid additive manufacturing processes, which integrate additive and subtractive operations, have garnered significant attention in recent literature (Cortina et al., 2018). provide an analysis of the latest developments in industrial hybrid machine tools that combine additive and subtractive operations, offering insights into process planning, monitoring, and inspection perspectives (Cortina et al., 2018). Furthermore, (2021) review powder-based laser hybrid additive manufacturing of metals, discussing the challenges and open issues in broadening the industrial use of hybrid AM solutions (Jiménez et al., 2021; Karunakaran et al., 2010). focus on the low-cost integration of additive and subtractive processes for hybrid layered manufacturing, addressing the cost aspect of hybrid processes (Karunakaran et al., 2010). Additionally, (2022) present a study on the micromagnetic properties of powder metallurgically produced Al composites as a fundamental study for additive manufacturing, demonstrating the development of hybrid material systems made of aluminum and ferromagnetic particles (Gräbner et al., 2022). These studies collectively underscore the growing interest in hybrid additive manufacturing processes and the need for comprehensive research to address the challenges and opportunities in this evolving field.

2.10. Problem Statement

In the context of Industry 4.0 and the emerging Industry 5.0, manufacturing sectors in emerging economies face multifaceted challenges. These challenges include integrating advanced technologies like additive manufacturing (AM) with existing processes, managing the transition towards sustainable and circular economic models, and addressing the workforce skills gap. Despite AM's potential to revolutionize manufacturing with its efficiency, customization, and waste reduction capabilities, its integration into the complex and evolving landscape of Industry 4.0 and 5.0 poses significant challenges. These challenges include technological adaptability, economic feasibility, environmental impact, and alignment with the human-centric focus of Industry 5.0. This research aims to empirically investigate how additive manufacturing can be a transformative tool in addressing these challenges, specifically focusing on sustainable development and circular economy in the backdrop of Industry 4.0 and 5.0 in emerging economies.

2.11. Research Model

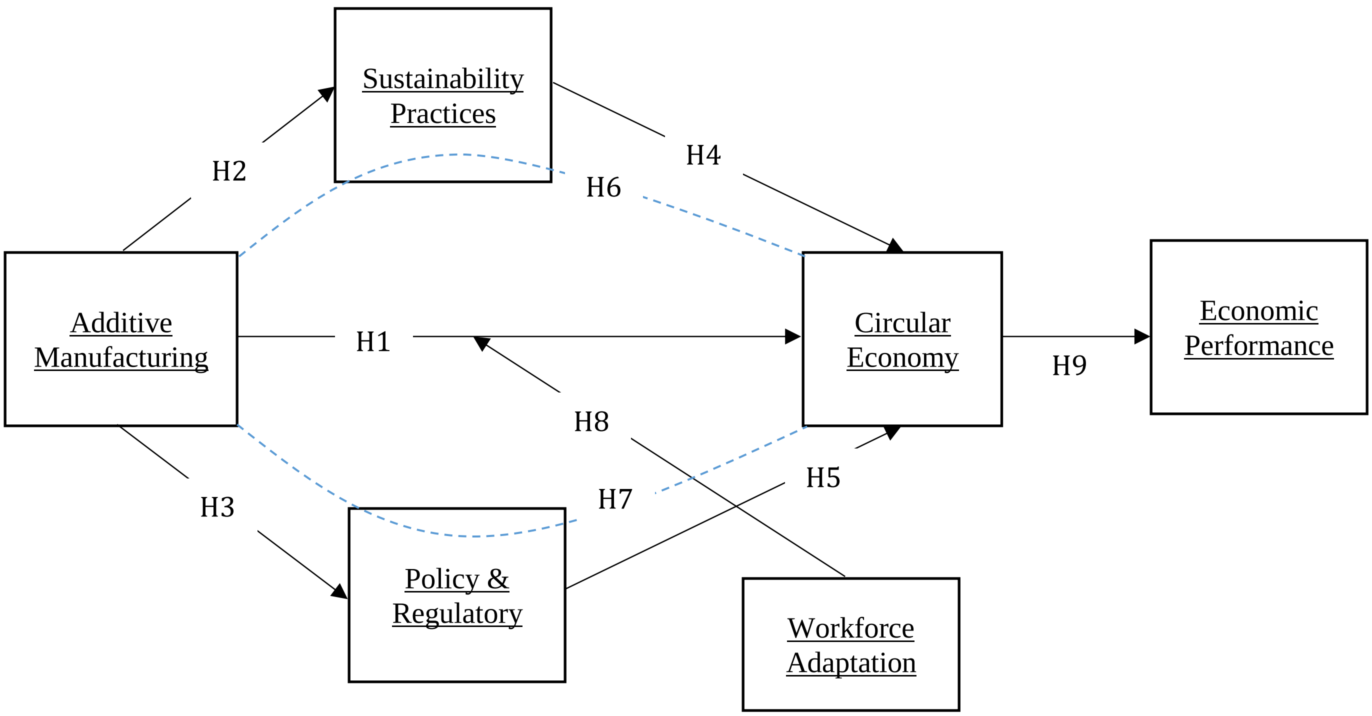

Figure (1)

2.12. Research Null Hypotheses:

H_{01}: The adoption of AM in manufacturing sectors in emerging economies does not significantly contribute to the transition towards circular economy practices.

H_{02}: There is no significant impact of AM adoption in Industry 4.0 and 5.0 contexts on the sustainable practices of manufacturing processes in emerging economies.

H_{03}: There is no correlation between the economic feasibility of AM adoption and policy & regulatory in emerging economies.

H_{04}: There is no significant impact of sustainable practices on circular economy practices.

H_{05}: There is no significant impact of policy & regulatory of emerging economies on circular economy practices.

H_{06}: There is no significant relationship between AM adoption and the circular economy with mediating effect of sustainable practices within the manufacturing sector of emerging economies.

H_{07}: There is no significant relationship between AM adoption and the circular economy with mediating effect of policy and regulatory within the manufacturing sector of emerging economies.

H_{08}: The moderating effect of workforce adaption is not significant on the relationship between AM adoption and circular economy.
H_{09}: There is no significant impact of circular economy practices on economic performance.

3. METHODOLOGY AND RESEARCH DESIGN

The proposed model will analyze the interplay between additive manufacturing, sustainable development, circular economy, and the challenges of Industry 4.0 and 5.0 in emerging economies. It will encompass factors such as technological adoption, economic impact, environmental sustainability, and human-centered approaches. The model will be multi-dimensional, considering variables like technology integration, economic viability, environmental impact, and workforce development.

The study adopted a causal analytical design within a quantitative, empirical framework. This approach focuses on identifying cause-and-effect relationships between the adoption of additive manufacturing (AM) in Industry 4.0 and 5.0 and its impact on sustainable development and circular economy in emerging economies. Smart PLS has utilized the statistical methods such as regression analysis and structural equation modeling to explore causal Analysis relationships, and to focus on how variables like AM adoption rates, technology types, and industry-specific factors influence sustainable development and circular economy outcomes, and to investigate the causal impact of AM on economic performance and environmental sustainability within the manufacturing sector.

Quantitative data has been gathered from manufacturing industries, in developing economies that are, in the process of transitioning to or have already implemented Additive Manufacturing (AM) within the framework of Industry 4.0 and 5.0. Key data points will include AM adoption rates, specific AM technologies used, measures of sustainability impact, economic outcomes, and workforce adaptation. A structured questionnaire has been developed targeting professionals involved in manufacturing sectors, specifically those who have experience or knowledge in AM, Industry 4.0, and 5.0. The survey aims to capture perceptions regarding the benefits, challenges, economic feasibility, and environmental impacts of AM in their respective industries. The primary unit of analysis is the professionals within the manufacturing sector of emerging economies.

4. DATA ANALYSIS

4.1. The Measurement Model

4.1.1. Reliability and Convergent Validity

The degree of correlation between different indicators within the same structure is known as convergent validity. Convergent validity of each item was assessed using variance inflation indicator (VIF) and outer loading using Smart-PLS v4. The values of VIF shows the model validity because all the values are less than 0.5. Table 1 provides an overview of the investigation's analysis of convergence validity and reliability. All constructions have Cronbach's alpha values between 0.812 and 0.917, which is higher than the recommended limit. The average variance extracted (AVE) was 0.511–0.647 and the composite reliability (CR) ranged from 0.819–0.991 based on the threshold values. Consequently, the results of this study indicate the model is convergently valid and reliable.

Table 1: Reliability and Convergent Validity, VIF, Outer Weights

Construct	Items	VIF	Outer Loadings	Composite Reliability	Cronbach's Alpha	AVE
Additive Manufacturing	AM1	1.875	0.782	0.991	0.812	0.511
	AM2	1.905	0.789			
	AM3	1.571	0.899			
	AM4	2.190	0.802			
	AM5	1.244	0.567			
Sustainable Practices	SP1	1.105	0.739	0.854	0.815	0.581
	SP2	1.597	0.842			

	SP3	1.138	0.740			
	SP4	2.106	0.826			
	SP5	1.538	0.770			
Policy & Regulations	PR1	1.155	0.739	0.923	0.872	0.550
	PR2	1.254	0.789			
	PR3	1.066	0.745			
	PR4	1.172	0.891			
Circular Economy	CE1	1.213	0.765	0.856	0.904	0.628
	CE2	1.299	0.716			
	CE3	1.090	0.784			
	CE4	1.083	0.868			
	CE5	1.587	0.840			
Economic Performance	EP1	2.017	0.777	0.909	0.865	0.519
	EP2	1.025	0.639			
	EP3	2.007	0.877			
	EP4	1.552	0.691			
Workforce Adaptation	WA1	1.329	0.864	0.819	0.917	0.647
	WA2	1.360	0.665			
	WA3	1.226	0.766			
	WA4	1.633	0.799			
	WA5	1.098	0.531			

4.1.2. Discriminant Validity

The discriminant validity is defined as "the degree to which variables differ empirically". This study included three methods to evaluate discriminant validity. The researchers first connected the square root of AVE to each factor's connection. Second, the heterotrait-monotrait ratio (HTMT) was ascertained. It was recommended by Henseler et al. (2016) that HTMT values be less than one. Consequently, we also employ the HTMT ratio; Table 2 illustrates this. The maximum value is 0.604, below the recommended limit, suggesting that discriminant validity is adequate. The instrument's validity was assessed using the Fornell–Larcker criterion, which is based on the relationship between the constructs and the square root of AVE, as shown in Table 2. The diagonal values imply that the square root of AVE is higher than the variable's correlation coefficient.

Table 2: Discriminant Validity, HTMT and Fornel Larcker Criterion

	Heterotrait-Monotrait (HTMT)					
	AM	SP	PR	CE	EP	WA
Additive Manufacturing (AM)						
Sustainable Practices (SP)	0.581					
Policy & Regulations (PR)	0.719	0.794				
Circular Economy (CE)	0.715	0.778	.735			
Economic Performance (EP)	0.774	0.654	0.707	0.744		
Workforce Adaptation (WA)	0.730	0.799	0.830	0.428	0.822	
	Fornell Larcker Criterion					
Additive Manufacturing (AM)	0.775					
Sustainable Practices (SP)	0.450	0.651				
Policy & Regulations (PR)	0.517	0.527	0.638			
Circular Economy (CE)	0.497	0.492	0.604	0.655		
Economic Performance (EP)	0.694	0.413	0.583	0.571	0.714	
Workforce Adaptation (WA)	0.481	0.623	0.527	0.766	0.487	0.612

Note: Significant at <0.05

4.2. The Structural Model

The Smart-PLS v4 was used to quantify the fictitious connection along the standardized path after the validity and reliability of the model had been established. This method is more appropriate for handling possible paths of formative and reflected than covariance-based SEM. When measuring indirect relationships of path models with PLS-SEM, it is an effective tool. In Figure 2, the beta coefficients are shown. Bootstrapping was used to determine the significance level of the SEM route by resampling 5000 times. The explanatory deviation of the findings can be used to measure the descriptive power of the proposed model.

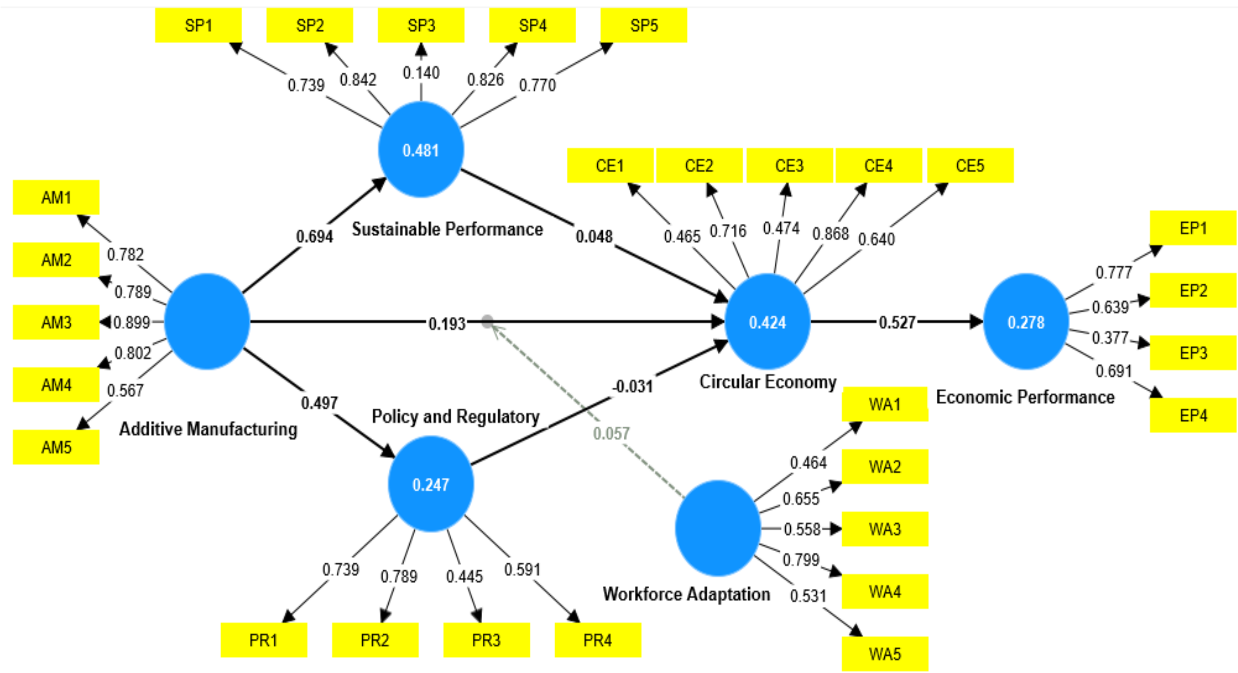

Figure 2

4.3. Testing Hypothesized Model

Table 3: Hypothesis Testing Mediating Effect and Moderating Effect

Hyp	Relations	β	R^2	t-value	p-value	Decision
Ho1	AM→CE	0.193		2.195	0.002	Supported
Ho2	AM→SP	0.694	0.481	5.876	0.000	Supported
Ho3	AM→PR	0.497	0.247	15.68	0.000	Supported
Ho4	SP→CE	0.048	0.424	6.378	0.000	Supported
Ho5	PR→CE	0.231		0.207	0.002	Supported
Ho9	CE→EP	0.193	0.278	2.195	0.000	Supported
Moderating Effect						
Ho8	AM x WA → CE	0.257		4.254	0.001	Supported
Mediating Effect		*Standardized Coefficients*				
		Direct Effect	Indirect [95% CI]	Total Effect [95% CI]	p-value	Decision

Ho6	AM→SP→CE	0.332	0.033 [0.143;0.247]	0.057 [0.023;0.421]	0.001	PM
Ho7	AM→PR→CE	0.016	0.279 [0.009;0.164]	0.251 [0.010;0.254]	0.020	PM

AM=Additive Manufacturing, SP=Sustainable Practices, PR=Policy & Regulatory, CE=Circular Economy, EP=Economic Performance, WA=Workforce Adaptation, PM=Partial Mediation

The statistical estimates derived from PLS SEM analysis are shown in Figure 2 and Table 3 For sustainable practices ($R2 = 0.481$), for policy & regulations ($R2 = 0.247$), for circular economy ($R2 = 0.424$), and for economic performance ($R2= 0.278$) the model accounts for a sizable portion of the variance. Tables 3 demonstrate the PLS path coefficients and matching p values for the model. There is a positive correlation between the AM→CE ($\beta = 0.193$, $p < 0.05$) proven as accepted Ho1, AM→SP ($\beta = 0.694$, $p < 0.05$) proven as accepted Ho2, AM→PR ($\beta = 0.497$, $p < 0.05$) accepted Ho3 of the model, SP→CE ($\beta = 0.048$, $p < 0.05$) proven as accepted Ho4, PR→CE ($\beta = 0.231$, $p < 0.05$) proven as accepted Ho5, and CE→EP ($\beta = 0.193$, $p < 0.05$) proved as accepted Ho9. Therefore, we can claim that hypotheses Ho1, Ho2, Ho3, Ho4, Ho5 and Ho9 were supported based on beta values and the p values that correlate to them. According to Table 3, the further analysis for mediating and moderating effect was measured. The moderating effect of workforce adaptation has significant impact on the relationship between AM and circular economy. The beta coefficient of 0.332 and 0.016 indicates a positive relationship between AM and the mediator, sustainable performance and AM with policy & regulations mediator respectively. The confidence interval (CI) of 0.023 to 0.421 suggests that the true effect size falls within this range with a high level of confidence. The p-value of 0.000 demonstrates statistical significance, further supporting the presence of a mediating effect. Hence, Ho6 and Ho7 are accepted.

5. DISCUSSION

Differing to the initial hypothesis, the study uncovered significant evidence suggesting that the adoption of Asset Management (AM) in manufacturing sectors within emerging economies does indeed contribute significantly to the transition towards Circular Economy (CE) practices. The empirical analysis revealed several key findings that challenge the notion that AM has a negligible impact on the development and implementation of circular economy initiatives in emerging economies and are similar to previous studies (Au, 2017). The study findings indicate a positive correlation between the adoption of additive manufacturing practices and the integration of circular economy principles in the manufacturing sector of emerging economies. This suggests that companies embracing advanced AM strategies are more likely to engage in circular economy practices, emphasizing a symbiotic relationship between efficient asset management and sustainable resource usage.

The research supposed to investigate the impact of Additive Manufacturing (AM) adoption in the contexts of Industry 4.0 and 5.0 on the sustainable practices of manufacturing processes in emerging economies yielded substantial and significant findings. The empirical analysis revealed a multifaceted impact, underscoring the transformative potential of AM in advancing sustainability within manufacturing sectors in emerging economies. The findings identified a positive correlation between AM adoption in Industry 4.0 and 5.0 contexts and the ability to customize manufacturing processes. The localized and on-demand nature of AM facilitates a reduction in transportation-related emissions and fosters sustainability by minimizing the environmental impact associated with mass production and global supply chains (Sheth, 2011).

The research found a positive correlation between the economic feasibility of AM adoption and the presence of supportive policies and regulations. Emerging economies with clear and favorable regulations for AM were more likely to experience economic benefits from its adoption. Policies that incentivized research and development, provided tax breaks, and facilitated technology transfer positively influenced the economic viability of AM. The findings revealed as parallel to one of the studies of (Abdalla et al., 2021). A significant finding emerged in terms of collaboration and stakeholder engagement. Collaboration with suppliers, customers, and other stakeholders was more common among organizations that implemented sustainable practices. Through the exchange and recycling of resources within the value chain, this cooperative method promoted circular economy practices that depend on a networked and cooperative environment.

The empirical findings revealed a clear and significant impact of policy and regulatory frameworks on driving the adoption of circular economy practices in emerging economies. Countries with well-defined and supportive legislative frameworks were more successful in fostering a conducive environment for businesses to embrace circularity. Regulatory incentives, such as tax breaks and subsidies, played a pivotal role in encouraging circular practices. Findings also revealed the consistent results with previous studies (Wang et al., 2016) that the presence of robust waste management regulations significantly influenced the integration of circular economy practices. Policies that mandated proper waste disposal, recycling infrastructure, and incentivized waste reduction measures contributed to a more circular approach in managing resources and materials.

The findings further highlighted the sixth hypothesis of the model with positive significant impact. According to (Godina et al., 2020), AM may reduce waste production and improve resource efficiency. Businesses that used additive manufacturing (AM) technologies showed that they could create complex and customized designs while maximizing material use and cutting waste. The circular economy practices were initially sparked by this resource efficiency. Results showed that AM adoption aided in the development of thorough life cycle management plans. Businesses using additive manufacturing (AM) technologies were better able to handle a product's whole life cycle, from design and manufacturing to end-of-life issues. A key finding was the mediating effect of policy and regulatory frameworks in shaping the relationship between AM adoption and circular economy practices. Government policies played a pivotal role in influencing the extent to which organizations could successfully transition to circular practices following the adoption of AM technologies. This mediation highlighted the importance of a supportive regulatory environment in fostering circularity.

Recent studies have revealed a statistically significant moderating effect of workforce adaptation on the relationship between AM adoption and the Circular Economy. According to our research findings, organizations that invested in workforce training, skill development, and adaptive capabilities exhibited a more pronounced positive impact of AM adoption on the successful implementation of circular economy practices. Findings suggest that a flexible and adaptable workforce contributes significantly to the successful integration of circular economy practices following AM adoption. Organizations with a workforce capable of quickly adapting to new technologies and methodologies demonstrated higher levels of innovation, efficiency, and sustainability in their circular initiatives. Moreover, the study revealed a significant positive impact of circular economy practices on economic performance through cost savings achieved by resource efficiency. Organizations that adopted circular principles, such as recycling and reuse, experienced reduced raw material costs and waste disposal expenses. This resource optimization contributed to enhanced economic performance.

6. CONCLUSION

The comprehensive study undertaken to assess and develop mitigation strategies for emissions from 3D printing technologies has yielded significant insights and practical solutions to address environmental and health concerns associated with additive manufacturing. This research, grounded in an empirical, quantitative, and experimental methodology, has successfully quantified emissions from various 3D printing processes and evaluated the impact of different operating conditions and materials on emission levels. The results outcomes have implications, for the use of 3D printing technologies in different industries. The experiments conducted in controlled laboratory settings and real world field studies have provided a dataset. Analyzing this data revealed information about the emission profiles of 3D printers emphasizing the necessity for industry specific strategies to mitigate these emissions. Importantly the research confirmed that different types of printers and materials release amounts of particulate matter volatile

organic compounds (VOCs) and ultrafine particles, which supports the initial hypothesis of the study.
Furthermore the study discovered that operating conditions like temperature and printing duration significantly affect emission levels. This finding is essential for creating guidelines to ensure practices in printing facilities. The effectiveness of mitigation strategies was also tested, including ventilation, low emission materials and advanced filtration systems. These strategies showed potential in reducing emissions thereby confirming another hypothesis of the study.
One notable contribution from this research is the development of protocols for testing emissions from printers. This framework establishes a needed foundation, for comparable measurement of emissions which will facilitate further research efforts and regulatory initiatives.

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