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3D Printing Adoption, Regulatory Compliance and Environmental Sustainability in South Africa

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Abstract – 3D printing adoption, regulatory compliance and environmental sustainability has become relevant in research since attention has been drawn to environmental consequences related to operations of 3D printing firms. This study seeks to examine the direct and mediating relationships between 3D printing technology adoption, regulatory compliance and environmental sustainability among 3D printing firms in South Africa. The study randomly selected 152 employees of 3D printing firms to participate in the study using questionnaires. Results showed that a non-significant positive relationship exists between 3D printing technology adoption and environmental sustainability, while a significant negative relationship exists between 3D printing technology adoption and regulatory compliance. A significant positive relationship was found to exist between 3D printing regulatory compliance and environmental sustainability. 3D printing regulatory compliance was found to negatively mediate the relationship between 3D printing technology adoption and environmental sustainability. The results of the study have implications on the need for 3D printing firms to invest in regulatory compliance as a strategic element to achieve environmental sustainability.

Keywords – 3D Printing, Sustainability, Validity, Reliability, Technology, Compliance

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1 Introduction

The emergence of 3D printing technology, has significantly transformed the manufacturing industry by providing exceptional prospects for quick prototyping, customization, and decentralized production (Bogue, 2020). Nevertheless, as this revolutionary 3D printing technology increasingly gains popularity, it is crucial to analyze the environmental consequences of its broad use, specifically within South Africa's 3D printing sector. We find it relevant to carefully examine the direct and indirect (mediating) relationships between 3D printing technology adoption, regulatory compliance and environmental sustainability in South Africa. This is because, our assessment of current body of research has realized that researchers have rather focused their attention on the advantages of 3D printing in promoting more streamlined and localized manufacturing methods, thereby decreasing the requirement for transportation and lowering waste by producing items as needed (Garmulewicz et al., 2018).

In the study conducted by Huang et al. (2017), it was realized that the utilization of 3D printing has the potential to greatly decrease emissions associated with transportation. Huang et al. (2017) further emphasized the capacity of 3D printing to minimize material waste by employing on-demand manufacturing, a process that creates things only when they are required, hence removing the necessity for surplus inventory. In addition, Chen et al. (2015) conducted a thorough examination to assess the sustainability prospects of 3D printing in several sectors. Chen et al. (2015) emphasized the capacity of 3D printing to provide effective design optimization, resulting in the development of lightweight and optimized items which does not only decrease the amount of material used but also leads to energy conservation throughout the lifespan of the product. In addition, researchers have emphasized the capacity of 3D printing technology to facilitate the development of lightweight and optimal designs, resulting in decreased utilization of materials and energy conservation throughout the lifespan of the product (Saade, Yahia & Amor, 2020; Pal, Mohanty & Misra, 2021). However, Naghshineh, Ribeiro, Jacinto and Carvalho (2021) argue that the environmental consequences of 3D printing are inherently connected to the selection of materials, energy sources, and the legal framework that governs its use.

However, there is a lack of research on the role of regulatory compliance in addressing this issue. Existing research has mostly concentrated on the technical and economic dimensions of 3D printing (De Schutter, Lesage, Mechtcherine, Nerella, Habert & Agusti-Juan, 2018), with insufficient investigation into the relationship between technological adoption, and environmental sustainability from the perspective of regulatory compliance. In addition, although South Africa has made progress in formulating environmental legislation and regulations, the rapid rate of technology progress frequently surpasses the policymakers' capacity to stay updated (Andreoni & Tregenna, 2020). Moreover, the absence of thorough life cycle assessments (LCAs) and defined methodology for assessing the environmental consequences of 3D printing procedures and materials presents a notable challenge (Bours, Adzima, Gladwin, Cabral & Mau, 2017). Nevertheless, the existing body of research fails to provide a comprehensive analysis of how regulatory compliance contributes to addressing the relationship between technological adoption, and environmental sustainability in the field of 3D printing, which creates a knowledge gap in 3D printing research. Our study therefore seeks to contribute to knowledge by examining the effect of 3D printing technology adoption on environmental sustainability among 3D printing firms in South Africa. Our study also seeks to examine the mediating effect of regulatory compliance on the relationships between 3D printing technology adoption on environmental sustainability among 3D printing firms.

2 Literature Review

2.1 3D printing technology adoption

The adoption of 3D printing technology, also known as additive manufacturing, involves integrating advanced manufacturing methods into a company's operations to create three-dimensional objects from digital models (Schniederjans, 2017). This technology builds objects layer by layer, using materials such as plastics, metals, and composites, based on precise digital designs (Ukobitz, 2020). 3D printing adoption is highly relevant in today's manufacturing landscape due to its ability to revolutionize production processes and product development (Calli & Calli, 2020). It allows for rapid prototyping, enabling companies to quickly and cost-effectively create and test design concepts (Calli & Calli, 2020). According to Sun, Peng, Zhou, Fuh, Hong and Chiu (2015) 3D printing facilitates customized production, making it possible to produce unique, complex geometries that would be difficult or impossible to achieve with traditional manufacturing methods. This is particularly valuable in industries such as aerospace, healthcare, and automotive, where bespoke parts and components are often required (Sun et al., 2015).

2.2 Environmental sustainability in 3D printing

Environmental sustainability in 3D printing involves intentional strategies to minimize the negative environmental impacts associated with additive manufacturing throughout the entire lifecycle of a product (Pakkanen, Manfredi, Minetola & Iuliano, 2017). According to Khosravani and Reinicke (2020) environmental sustainability, encompasses various stages, from material selection and energy consumption to waste management and end-of-life disposal or recycling. Pakkanen et al. (2017) attests that, the primary aim of environmental sustainability is to ensure that every phase of the 3D printing process contributes to sustainability goals. The choice of materials plays a crucial role in sustainable 3D printing (Jandyal, Chaturvedi, Wazir, Raina & Haq, 2022). Environmentally friendly materials, such as biodegradable plastics and recycled composites, are preferred to reduce the ecological footprint (Jandyal et al., 2022). Energy consumption is another critical factor relating to environmental sustainability (Delaney, Liu, Zhu, Xu & Dai, 2022). Accord-

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ing to Delaney et al. (2022), 3D printing technology adoption can be energy intensive, but adopting energy efficient techniques and utilizing renewable energy sources can significantly lower the environmental impact. Implementing advanced technologies and optimizing production processes to reduce energy usage is essential for sustainability. Waste management is also a significant consideration in sustainable 3D printing (Dey, Srinivas, Panda, Suraneni, P., & Sitharam, 2022). Nadagouda, Ginn and Rastogi (2020) notes that efforts are made to minimize waste production by improving the precision of additive manufacturing processes, thus reducing material excess. Moreover, any waste generated is managed through recycling programs, where leftover materials are repurposed for future use, thereby reducing the amount of waste that ends up in landfills. At the end of a product's life, sustainable practices involve the proper disposal or recycling of 3D printed items (Nadagouda et al., 2020). As Subramani et al. (2024) highlight, sustainable 3D printing aims to reduce resource consumption, greenhouse gas emissions, and waste generation.

2.3 3D printing regulatory compliance

Regulatory compliance in the context of 3D printing involves the rigorous adherence to a broad spectrum of rules, regulations, and standards governing the use of additive manufacturing technology (Khairuzzaman, 2018). According to Dagne (2019), regulatory compliance encompasses various aspects, including environmental regulations, health and safety standards, intellectual property laws, and industry-specific requirements. Adhering to environmental regulations ensures that 3D printing processes minimize their ecological footprint by controlling emissions, managing waste, and using sustainable materials (Peng, Kellens, Tang, Chen & Chen, 2018). Compliance with health and safety standards is crucial to protect workers and consumers from potential hazards associated with 3D printing operations, such as exposure to harmful substances or mechanical risks (Savitt, Haertlein & Dubois, 2022). Sople (2016) notes that, observance of intellectual property laws is also vital, as it safeguards the rights of creators and prevents unauthorized use of patented designs and technologies. Ensuring regulatory compliance is essential for conducting 3D printing operations responsibly and sustainably (Kamble, Belhadi, Gupta, Islam, Verma and Solima, L. (2023). Kamble et al. (2023) also attests that regulatory compliance enhances the credibility and market acceptance of 3D printed products. By adhering to these regulations, companies can operate within legal frameworks, avoid penalties, and contribute to a safer and more sustainable industry (Nissan, 2016).

2.4 Hypotheses Development

This section presents literature for hypotheses development on direct and mediating relationships between 3D printing technology adoption, regulatory

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compliance and environmental sustainability among 3D printing firms in South Africa.

Impact of 3D printing technology adoption on environmental sustainability

Khan, Koç and Al-Ghamdi (2021) conducted a study to examine the ecological consequences of dispersed manufacturing through the utilization of 3D printing technology. The researchers performed a life cycle assessment (LCA) and compared the environmental impact of conventional centralized production with a dispersed manufacturing scenario facilitated by 3D printing. Their research showed that implementing 3D printing for decentralized production could substantially decrease emissions and energy usage associated with transportation, therefore promoting environmental sustainability. Cerdas, Juraschek, Thiede and Herrmann (2017) conducted an extensive examination of life cycle assessments (LCAs) pertaining to decentralized manufacturing using 3D printing technology. Their investigation demonstrated that the implementation of 3D printing technology could result in environmental sustainability, including decreased material waste, transportation emissions, and energy usage, in comparison to conventional centralized production processes. Waqar, Othman and Pomares (2023) conducted an empirical research that specifically examined the environmental consequences of implementing 3D printing technology in the building sector. The researchers performed a comparative Life Cycle Assessment (LCA) to compare traditional building methods with construction techniques through the usage of 3D printing technology. Their research revealed that using 3D printing technology in the construction industry has the potential to greatly enhance environmental sustainability by ensuring decrease in material waste, energy use, and greenhouse gas emissions. Based on the empirical literature, we hypothesize that: *H1: There is a significant positive relationship between 3D printing technology adoption and environmental sustainability.*

Impact of 3D printing regulatory compliance on environmental sustainability

A research conducted by Taylor, Freeman and van der Ploeg (2021) investigated the influence of environmental legislation on the implementation of 3D printing technology inside the European Union (EU). The researchers conducted a survey and interviews with stakeholders from the 3D printing sector to gain insights into their viewpoints on the current regulatory framework and how it affects sustainable practices. The study revealed that although the EU has implemented rules pertaining to waste management, material safety, and energy economy, it lacks precise norms and standards for 3D printing procedures. Bianchi, Volpe, Fiorito, Forcellese and Sangiorgio (2024) performed a comprehensive evaluation of life cycle assessments (LCAs) of additive manufacturing techniques, which encompass 3D printing. The researchers emphasized the necessity of implementing uniform methodology and regulatory frameworks in order to guarantee consistent and dependable life cycle assessment (LCA) processes within the 3D printing sector. Aghimien, Aigbavboa, Aghimien, Thwala and Ndlovu (2021) conducted a study in South Africa to examine the variables that facilitate or hinder the adoption of 3D printing technology. The authors of the research recognized that regulatory compliance plays a crucial role in enabling the responsible and sustainable adoption of 3D printing. The study by Aghimien et al. (2021) emphasized the necessity of a strong regulatory framework to tackle concerns related to material safety, waste management, and energy efficiency linked to 3D printing procedures. Based on the empirical literature, we hypothesize that: *H2: There is a significant positive relationship between regulatory compliance and environmental sustainability.*

Impact of 3D printing regulatory compliance on environmental sustainability

Khosravani and Reinicke (2020) undertook an extensive examination of the sustainability implications of 3D printing. The researchers discovered that the extent to which 3D printing may enhance the effective utilization of resources and energy is contingent upon the degree to which enterprises adhere to both current and forthcoming rules, hence determining its environmental sustainability. The study by Montes (2017) also found that companies that deliberately modify their 3D printing technology adoption to meet or surpass regulatory standards generally attain greater levels of environmental sustainability. Additionally, Kumar Ali, Ali, Jain, Anwer, Iqbal, and Mirza (2022) investigated the impact of regulatory frameworks on the use of 3D printing technology in the healthcare industry. Their research unveiled that strict rules concerning patient safety and the quality of medical devices unintentionally resulted in the adoption of more sustainable practices. The finding by Kumar et al. (2022) further indicated that companies that have used 3D printing for medical purposes have had to allocate resources towards stringent quality control measures and waste minimization in order to adhere to these restrictions Based on the literature, the study hypothesizes that: *H3: There is a significant positive relationship between 3D printing regulatory compliance and environmental sustainability*

Mediating role of regulatory compliance on the relationship between 3D printing technology adoption and environmental sustainability

A study conducted by Alami, Olabi, Alashkar, Alasad, Aljaghoub, Rezk, and Abdelkareem (2023) revealed that the implementation of 3D printing in the aerospace and automotive sectors is significantly influenced by strict adherence to safety and emissions requirements. These industries are bound by rigorous guidelines that ensure the durability of components and regulate the emissions produced over their lifespan. The research indicated that companies leveraging 3D printing technology to manufacture lighter and more complex components achieved greater compliance with fuel economy and pollution regulations. Specifically, the use of 3D printing allowed for the creation of intricate designs that reduced overall weight, leading to enhanced fuel efficiency and lower emissions. The study emphasized that this technological advancement is not just beneficial for regulatory compliance but also contributes to the overall sustainability of the aerospace and automotive industries. By adopting 3D printing, these sectors can meet stringent environmental standards while simultaneously improving performance and efficiency. This finding aligns with earlier research by Huang et al. (2019), which highlighted the role of advanced manufacturing technologies in promoting environmental sustainability. Thus, the strategic implementation of 3D printing in these industries is crucial for achieving regulatory compliance and advancing sustainable practices. Based on the empirical literature, we hypothesize that: *H4: Regulatory compliance will mediate the relationship between 3D printing technology adoption and environmental sustainability.*

2.5 Theoretical and Conceptual Framework

The Technology-Organization-Environment (TOE) theory, proposed by Tornatzky and Fleischer (1990), is the most suitable theory for expounding the connections between the variables of interest which comprise 3D printing cost, technology adoption, regulatory compliance and environmental sustainability. The TOE theory is commonly used to analyze the elements that impact the acceptance and deployment of new technologies in businesses (Awa, Ojiabo & Orokor, 2017). The TOE theory posits that the assimilation of a new technology is impacted by three distinct contexts: technical, organizational, and environmental (Cheng & Olesen, 2017). The technical context refers to the inherent attributes of the technology, including its cost, complexity, compatibility, and perceived advantages (Oettmeier & Hofmann, 2017). The organizational context encompasses the inherent attributes of the organization, including its magnitude, framework, assets, and willingness to embrace new technology (Adegbite, Simintiras, Dwivedi & Ifie, 2017). The environmental context refers to external elements that affect the company, including the regulatory environment, competitive challenges, and industry trends (Ahmed & Streimikiene, 2021).

We argue that the TOE theory is justified for this study because it provides a comprehensive lens to examine the direct and mediating relationships between 3D printing technology adoption, regulatory compliance and environmental sustainability among 3D printing firms in South Africa. We contend that, the adoption of 3D printing technology aligns with the technological context of TOE, influencing the adoption decision, particularly for 3D printing firms in South Africa. Meanwhile, the organizational context, encompasses financial resources, technical expertise, and organizational culture, which shape the effective adoption of 3D printing technology. Finally, the study argues that the environmental context, emphasize the importance of regulatory compliance and environmental sustainable practices in the adoption and deployment of 3D printing technology in South Africa.

2.6 Conceptual framework

The study dwelled on the TOE theory to propose three (3) hypotheses in this conceptual framework, for the direct and mediating relationships between 3D printing technology adoption, regulatory compliance and environmental sustainability among 3D printing firms in South Africa. The hypotheses were developed based on e[illegible]ch hypothesize positive relationships between3D printi[illegible]on and environmental sustainability, as well as 3D pri[illegible]iance and environmental sustainability. Based on emp[illegible]tudy also hypothesized that, regulatory compliance will mediate the relationship between 3D printing technology adoption and environmental sustainability.

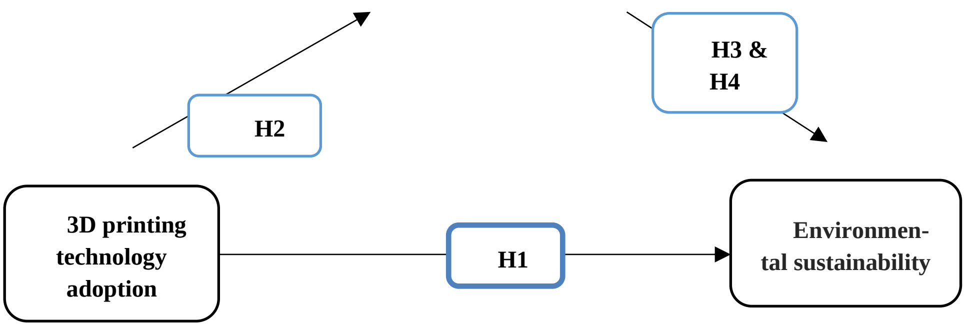

Figure 1: Conceptual framework

Source: Authors' construct, 2024

3 Methodology

3.1 Population, Sampling Technique and Sample

The study population consisted of employees from 3D printing firms who attended the 23rd Annual RAPDASA (Rapid Product Development Association of South Africa) Conference in South Africa. To determine the appropriate sample size, the Macorr sample size calculator was initially utilized for a population of 275. Using the Macorr sample Size calculator, at a 95% confidence level, the suitable sample size for this population is 161.A simple random sampling technique was employed to select the respondents. Google Forms was used for online data collection, ensuring that each participant had an equal chance of being selected. To implement this technique, numbers were assigned to the emails of the 275 employees from the 3D printing firms and institutions that participated in the conference. The Statistical Package for Social Sciences (SPSS) version 26 random number generator function was then used to select random numbers corresponding to 161 participant emails out of the total population of 275. However, out of the 161 respondents, 154 responded to the questionnaires, thereby giving a response rate of 95.7%

3.2 Data Collection

Data collection was conducted online using Google Forms. An approved questionnaire was converted to an online format with Google Forms and then emailed to participants who were randomly selected by the researcher using the SPSS random generator. The data gathering process spanned four months, primarily due to delays by respondents in completing the online questionnaires. To address this, email reminders were periodically sent until an acceptable response rate was achieved for data analysis.

3.3 Measures

Questionnaires served as the data collection instruments of the study. The questionnaires were designed based on the objectives of the study. During the questionnaire design process, the study dwelled on relevant literature to construct the items of the questionnaire for measuring each of the constructs under investigation. 3D printing technology adoption was measured using three (3) items adopted from Ukobitz (2020). Meanwhile, regulatory compliance was measured using five (5) items adopted from (Khairuzzaman, 2018). Environmental sustainability was measured using three (3) items, adopted from Delaney et al. (2022).

3.4 Data Analysis

First, the data gathered from Google Forms was extracted into Microsoft Excel format and then imported into the Statistical Package for Social Sciences (SPSS) version 26 software. The data was coded by assigning appropriate numerical values and entered into the SPSS software. The SPSS software was also used to analyze the demographic data of the participants as well as descriptive statistics of the variables, such as minimum, maximum, mean and standard deviations. After importing the data from SPSS, the researcher utilized Smart PLS 4 software to conduct direct and indirect (mediating) analysis for testing the proposed hypotheses. This analysis was performed using Partial Least Squares (PLS) Structural Equation Modeling (SEM). PLS-SEM is a statistical technique commonly employed in social sciences research to examine direct and indirect relationships between variables (Hair et al., 2021). It allows researchers to assess both the direct and indirect effects of variables on the outcome of interest (Cepeda-Carrion et al., 2018). In this study therefore, we utilized PLS-SEM to examine the direct and mediating relationships between 3D printing technology adoption, regulatory compliance and environmental sustainability among 3D printing firms in South Africa.

4 Results

4.1 Demographic data of respondents

Results from table 1 indicate that majority of respondents were between the ages of 36-40 years as they were represented by 36.2% of the total respondents. Meanwhile 20.4% were between the ages of 31-35 years, 18.4% were between the ages of 41-45 years, 12.5% were between the ages of 26-30 years, 9.2% were between 46-50 years while 3.3% were more than 50 years. In terms of gender distribution, the study was dominated by the opinions of males as they constituted 74.3% while females constituted 25.7%. For educational level of respondents, majority of them have attained their master's degree (33.6%), 28.3% have attained their honors or postgraduate diploma, 17.8% have attained their bachelors or advanced diploma (17.8%), 11.2% have attained their doctorate degree, 6.6% have attained their diploma while 2.6% have attained their advanced certificate. In terms of work title of respondents, it was found that majority of them are CAD designers (28.3%), 19.7% are operations officers, 13.2% are business developers, 12.5% are researchers, 11.8% are IT personnel, 8.6% are sales personnel and 5.9% are marketing officers. For firm category of respondents, it was found that majority of respondents work in 3D consulting as well as software and related technologies (71%), 12.5% work in 3D material supplier firms, 9.9% work in 3D design and tool making firms while 6.6% work in 3D machine reseller firms. In terms of the ethnic origin of the respondents, majority of them are Black South Africans (51.3%), 19.7% are white South Africans, 15.8% are other Black Africans while 13.2% are Indians and Asians. Regarding the tenure of respondents, it was found that majority of them have worked in 3D printing firms for 4-6 years (45.4%), 23.7% have worked in 3D printing firms for 7-10 years, 19.7% have worked in 3D printing firms for 1-3 years while 11.2% have worked in 3D printing firms for more than 10 years.

Table 1: Demographic information of participants

Age	**Frequency**	**Percentage (%)**
26-30 years	19	12.5
31-35 years	31	20.4
36-40 years	55	36.2
41-45 years	28	18.4
46-50 years	14	9.2
More than 50 years	5	3.3
Total	**152**	**100**
Gender	**Frequency**	**Percentage (%)**
Male	113	74.3
Female	39	25.7
Total	**152**	**100**
Highest Educational Level	**Frequency**	**Percentage (%)**
Advanced Certificate	4	2.6
Diploma	10	6.6

Bachelors/Advanced Diploma	27	17.8
Honours/Postgraduate Diploma		
Masters	43	28.3
Doctorate	51	33.6
Total	17	11.2
	152	**100**
Work Title	**Frequency**	**Percentage (%)**
Business developer	20	13.2
IT personnel	18	11.8
CAD designer	43	28.3
Operations officers	30	19.7
Sales personnel	13	8.6
Researcher	19	12.5
Marketing officer	9	5.9
Total	**152**	**100**
3D printing Firm Category	**Frequency**	**Percentage (%)**
3D machine reseller	10	6.6
3D Material supplier	19	12.5
Consulting	54	35.5
3D Software and related technologies	54	35.5
Design and tool making	15	9.9
Total	**152**	**100**
Ethnic Origin	**Frequency**	**Percentage (%)**
Black South African	78	51.3
Other Black African	24	15.8
White South Africa	30	19.7
Indian/Asian	20	13.2
Total	**152**	**100**
Tenure	**Frequency**	**Percentage (%)**
1-3 years	30	19.7
4-6 years	69	45.4
7-10 years	36	23.7
More than 10 years	17	11.2
Total	**152**	**100**

4.2 Validity and reliability analysis

We used Smart PLS 4 software to conduct validity and reliability analysis on the variables of the study namely: construct validity, convergent validity, discriminant validity and reliability statistics.

Construct validity

Construct validity pertains to the extent to which the measurement model properly represents the measured construct (Clark & Watson, 2019). In structural equation modeling (SEM), the assessment of construct validity is

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commonly done by analyzing the factor loadings of the observable indicators on the latent variable. Factor loadings quantify the degree of association between the underlying variable and the observable measure. Tabachnick and Fidell (2019) state that factor loadings equal to or greater than 0.5 are regarded as a reliable measure of construct validity. From Table 2, the five (5) items used for measuring regulatory compliance as well as the three items (3) items used for measuring 3D printing technology adoption also had factor loadings that were greater than 0.5. Finally, the three (3) items used for measuring environmental sustainability also had factor loadings that were greater than 0.5, thereby meeting the criteria for construct validity.

Table 2: Construct validity

	3D printing regulatory compliance	**3D printing technology adoption**	**Environmental sustainability**
ES1			0.972
ES2			0.924
ES3			0.927
RC1	0.601		
RC2	0.770		
RC3	0.965		
RC4	0.909		
RC5	0.897		
TA1		0.922	
TA2		0.586	
TA3		0.945	

Convergent validity and reliability statistics

Convergent validity is a type of validity that examines the extent to which multiple measures of the same construct are positively related to each other (Cheung, Cooper-Thomas, Lau & Wang, 2023). Convergent validity is typically assessed by examining each construct's average variance extracted (AVE) (Cheung et al., 2023). The AVE is a measure of the amount of variance in the observed indicators that is explained by the construct. A rule of thumb for AVE suggests that the AVE value should be 0.5 to indicate good convergent validity (Ahmad, Zulkurnain & Khairushalimi, 2016).

Cronbach's alpha, composite reliability (rho_A), and composite reliability (rho_C) are all measures of the internal consistency of a scale or set of items, commonly used to assess the reliability of a measure. According to Park (2021), cronbach alpha values greater than 0.7 indicate a good measure of internal consistency or reliability of items used for measuring the con-

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structs.From Table 3, Cronbach alpha values attained were greater than 0.9 showing strong internal consistency of the items used for measuring the variables or constructs. Composite reliability (rho_A) is a measure of the internal consistency of a set of items which is based on the factor loadings of the items on the underlying construct. Values that are greater than 0.7 indicate a good measure of internal consistency (Park, 2021). For this study, composite reliability (rho_A) values were greater than 0.9, which shows a strong measure of internal consistency of items used for measuring 3D printing technology adoption, 3D printing regulatory compliance, and environmental sustainability.

Table 3: Convergent validity and reliability

	Cronbach's alpha	**Composite reliability (rho_a)**	**Composite reliability (rho_c)**	**Average variance extracted (AVE)**
3D printing regulatory compliance	0.888	0.916	0.920	0.703
3D printing technology adoption	0.789	0.922	0.868	0.695
Environmental sustainability	0.936	0.955	0.959	0.886

Discriminant validity using Heterotrait-Monotrait (HTMT) ratio

Discriminant validity using the Heterotrait-Monotrait (HTMT) ratio assesses whether constructs in a model are truly distinct from each other. HTMT values below 0.85 suggest good discriminant validity, indicating that the constructs do not excessively overlap and measure different concepts. This method compares the average correlations between indicators of different constructs to the average correlations within the same construct, ensuring the constructs are unique and not reflecting the same underlying factor. The table presents the Heterotrait-Monotrait (HTMT) ratios for various constructs related to 3D printing: cost, regulatory compliance, technology adoption, and environmental sustainability. HTMT ratios below 0.85 suggest good discriminant validity, indicating that the constructs are distinct from each other. From table 4, the HTMT ratios range from 0.075 to 0.630, which are below the 0.85 threshold.

Table 4: Discriminant validity using Heterotrait-monotrait ratio (HTMT)

	Heterotrait-monotrait ratio (HTMT)
3D printing technology adoption <-> 3D printing regulatory compliance	0.272
Environmental sustainability <-> 3D printing regulatory compliance	0.630

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Environmental sustainability <-> 3D printing technology adoption	0.075

R-square and adjusted R-square

In Structural Equation Modelling (SEM), the R-square measures the proportion of variance in the dependent variable that can be explained by the independent variables in the model. The adjusted R-square is a modified version of the R-square that considers the number of independent variables in the model. According to the R-square value of 0.040, it could be rightly inferred that 4% of the variation in 3D printing regulatory compliance could be explained by 3D printing technology adoption. Moreover, the r-square value of 0.362 means that 36.2% of the variation in environmental sustainability could be explained by 3D printing technology adoption.

Table 5: R-square and adjusted r-square

	R-square	R-square adjusted
3D printing regulatory compliance	0.040	0.034
Environmental sustainability	0.362	0.353

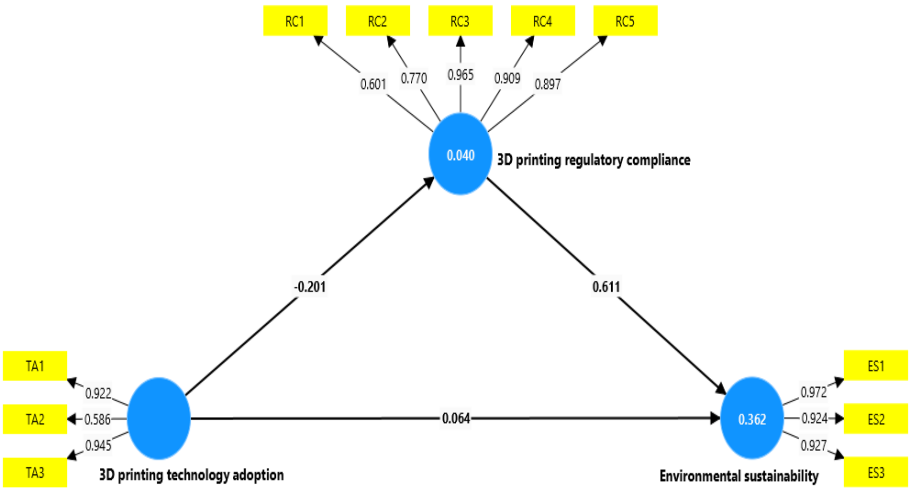

Figure 2: Structural equation modelling for direct and mediating relationships between 3D printing technology adoption, 3D printing regulatory compliance and environmental sustainability

Hypothesis testing

This section tests the hypotheses proposed for direct and indirect (mediating) effects. Decisions were taken as to whether the hypotheses tested were supported or not. Furthermore, the results based on the research hypotheses were discussed in line with the relevant literature.

Table 6: Direct and mediating relationships among variables

	B-	t-statistics	p-value

	value		
H1: 3D printing technology adoption -> Environmental sustainability	0.064	1.065	0.287
H2: 3D printing technology adoption -> 3D printing regulatory compliance	-0.201	3.161	0.002
H3: 3D printing regulatory compliance -> Environmental sustainability	0.611	9.641	0.000
H4: 3D printing technology adoption -> 3D printing regulatory compliance -> Environmental sustainability	-0.123	2.708	0.007

Results from table 6 shows that a non-significant positive relationship exists between 3D printing technology adoption and environmental sustainability (B=0.064, p=0.287). Hypothesis 1 was therefore not supported. The results of the study also showed that a significant negative relationship exists between 3D printing technology adoption and environmental sustainability (B=-0.201, p=0.002). Hypothesis 2 was therefore not supported. The result indicated that a significant positive relationship exists between 3D printing regulatory compliance and environmental sustainability (B=0.611, p=0.000). Hypothesis 3 was therefore supported. Finally, the result showed that regulatory compliance negatively mediates the relationship between 3D printing technology adoption and environmental sustainability (B=-0.123, p=0.007). Hypothesis 4 was therefore supported.

Hypotheses testing for direct and mediating relationships

Results from table 7 showed that a significant positive relationship exists between leader emotional intelligence and employee job performance among 3D printing firms (B=0.712, p=0.000). Hypothesis 1 was accepted. The result also shows that a significant positive relationship exists between leader emotional intelligence and leader emotional behaviour among 3D printing firms in South Africa (B=0.698, p=0.000). Hypothesis 2 was therefore accepted. The result also indicated that a significant positive relationship exists between leader emotional behaviour and employee job performance among 3D printing firms in South Africa (B=0.191, p=0.000).

The fourth hypothesis was also accepted as the result showed that leader emotional behaviour mediated the relationship between leader emotional intelligence and employee job performance among 3D printing firms in South Africa (B=0.133, p=0.000).

Table 7: Hypotheses testing

Hypotheses	B-value	t-statistic	p-value
H1: Leader emotional intelligence -> employee job performance	0.712	9.643	0.000
H2: Leader emotional intelligence -> leader emotional behaviour	0.698	11.027	0.000
H3: Leader emotional behaviour -> employee job performance	0.191	2.370	0.018
H4: Leader emotional intelligence -> leader emotional behaviour -> employee job performance	0.133	0.064	0.038

5 Discussions of results

The results of the current study showed a non-significant positive relationship between 3D printing technology adoption and environmental sustainability (B=0.064, p=0.287), indicating that Hypothesis 1 was not supported. This means that while there is a slight indication that adopting 3D printing technology might be associated with improved environmental sustainability, the evidence is not strong enough to conclude a significant impact. Contrary to these findings, previous research suggests a more favorable outcome for environmental sustainability through the adoption of 3D printing technology, particularly in the context of decentralized manufacturing. For instance, Khan, Koç, and Al-Ghamdi (2021) conducted a study examining the ecological consequences of dispersed manufacturing facilitated by 3D printing technology. They performed a life cycle assessment (LCA) comparing the environmental impact of conventional centralized production with that of decentralized production using 3D printing. Their research demonstrated that implementing 3D printing for decentralized production could substantially decrease emissions and energy usage associated with transportation, thereby promoting environmental sustainability. Similarly, Cerdas, Juraschek, Thiede, and Herrmann (2017) conducted an extensive examination of LCAs related to decentralized manufacturing using 3D printing technology. Their investigation revealed that 3D printing technology could enhance environmental sustainability by reducing material waste, transportation emissions, and energy usage compared to conventional centralized production processes.

The results of the current study indicate a significant positive relationship between 3D printing regulatory compliance and environmental sustainability (B=0.611, p=0.000), thereby supporting Hypothesis 2. This suggests that adhering to regulatory standards in the 3D printing sector significantly enhances environmental sustainability. This finding aligns with the broader literature, which underscores the importance of regulatory frameworks in promoting sustainable practices. Taylor, Freeman, and van der Ploeg (2021) investigated the influence of environmental legislation on the implementation of 3D printing technology within the European Union (EU). Through surveys and interviews with stakeholders in the 3D printing sector, the study revealed that while the EU has regulations related to waste management, material safety, and energy efficiency, it lacks specific norms and standards for 3D printing procedures. The positive relationship observed in the current study suggests that even in the absence of precise regulations for 3D printing, existing environmental legislation can effectively promote sustainable practices within the industry. This implies that regulatory compliance in areas such as waste management and energy efficiency contributes significantly to enhancing environmental sustainability. Further supporting this notion, Bianchi, Volpe, Fiorito, Forcellese, and Sangiorgio (2024) conducted a comprehensive evaluation of life cycle assessments (LCAs) of additive manufacturing techniques, including 3D printing. Their research emphasized the need for uniform methodologies and regulatory frameworks to ensure consistent and reliable LCA processes within the 3D printing sector. The significant positive relationship found in the current study highlights the impact of regulatory compliance on environmental sustainability and reinforces the necessity of implementing standardized regulatory frameworks to maximize the environmental benefits of 3D printing.

The study results revealed a significant negative relationship between 3D printing technology adoption and 3D printing regulatory compliance (B=-0.201, p=0.002), indicating that Hypothesis 3 was not supported. This suggests that as the adoption of 3D printing technology increases, compliance with regulatory standards tends to decrease. This finding is somewhat counterintuitive and contrasts with the positive implications suggested by some existing literature. For instance, Montes (2017) found that companies that deliberately modify their 3D printing technology adoption to meet or surpass regulatory standards generally attain greater levels of environmental sustainability. This suggests that regulatory compliance can be a driver of enhanced environmental performance when companies adjust their technology adoption strategies accordingly. However, the negative relationship observed in the current study implies that increased adoption of 3D printing technology might not always align with regulatory compliance, potentially due to the rapid pace of technological advancements outstripping the regulatory frameworks designed to govern them. Similarly, Kumar Ali, Ali, Jain, Anwer, Iqbal, and Mirza (2022) examined the impact of regulatory frameworks on the use of 3D printing technology in the healthcare industry. Their research revealed that strict regulations concerning patient safety and the quality of medical devices unintentionally led to the adoption of more sustainable practices. This finding underscores the potential for regulatory frameworks to drive sustainable practices, even if indirectly. However, the significant negative relationship found in the current study might suggest that in some industries or contexts, regulatory compliance could be perceived as a barrier or challenge, leading to a decrease in compliance as technology adoption increases.

The results of the study indicated that regulatory compliance negatively mediates the relationship between 3D printing technology adoption and environmental sustainability (B=-0.123, p=0.007), supporting Hypothesis 4. This suggests that while adopting 3D printing technology has the potential to enhance environmental sustainability, regulatory compliance can hinder this positive impact, possibly due to the constraints and challenges associated with meeting regulatory standards. This finding aligns with the complexities observed in existing literature. Alami et al. (2023) found that the implementation of 3D printing in the aerospace and automotive sectors is significantly influenced by adherence to safety and emissions requirements. These industries face stringent guidelines regarding the durability of components and the emissions produced during their lifespan. The study demonstrated that companies using 3D printing technology to create lighter and more intricate components were better at meeting fuel economy and pollution regulations. This suggests that regulatory compliance can drive the adoption of sustainable practices, but it also highlights the challenges companies face in balancing innovation with regulatory requirements. Similarly, Huang et al. (2019) indicated that enterprises in the aerospace and automotive industries proficiently adhering to fuel economy and pollution regulations were more likely to adopt 3D printing technologies effectively. This further underscores the role of regulatory frameworks in shaping the adoption and implementation of 3D printing technology, emphasizing the need for regulations that support rather than hinder sustainable innovation. Moreover, Khosravani and Reinicke (2020) examined the sustainability implications of 3D printing and found that the extent to which 3D printing can enhance resource and energy efficiency depends significantly on the degree of adherence to both current and forthcoming regulations. Their findings suggest that regulatory compliance can serve as both a driver and a barrier to achieving environmental sustainability, depending on how regulations are structured and enforced. The negative mediation effect observed in the current study indicates that regulatory compliance, while necessary, can introduce additional layers of complexity and cost that may offset some of the environmental benefits of adopting 3D printing technology. This highlights a potential misalignment between regulatory requirements and the environmental goals that 3D printing technology seeks to achieve. For instance, the costs and resources required to comply with stringent regulations might reduce the overall efficiency and sustainability gains that 3D printing technology can offer.

6 Conclusion

The study examined the direct and mediating relationships between 3D printing technology adoption, regulatory compliance and environmental sustainability among 3D printing firms in South Africa. The findings of the study emphasize the importance of the technological context within the TOE framework. Despite finding a non-significant positive relationship and a significant negative relationship between 3D printing technology adoption and environmental sustainability, the results indicate that the mere adoption of technology does not guarantee environmental benefits. This suggests that additional technological factors, such as the type of 3D printing technology and its specific applications, must be considered to fully understand the environmental impact. The mixed results highlight the complexity of technology adoption and suggest that more nuanced technological considerations are needed for achieving environmental sustainability.

The significant positive relationship between 3D printing regulatory compliance and environmental sustainability indicates that organizational factors such as financial resources, technical expertise, and organizational culture are crucial in shaping the outcomes of technology adoption. This implies that 3D printing firms with better resources and expertise are more likely to achieve environmental sustainability through compliance with regulations. The study adds to the TOE framework by emphasizing the need for robust organizational capabilities to realize the environmental benefits of 3D printing technology.

The contrasting results regarding the direct and mediating effects of 3D printing technology adoption on environmental sustainability illustrate the complex interplay between the TOE dimensions. The negative mediation effect of regulatory compliance suggests that without proper regulatory frameworks, technology adoption alone may not lead to positive environmental outcomes. This complexity indicates that a holistic approach, considering technological capabilities, organizational readiness, and environmental regulations, is necessary for achieving sustainable outcomes. The study thus reinforces the TOE framework by demonstrating that successful technology adoption for sustainability requires a balanced consideration of all three contexts.

The study reveals significant practical implications for 3D printing firms striving for environmental sustainability. Firstly, 3D printing firms must strategically invest in regulatory compliance, recognizing it as a pivotal element for achieving environmental sustainability. This entails allocating resources to ensure adherence to environmental regulations through compliance training, monitoring systems, and adoption of technologies that support regulatory standards. By doing so, firms can enhance their environmental outcomes and avoid potential legal and financial penalties. Secondly, 3D printing companies should develop comprehensive sustainability strategies that integrate technological advancements, regulatory compliance, and organizational practices.

This holistic approach includes conducting regular environmental impact assessments, setting sustainability goals, and implementing cross-functional teams to oversee sustainability initiatives. By embedding sustainability into the core of their operations, firms can create a culture that prioritizes environmental responsibility and drives continuous improvement.

Thirdly, proactive collaboration with regulatory bodies is essential. Engaging with regulators allows firms to stay informed about current and upcoming regulations, participate in developing industry standards, and ensure their practices align with regulatory expectations. This proactive stance not only helps firms stay ahead of compliance requirements but also positions them as industry leaders advocating for sustainable practices. By influencing favorable regulatory outcomes, firms can contribute to shaping a more sustainable industry landscape.

Lastly, firms need to invest in sustainable 3D printing technologies and practices. This involves selecting environmentally friendly materials, optimizing production processes to reduce waste, and adopting technologies that minimize energy consumption. Such investments are crucial to mitigate the potential negative environmental impacts of 3D printing technology adoption. By prioritizing sustainability in their technological choices, firms can balance innovation with environmental responsibility, ensuring that their growth does not come at the expense of the planet.

The study has three primary limitations. Firstly, it focuses exclusively on 3D printing firms in South Africa, which may limit the generalizability of the findings to other regions with different regulatory environments and market conditions. Future research should consider comparative studies across multiple countries to understand how regional differences impact the relationship between 3D printing technology adoption and environmental sustainability.

Secondly, the study primarily relies on quantitative data, potentially overlooking qualitative insights that could provide a deeper understanding of the underlying mechanisms. Future studies should incorporate qualitative methods, such as interviews and case studies, to capture the nuanced perspectives of industry practitioners and uncover additional factors influencing sustainability outcomes.

Lastly, the research di not differentiate between various types of 3D printing technologies and materials, which may have distinct environmental impacts. Future research should explore these variations to provide more specific guidelines on which technologies and materials are most beneficial for environmental sustainability. By addressing these limitations, future studies can offer a more comprehensive and nuanced understanding of how 3D printing technology adoption influences environmental sustainability, thus guiding more effective strategies for firms and policymakers.

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