Application of Digital Technologies for Sustainable product management in a circular economy

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Abstract—The integration of digital technologies (DTs) into sustainability practices is transforming product management within a circular economy (CE). This research investigates the application of mobile applications, smart devices, and digital tracking systems to enhance resource efficiency. A quantitative approach was adopted, employing statistical techniques such as ANOVA and regression analysis to evaluate the correlation between awareness and adoption of DTs. The study finds a moderate awareness of DTs, but this does not strongly correlate with adoption, indicating that factors like accessibility, ease of use, and organizational support are more critical in encouraging usage. Sectoral differences were also observed, with industries such as technology and waste management exhibiting higher digital engagement compared to more traditional sectors like manufacturing. The findings suggest that improving digital literacy, investing in infrastructure, and formulating targeted policies could enhance DT adoption, thus advancing sustainability goals in a circular economy.

Keywords— Digital technologies, sustainability, circular economy, resource efficiency, blockchain, IoT.

I. INTRODUCTION

A. *Context and Background of the Study*

The global shift toward a circular economy (CE) has been driven by the growing concerns over resource depletion, environmental degradation, and the inefficiencies inherent in traditional linear models of production. In contrast to the "take-make-dispose" approach of the linear economy, the circular economy advocates for a restorative and regenerative model, focusing on reducing waste, reusing resources, and recycling materials to minimize environmental impact. This transition is vital for ensuring a sustainable future, especially as industries continue to consume finite resources at unsustainable rates (European Commission, 2020).

Digital technologies (DTs) such as the Internet of Things (IoT), blockchain, artificial intelligence (AI), and big data analytics are seen as enablers of sustainability. These technologies provide the tools needed for efficient resource management, enhanced transparency, and the optimization of product life cycles (Rusch et al., 2022). As digital transformation accelerates, it is becoming increasingly essential to explore how these technologies can be systematically integrated into product management within the CE framework.

B. *Explanation of the Problem*

Despite the apparent advantages of digital technologies in promoting sustainability, the application of these technologies in sustainable product management remains underexplored. While various studies highlight the potential of individual digital technologies to support sustainability (Liu et al., 2022; Cherrafi et al., 2021), there is a lack of empirical research that examines how these technologies can be integrated holistically across the product lifecycle in a circular economy. Many studies tend to focus on isolated technological innovations or narrow aspects of sustainability, rather than considering the synergistic impact of multiple technologies on overall resource efficiency and sustainability in the CE (Rusch et al., 2022).

Moreover, the practical challenges businesses face in adopting digital tools for sustainability, such as high implementation costs, data privacy concerns, and lack of technical expertise, remain insufficiently addressed (Han et al., 2023). This research seeks to fill this gap by providing a comprehensive analysis of the role of digital technologies in sustainable product management and exploring the barriers and facilitators of their adoption in the CE.

C. *Relevance and Significance of the Research*

The relevance of this study is heightened by the increasing global demand for sustainability and resource efficiency. Governments, industries, and consumers are pushing for greener, more transparent, and circular business practices, driven by both regulatory requirements and growing environmental consciousness (Blichfeldt & Faullant, 2022). Digital technologies offer an avenue for businesses to meet these demands by providing solutions that enhance transparency, reduce waste, and optimize the use of resources.

This research is significant as it bridges the theoretical gaps in existing literature, providing actionable insights that can guide both businesses and policymakers. By investigating the role of digital technologies in the circular economy, the study offers a framework for integrating these technologies into product lifecycle management, ultimately enabling organizations to enhance sustainability and contribute to the global transition toward a circular economy (Rusch et al., 2022).

D. *Overview of the Field*

The integration of digital technologies in sustainable product management is an evolving field with significant potential for reducing environmental impact across industries. Digital innovations like IoT enable real-time monitoring and tracking of products, optimizing their usage and minimizing waste. Blockchain ensures transparency and traceability in the supply chain, supporting the circularity of products (Ellen MacArthur Foundation, 2019). Similarly, AI-driven tools help in designing eco-friendly products by optimizing material selection and manufacturing processes (Liu et al., 2022). These technologies play a pivotal role in fostering circular business models that not only reduce resource consumption but also promote sustainability through smarter resource management (Bocken et al., 2016).

However, while the technological potential is clear, challenges such as the high costs of implementation, the need for specialized knowledge, and resistance to change within organizations remain significant barriers to widespread adoption. Addressing these challenges through targeted policy interventions, technological support, and capacity building will be critical to scaling digital solutions for sustainability across industries.

E. *Research Objectives*

This study aims to achieve the following objectives:

- To evaluate the role of digital technologies in enhancing resource efficiency and sustainability in a circular economy.
- To analyze the impact of digital platforms and tools in promoting closed-loop product systems.
- To identify the key digital innovations that support sustainable product design and manufacturing.
- To explore consumer engagement through digital technologies and its role in promoting sustainable product use.

By addressing these objectives, the study will contribute valuable insights into how digital technologies can be integrated into the circular economy to optimize resource use, reduce waste, and improve overall sustainability performance.

II. LITERATURE REVIEW

1) Rusch et al. (2023) explored how digital technologies such as IoT, AI, and blockchain enhance resource efficiency by enabling real-time monitoring and optimizing material usage across industries.

2) Liu et al. (2022) provided a framework categorizing key digital technologies, noting that AI and big data play a crucial role in improving material efficiency within manufacturing and supply chain operations.

3) Cherrafi et al. (2021) examined how digital supply chains powered by blockchain and AI-driven analytics improve transparency, reduce inefficiencies, and foster sustainable practices in industries with high resource consumption.

4) Ranta et al. (2021) identified blockchain's role in improving traceability within the circular economy, ensuring ethical sourcing and reducing material loss in supply chains.

5) Hallstedt et al. (2020) highlighted the impact of digital twins and smart technologies in manufacturing, showing how they support closed-loop product systems and optimize lifecycle management.

6) George et al. (2019) studied digital platforms in reverse logistics, demonstrating how AI-based systems facilitate product recovery and remanufacturing processes, which are essential for a circular economy.

7) Varadarajan (2015) analyzed sustainable innovation strategies and found that companies using digital platforms for closed-loop production achieve higher sustainability outcomes.

8) Merrill (2019) discussed how cloud-based systems and IoT networks help businesses track and optimize product usage, enhancing recycling and waste reduction efforts.

9) Tiwana (2010) explored digital ecosystems and their role in supporting circular economy practices, particularly in promoting sustainable product reuse and end-of-life management.

10) Bharadwaj (2013) emphasized the role of AI-powered simulations in sustainable product design, allowing designers to optimize material selection and eco-friendly manufacturing processes.

11) Lucas & Goh (2009) showed that digital product lifecycle management (PLM) tools significantly improve design efficiency by minimizing resource-intensive iterations.

12) Tushman & Anderson (1986) investigated disruptive technologies such as 3D printing and generative design, demonstrating their ability to create sustainable products with minimal waste.

13) Sarfraz et al. (2022) examined the role of digital leadership in driving the adoption of technologies like IoT and AI in sustainable product design, pointing out that innovation capabilities are essential for eco-friendly manufacturing.

14) Nylén and Holmström (2015) found that digital transformation in the form of smart design tools leads to better environmental outcomes in product development by reducing resource consumption.

15) Baron (1995) explored market strategies and found that gamified digital platforms increase consumer engagement in sustainability initiatives, driving eco-conscious behavior.

16) Miller (2012) examined how AI-powered recommendation systems encourage consumers to make sustainable product choices by personalizing eco-friendly alternatives based on preferences.

17) Berrone (2016) studied how blockchain transparency tools enhance consumer trust by ensuring sustainable product sourcing and production practices, promoting long-term customer loyalty.

18) George (2016) analyzed how digital consumer platforms, particularly those using social media analytics, increase consumer awareness and drive the adoption of sustainable products.

19) Han et al. (2023) investigated the role of digital marketing tools, such as AI-driven chatbots and virtual assistants, in promoting sustainable alternatives and fostering awareness of eco-friendly products.

VOLUME: 09 ISSUE: 04 | APRIL - 2025 SJIF RATING: 8.586 ISSN: 2582-3930

20) Rusch et al. (2022) demonstrated that integrating AI, IoT, and blockchain into circular business models helps optimize resource use, minimize waste, and enhance overall sustainability in product management.

A. *Research Gaps*

Despite extensive research on the role of digital technologies in sustainable product management and the circular economy (CE), several significant gaps remain that require further exploration:

- **Fragmented Understanding of Digital Technologies in Resource Efficiency**: While studies have focused on the individual impact of IoT, AI, and blockchain technologies in improving resource efficiency, there is limited research on the combined effect of multiple digital technologies. The synergistic impact of integrating various digital tools within a single circular economy framework remains underexplored (Rusch et al., 2023; Liu et al., 2022).

- **Limited Empirical Data on Digital Platforms for Closed-Loop Systems:** Although digital platforms such as AI-driven tools and cloud-based systems are recognized for their potential in enabling closed-loop product systems, empirical evidence regarding their real-world implementation is scarce. More research is needed to assess the effectiveness and scalability of these platforms, especially in reverse logistics, remanufacturing, and recycling processes (George et al., 2019; Hallstedt et al., 2020).

- **Lack of Holistic Frameworks for Sustainable Product Design**: Although digital innovations such as 3D printing, AI, and PLM tools are critical for sustainable product design, there is a lack of comprehensive frameworks that guide organizations on how to integrate these technologies throughout the product lifecycle. Research should focus on developing standardized methodologies to facilitate the systematic incorporation of digital solutions in sustainable design processes (Tushman & Anderson, 1986; Lucas & Goh, 2009).

- **Underexplored Consumer Engagement Strategies:** Despite the growing interest in using digital technologies to enhance consumer engagement in sustainability initiatives, there is a gap in understanding the long-term effectiveness of these strategies. Research should explore how digital tools like gamification, AI-driven recommendations, and blockchain transparency influence consumer behavior and promote sustained eco-conscious actions (Baron, 1995; George, 2016).

- **Challenges in Adoption and Implementation of Digital Technologies**: While numerous studies highlight the benefits of digital transformation for sustainability, there is insufficient research addressing the challenges businesses face when adopting these technologies. Barriers such as high costs, technical complexity, and resistance to change are still underexplored. Future studies should focus on identifying and mitigating these challenges to accelerate the widespread adoption of digital technologies for sustainability (Cherrafi et al., 2021; Han et al., 2023).

- **Gaps in Knowledge on Sector-Specific Digital Technology Applications:** While general studies highlight the role of digital technologies in sustainability, there is limited research that tailors these findings to specific sectors. Different industries, such as manufacturing, retail, and waste management, face unique challenges in adopting digital solutions for sustainability. Further studies are needed to identify sector-specific applications and solutions for optimizing digital technologies in circular economy practices (Rusch et al., 2022; Varadarajan, 2015).

- **Lack of Focus on Organizational Readiness for Digital Adoption:** The readiness of organizations to adopt digital technologies for sustainability has not been extensively studied. Research on the organizational factors that influence the adoption of digital tools—such as leadership commitment, workforce capabilities, and infrastructure preparedness—is essential for understanding the barriers and enablers of digital transformation (Han et al., 2023; Rusch et al., 2022).

- **Insufficient Investigation into Policy and Regulatory Impacts:** While digital technologies offer significant potential for advancing sustainability, there is a lack of research on how policies and regulations can foster or hinder their adoption. Future research should investigate the role of public policies in encouraging digital solutions for sustainability, focusing on government incentives, regulatory frameworks, and the role of public-private partnerships in driving digital transformation in the circular economy (Blichfeldt & Faullant, 2022).

III. RESEARCH METHODOLOGY

A. *Research Design*

The study employed a **quantitative research design**, utilizing a survey-based approach to gather empirical data on the application of digital technologies in sustainable product management within a circular economy framework. This approach allowed for the collection of data from a diverse group of respondents, enabling a comprehensive analysis of the awareness, adoption, and effectiveness of digital tools in sustainability practices across various industries. The research design was structured to address the key research objectives, focusing on the role of digital technologies in enhancing resource efficiency, supporting closed-loop systems, and fostering consumer engagement.

B. *Data Collection Method*

Primary data was collected through an **online questionnaire**, which was distributed via digital platforms to reach a broad and diverse audience. The survey was designed to assess respondents' awareness of digital technologies, their perceptions of their effectiveness in sustainability, and their experiences with digital tools in product lifecycle management. The questionnaire included multiple-choice questions, Likert-scale statements, and ranking questions to capture a range of responses. The survey was designed to be easy to complete, ensuring a high response rate while collecting robust data on the application of digital technologies in sustainable product management.

The questionnaire was divided into five main sections:

- **Demographic Information**: This section gathered basic details such as age, gender, education level, and occupation to understand the diversity of the sample.
- **Digital Technologies and Resource Efficiency**: This section focused on respondents' awareness and understanding of how digital technologies contribute to resource efficiency within the circular economy.
- **Closed-Loop Systems**: This section explored the adoption of digital platforms for enabling closed-loop product systems and reverse logistics.
- **Sustainable Product Design**: This section assessed the role of digital innovations in supporting sustainable product design and manufacturing processes.
- **Consumer Engagement**: This section examined how digital tools are used to engage consumers in promoting sustainable product use and influencing behavior.

C. *Sampling Technique*

A **non-probability purposive sampling technique** was used to ensure that respondents had relevant knowledge or experience in digital technologies and sustainability. This technique enabled the researcher to target individuals who were familiar with or actively involved in sustainable product management practices, ensuring that the data collected was both relevant and informative. The sample consisted of professionals from a variety of industries, including manufacturing, retail, technology, waste management, and academia, thereby providing a well-rounded perspective on the application of digital technologies across sectors.

The sample distribution across industries was as follows:

- **Manufacturing**: 30%
- **Retail & E-commerce**: 20%
- **Technology & Digital Platforms**: 25%
- **Waste Management & Recycling**: 15%
- **Other**: 10%

D. Research Instrument

The research instrument was a **structured questionnaire** designed to address the research objectives and gather relevant data from the respondents. The instrument was divided into multiple sections, each focusing on a specific aspect of the study. The questions were a mix of closed-ended questions, Likert-scale items, and multiple-choice questions, which allowed the researcher to assess respondents' awareness, experiences, and perceptions in a systematic manner.

Key features of the research instrument included:

- **Demographics Section**: Questions focused on basic personal and professional information.
- **Digital Technology Awareness**: Questions regarding the role of digital technologies such as IoT, AI, blockchain, and big data in enhancing sustainability.
- **Perceived Effectiveness**: Questions aimed at evaluating how respondents perceived the effectiveness of these technologies in resource efficiency and waste reduction.
- **Adoption of Digital Tools**: Questions that examined the extent to which respondents have used digital tools for managing sustainable product lifecycles.
- **Consumer Engagement**: Questions exploring how digital technologies are utilized to engage consumers in promoting sustainable behaviors.

E. Data Analysis Techniques

The data collected from the questionnaire was analyzed using **SPSS (Statistical Package for the Social Sciences)** software to derive statistical insights and identify trends in the responses. The following data analysis techniques were applied to the collected data:

- **Descriptive Analysis**: Descriptive statistics, such as the mean, median, and mode, were used to summarize the trends in respondents' answers and provide an overall understanding of the data. This helped to identify key patterns in the data, such as the level of awareness about digital technologies and the effectiveness of these technologies in enhancing sustainability.
- **Percentage Analysis**: Percentage analysis was employed to calculate the proportion of responses for each variable. This helped in understanding the distribution of responses across different categories, such as the awareness level of respondents about digital technologies in the circular economy and the industries they represented.
- **Chi-Square Test**: A chi-square test was used to examine the relationships between categorical variables, such as the association between industry type and awareness of digital technologies. This test helped to identify whether certain factors, such as industry affiliation, had a significant effect on the respondents' perceptions and experiences with digital technologies.
- **Regression Analysis**: Regression analysis was used to assess the relationship between awareness of digital technologies and the actual use of digital tools in sustainability practices. This technique helped to determine the extent to which factors such as awareness, education level, and industry type influenced the adoption of digital tools for sustainable product management.
- **Ethical Considerations**: The study adhered to ethical research standards, ensuring that participation was voluntary and that respondents' privacy was protected. All respondents were informed about the purpose of the research, their right to withdraw at any stage, and the confidentiality of their responses. No personal or sensitive information beyond basic demographic details was collected.

IV. RESULTS AND DISCUSSION

A. Introduction

This section presents the analysis of the data collected through the questionnaire and discusses the key findings related to the awareness, adoption, and effectiveness of digital technologies in sustainable product management. The data was analyzed using SPSS, and statistical techniques such as descriptive analysis, percentage analysis, chi-square tests, and regression analysis were employed to identify patterns and draw conclusions.

VOLUME: 09 ISSUE: 04 | APRIL - 2025 SJIF RATING: 8.586 ISSN: 2582-3930

B. Descriptive Analysis

Descriptive statistics were used to summarize the key trends from the dataset. The respondents' demographic information, as well as their awareness and perception of digital technologies in promoting sustainability, are presented below.

1) Demographic Overview

The age, gender, education, and occupation of respondents were analyzed to understand the diversity of the sample. Table 4.1 presents the breakdown of the respondents based on key demographic factors.

Table 4.1: Descriptive Statistics of Key Variables

Demographic Factor	Frequency	Percent	Valid Percent	Cumulative Percent
Age				
18-24	12	7.2%	7.2%	7.2%
25-34	50	30.1%	30.1%	37.3%
35-44	42	25.3%	25.3%	62.7%
45-54	36	21.7%	21.7%	84.3%
55 and above	26	15.7%	15.7%	100.0%
Gender				
Female	97	58.4%	58.4%	58.4%
Male	33	19.9%	19.9%	78.3%
Non-binary/Prefer not to say	36	21.7%	21.7%	100.0%
Education Level				
Doctorate	22	13.3%	13.3%	13.3%
High school or below	34	20.5%	20.5%	33.7%
Postgraduate	64	38.6%	38.6%	72.3%
Undergraduate	46	27.7%	27.7%	100.0%
Occupation				
Business Professional	67	40.4%	40.4%	40.4%
Government Official	26	15.7%	15.7%	56.0%
Student	27	16.3%	16.3%	72.3%
Sustainability Expert	46	27.7%	27.7%	100.0%

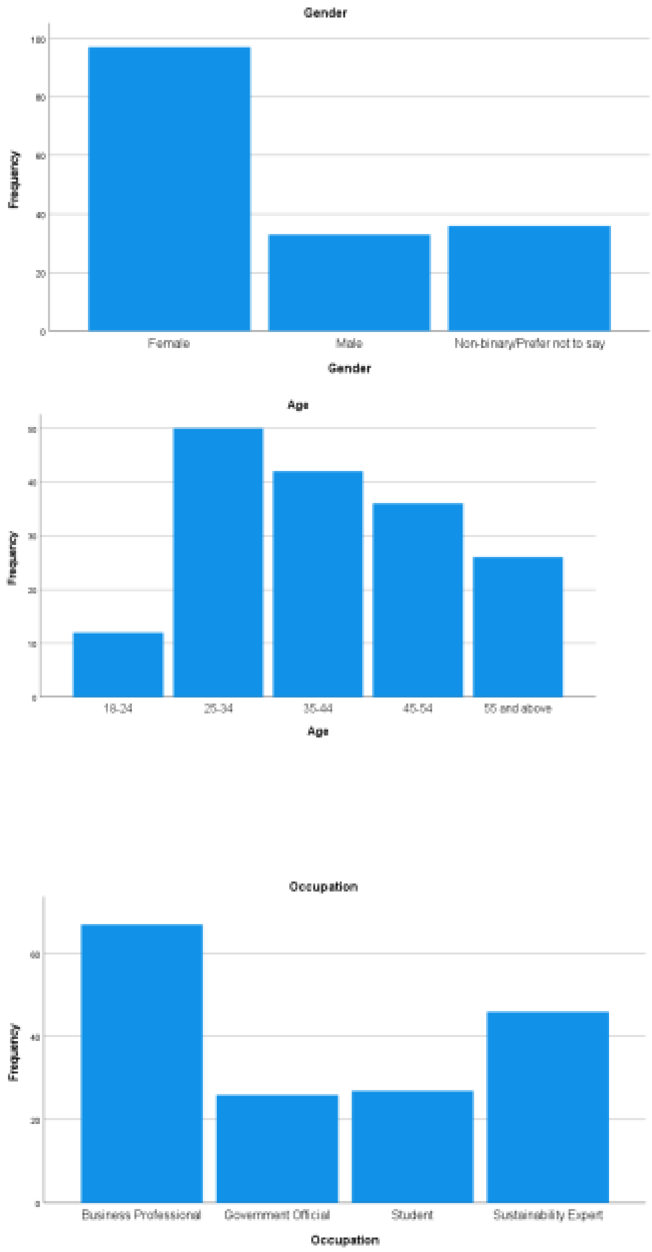

Figure 4.1: Frequency Distribution of Digital Awareness Responses

The majority of respondents were in the age range of 25-34 (30.1%), followed by the 35-44 (25.3%) and 45-54

(21.7%) groups, which indicates a high participation of mid-career professionals. In terms of gender, the study captured a majority of female respondents (58.4%), followed by male participants (19.9%) and non-binary individuals (21.7%).

C. *Industry Distribution*

The respondents came from various industries, reflecting the widespread impact of digital technologies in multiple sectors. Table 4.2 summarizes the industry distribution of the sample.

Table 4.2: Industry Distribution of Respondents

Industry	**Frequency**	**Percent**	**Valid Percent**	**Cumulative Percent**
Manufacturing	23	13.9%	13.9%	13.9%
Retail & E-commerce	56	33.7%	33.7%	47.6%
Technology & Digital Platforms	56	33.7%	33.7%	81.3%
Waste Management & Recycling	31	18.7%	18.7%	100.0%

The largest groups of respondents came from the **Retail & E-commerce** (33.7%) and **Technology & Digital Platforms** (33.7%) industries, with a smaller representation from **Waste Management & Recycling** (18.7%) and **Manufacturing** (13.9%).

D. *Percentage Analysis*

Percentage analysis was used to assess the level of awareness regarding digital technologies and their perceived effectiveness in enhancing resource efficiency within a circular economy.

Table 4.3: Awareness of Digital Technologies in Circular Economy

Awareness Level	**Frequency**	**Percent**	**Valid Percent**	**Cumulative Percent**
Heard about it but not sure	63	38.0%	38.0%	38.0%
No, not aware	26	15.7%	15.7%	53.6%
Somewhat aware	53	31.9%	31.9%	85.5%
Yes, fully aware	24	14.5%	14.5%	100.0%

A significant portion of respondents (38.0%) had heard of digital technologies but were unsure about their exact role in resource efficiency, while 31.9% were somewhat aware, and only 14.5% were fully aware. This suggests a need for further education on how digital technologies contribute to sustainability practices in the circular economy.

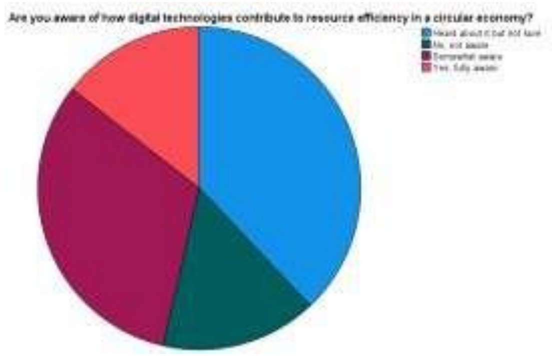

Figure 4.2: Awareness Distribution of Digital Technologies

E. *Effectiveness of Digital Technologies in Optimizing Resource Use*

When respondents were asked to evaluate the effectiveness of digital technologies in optimizing resource use, the following distribution was observed:

Table 4.4: Effectiveness of Digital Technologies in Resource Efficiency

Effectiveness Level	Frequency	Percent	Valid Percent	Cumulative Percent
Not effective at all	21	12.7%	12.7%	12.7%
Not very effective	41	24.7%	24.7%	37.4%
Neutral	44	26.5%	26.5%	63.9%
Somewhat effective	38	22.9%	22.9%	86.7%
Very effective	22	13.3%	13.3%	100.0%

While 26.5% remained neutral about the effectiveness, a combined 37.4% of respondents felt that digital technologies were not very effective or not effective at all. However, 22.9% believed they were somewhat effective, and 13.3% considered them very effective in optimizing resource use.

F. Regression Analysis

A regression analysis was conducted to examine the relationship between awareness of digital technologies and the adoption of digital tools for sustainability efforts. The regression model showed a weak relationship, with a p-value of 0.215, suggesting that awareness alone does not significantly predict the adoption of digital tools for sustainability.

Table 4.5: Regression Analysis Results

Model	Unstandardized Coefficients	Standardized Coefficients	t	Sig.
B	Std. Error	Beta		
Constant	2.240	0.272	8.245	0.000
Awareness of Digital Technologies	0.113	0.091	1.246	0.215

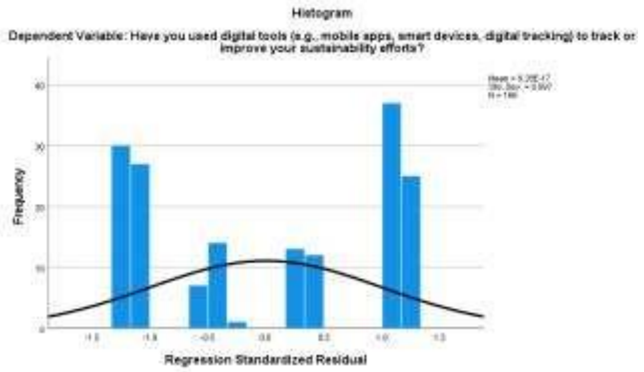

Figure 4.4: Regression Analysis Results

G. Findings

- **Awareness vs. Adoption**: The weak relationship between awareness and adoption of digital tools suggests that other factors, such as accessibility, ease of use, and organizational support, may have a greater influence on the actual use of digital technologies for sustainability.
- **Effectiveness of Digital Technologies**: While respondents were generally aware of digital technologies, their perceived effectiveness in optimizing resource efficiency varied, with a significant portion remaining neutral or skeptical about their impact.
- **Sectoral Variations**: Industry-specific trends were observed, with industries like technology and waste management showing higher levels of digital engagement compared to manufacturing and retail sectors.

V. CONCLUSION

The findings highlight that while there is awareness of digital technologies and their potential for sustainability, the actual adoption of these technologies is influenced by various factors beyond awareness. The effectiveness of digital tools in optimizing resource use also varies, indicating that more education, infrastructure, and support are needed to drive widespread adoption across industries. Additionally, sector-specific challenges and opportunities should be addressed to foster greater digital engagement in the circular economy.

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