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# Mitigating Cyber Risks in AI-Driven Circular Economy Implementations

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***Abstract*— This article explores the integration of artificial intelligence (AI) into circular economy (CE) systems, focusing on its potential to enhance sustainability by optimizing resource utilization, reducing waste, and improving supply chain processes. It highlights how AI-driven innovations such as predictive maintenance, waste sorting, and big data analytics contribute to the effective implementation of CE principles. At the same time, the study addresses the cybersecurity risks associated with these systems, including data breaches, system vulnerabilities, and ethical concerns. The research underscores the importance of adopting robust cybersecurity frameworks, such as the NIST AI Risk Management Framework and ISO/IEC 27001, to mitigate these risks and ensure the scalability and sustainability of AI-driven CE initiatives. Additionally, the article examines public perceptions of AI's societal impact, revealing optimism about productivity and efficiency but concerns regarding job market disruptions. Recommendations for organizations include proactive cybersecurity strategies, leveraging emerging technologies like blockchain, and fostering interdisciplinary collaboration. This study provides actionable insights for achieving a balance between technological advancement and sustainability in AI-enabled circular economy systems.**

**Keywords— Artificial Intelligence (AI), Circular Economy (CE), Cyber Security, Cyber Risks**

## I. INTRODUCTION

The circular economy represents a transformative approach to achieving sustainability by shifting from the traditional linear "take-make-dispose" model to one that emphasizes the continual use of resources through recycling, reuse, and regeneration (Bashynska et al., 2023). By prioritizing resource efficiency, reducing waste, and minimizing environmental impacts, circular economy principles align with global sustainability goals, such as those outlined in the United Nations' Sustainable Development Agenda.

Artificial intelligence (AI) has emerged as a critical enabler of the circular economy, offering innovative solutions to optimize resource utilization and streamline processes. For example, AI-driven systems can enhance predictive maintenance by monitoring the condition of equipment and predicting failures, reducing downtime and extending the lifecycle of assets. AI also improves waste sorting and recycling efficiency through advanced image recognition algorithms, enabling more effective material recovery (Cheng et al., 2024). Furthermore, it facilitates smart supply chains by leveraging data analytics to reduce resource consumption and optimize logistics.

However, as AI becomes an integral part of circular economy systems, it introduces new layers of complexity and vulnerability. The reliance on interconnected networks, smart devices, and large volumes of data creates opportunities for cyber risks, including data breaches, system manipulation, and disruptions to critical operations. These risks threaten not only the functionality and efficiency of circular economy initiatives but also their credibility and long-term adoption. Addressing these cybersecurity challenges is essential to ensuring the resilience and sustainability of AI-driven circular economy implementations.

This article aims to investigate the challenges and strategies

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for mitigating cyber risks in AI-driven circular economy implementations, emphasizing the need for secure and resilient systems. By doing so, we seek to address the following research questions:

What are the primary cyber risks associated with integrating AI technologies into circular economy models?

Which best practices and frameworks can organizations adopt to enhance cybersecurity in AI-driven circular systems?

How do cyber threats impact the scalability and sustainability of circular economy initiatives?

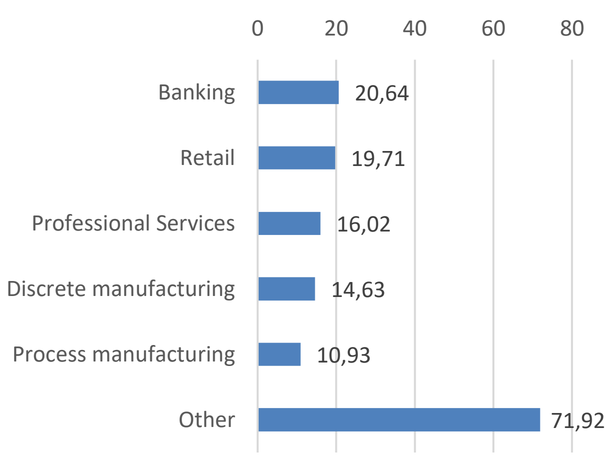
By examining these questions, this article offers actionable insights and practical solutions for ensuring the safe deployment of AI technologies in advancing circular economy goals, while addressing potential cybersecurity vulnerabilities.

## II. LITERATURE REVIEW

One of the critical aspects of integrating artificial intelligence into circular economy systems is understanding the industry's AI spending landscape and the associated cybersecurity risks. As industries rapidly adopt AI technologies, investment patterns reveal significant vulnerabilities that could become potential targets for cyber threats.

In 2023, global spending on AI reached an estimated $154 billion, with the banking and retail sectors leading the investments, accounting for $20.6 billion and $19.7 billion respectively (Fig. 1). Manufacturing, healthcare, energy, and transportation followed closely, indicating widespread adoption of AI across various critical sectors. These industries, essential to circular economy systems, heavily rely on interconnected AI-driven infrastructures, making them attractive targets for cyberattacks.

FIGURE 1. GLOBAL SPENDING ON AI 2023, BY INDUSTRY, SPENDING IN BILLION U.S. DOLLARS




Source: Statista, 2024a

The bar chart illustrates the distribution of AI spending across industries in 2023. The dominance of banking and retail demonstrates their reliance on AI for decision-making, predictive analytics, and customer interaction automation. However, the high levels of investment also highlight the pressing need for robust cybersecurity measures to protect sensitive data and ensure the integrity of AI systems.

Lower spending in industries like energy and transportation does not equate to lower risk. These sectors are critical to circular economy operations, where even minor disruptions can have cascading effects on supply chains and resource efficiency. Therefore, targeted cybersecurity strategies are imperative to safeguard AI-driven circular economy systems against emerging cyber threats.

This analysis underscores the importance of aligning AI adoption strategies with comprehensive cybersecurity measures to ensure sustainable and resilient circular economy implementations.

The integration of artificial intelligence into circular economy systems presents transformative opportunities for sustainability by optimizing resource use, enhancing waste management, and promoting circular business models. However, these advancements come with significant cybersecurity challenges. AI-driven systems, which rely heavily on interconnected devices, data exchange, and machine learning algorithms, are increasingly becoming targets for sophisticated cyberattacks. Addressing these risks is essential to ensuring the trustworthiness, resilience, and scalability of circular economy initiatives, as disruptions caused by cyber incidents could undermine their potential for sustainability and innovation.

### *A. Existing general frameworks for mitigating cyber risks in AI-Driven implementations*

A number of general frameworks and standards have been developed to address cybersecurity and risk management in AI systems, providing valuable guidance for AI-driven implementations across various sectors:

- NIST AI Risk Management Framework (AI RMF 1.0) (NIST, 2023). This framework offers a comprehensive approach to managing AI risks by emphasizing trustworthiness, accountability, and resilience. Its core functions—govern, map, measure, and manage – provide actionable steps for identifying and mitigating risks throughout the AI lifecycle. While not specific to circular economies, it serves as a foundational guideline for managing risks in AI applications.
- ISO/IEC 27001:2022 (2022). This international standard focuses on information security management systems and is widely applicable to AI systems handling sensitive data.
- AI Act (Regulation (EU) 2024/1689) (European Parliament & Council of the European Union, 2024). This upcoming regulatory framework emphasizes the need for transparency, accountability, and robust risk management in AI systems, aiming to mitigate ethical and technical risks.
- The Cybersecurity Framework (NIST, 2018). While broader in scope, this framework addresses security measures that are applicable to AI-driven implementations, such as securing IoT devices and protecting data integrity.

These frameworks highlight the need for proactive and adaptable cybersecurity measures in AI systems, but their generality requires adaptation to the unique characteristics of circular economy implementations.

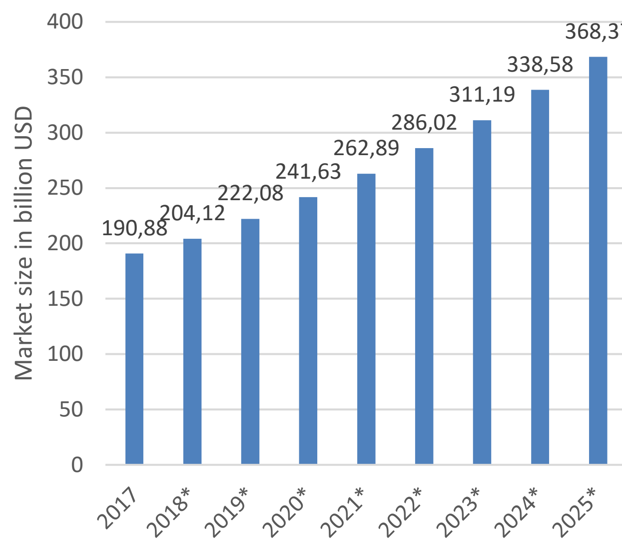
*B. Innovations driving the transition to AI-Driven circular economy (CE)*

The integration of AI into circular economy systems introduces unique cyber risks due to the interconnected and data-intensive nature of these systems. Recent advancements in AI technologies have showcased its transformative potential across various sectors of the CE:

- Localized frameworks and agricultural optimization. Studies such as those by Andono et al. (2022) and Ali et al. (2024) highlight AI's role in addressing local CE challenges. In Indonesia, AI and IoT are being deployed to optimize the onion farming supply chain, reducing waste and balancing supply and demand. Similarly, Pakistan's agriculture and food industries benefit from AI frameworks that streamline waste management and promote sustainable practices tailored to local socio-economic conditions.
- Big Data analytics and sustainable manufacturing. Bag et al. (2021) and Hernik (2022) underscore the dual role of big data in driving sustainable practices and fostering innovation. Bag et al. focus on AI-powered big data analytics in enhancing supply chain performance and CE capabilities in the automotive sector. Hernik emphasizes the utility of tools like Google Trends for identifying consumer needs and enabling innovation. Expanding this perspective, Al Halbusi et al. (2025) examine the moderating role of big data analytics and knowledge management systems in the relationship between AI capabilities and green innovation. Their study demonstrates that integrating AI with big data and knowledge management enhances sustainable performance and CE practices. Together, these studies illustrate how big data analytics acts as a transformative enabler in achieving sustainability goals across industries.
- Predictive analytics and deep learning. Akanbi et al. (2020) demonstrate how deep learning models predict demolition waste and salvageable materials with high accuracy. These models not only optimize resource recovery but also support decision-making for sustainable construction practices.
- AI in resource nexus management. D'Amore et al. (2022) examine AI's role in the water-energy-food nexus, emphasizing its potential to optimize interconnected resource systems. This holistic approach is vital for addressing complex sustainability challenges within CE frameworks.
- Robotic assembly and disassembly. Daneshmand et al. (2023) review the use of robotic systems in manufacturing and remanufacturing processes. Their work highlights how robotic assembly and disassembly enhance material recovery, minimize waste, and strengthen CE practices.
- Sustainable business models. Di Vaio et al. (2020) focus on AI's role in developing sustainable business models, emphasizing its ability to align production and consumption patterns with SDG № 12 (Responsible Consumption and Production). The study underscores the importance of knowledge management systems in facilitating cultural shifts toward sustainability.

Fig. 2 highlights the steady growth of the global factory automation market, reflecting the rising adoption of AI-driven solutions. This trend underscores the pivotal role of automation in advancing sustainable manufacturing practices and optimizing resource utilization within circular economy frameworks.

FIGURE 2. PROJECTED SIZE OF THE GLOBAL FACTORY AUTOMATION MARKET FROM 2017 TO 2025




Source: Statista, 2024b

Figure 3 illustrates the rapid growth of the global factory automation market, projected to reach $368.37 billion by 2025. This growth underscores the increasing adoption of AI-powered automation solutions in manufacturing, which play a critical role in enhancing resource efficiency and sustainability within circular economy frameworks.

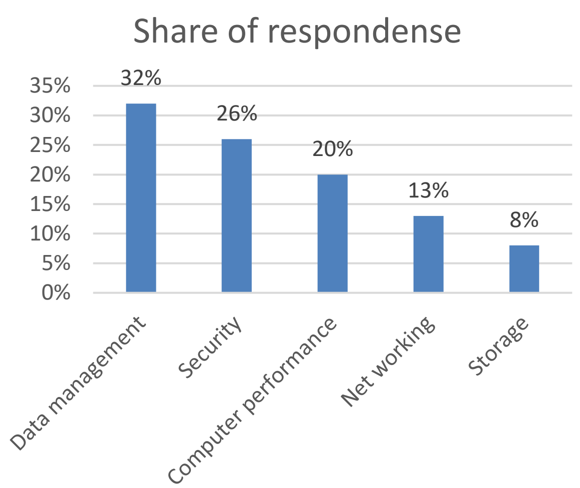
*C. Risks and challenges in implementing AI-Driven circular economy systems*

While AI offers significant benefits, its integration into CE practices introduces unique risks that must be carefully managed:

- Data integrity and cybersecurity risks. The reliance on vast datasets for training AI models poses significant vulnerabilities. Studies by Ali et al. (2024) and Bag et al. (2021) reveal how data breaches and unauthorized access can undermine the efficiency and security of AI-driven systems. These risks are further exacerbated in interconnected CE systems where cascading failures can occur.
- Implementation barriers. Challenges such as limited infrastructure, financial constraints, and fragmented supply chains hinder the adoption of AI in CE frameworks. Daneshmand et al. (2023) highlight technical and operational barriers in deploying robotic assembly and disassembly systems, emphasizing the need for interoperability and scalability.

As depicted in Figure 3, data management (32%) and security (26%) represent the most significant infrastructure challenges for AI developments worldwide. These challenges directly impact the scalability and sustainability of AI-driven circular economy systems by creating vulnerabilities that must be addressed through robust risk management strategies

FIGURE 3. LEADING INFRASTRUCTURE CHALLENGES FOR AI DEVELOPMENTS WORLDWIDE IN 2023




Source: Statista, 2024c

- Ethical and systemic concerns. Ethical issues, including biases in AI algorithms and privacy concerns, must be addressed to ensure equitable and responsible deployment. Moreover, the interconnectedness of CE models amplifies systemic vulnerabilities, requiring robust cybersecurity measures.

### *D. Future directions: leveraging AI for a secure and sustainable circular economy*

Emerging technologies and interdisciplinary approaches offer promising solutions for overcoming these challenges:

- Blockchain and secure data sharing. Bag et al. (2021); Bashynska et al. (2019) emphasize the role of blockchain in ensuring data integrity and transparency in supply chains, thereby mitigating cybersecurity risks.
- Federated learning for privacy preservation. Decentralized AI training, as highlighted by Singh (2025), reduces the exposure of sensitive data while maintaining model accuracy, making it a viable solution for secure CE systems.
- Advancing predictive analytics. Akanbi et al. (2020) demonstrate the potential of predictive models for optimizing resource recovery and waste reduction, which could be extended to broader CE applications.
- Collaborative efforts for integration. Rusko (2024) stresses the importance of interdisciplinary collaboration across technology, policy, and social sciences to bridge implementation gaps and foster innovation.
- Expanding AI's role in resource nexus management. D'Amore et al. (2022) propose a multi-stakeholder approach to managing the WEF nexus through AI, aligning resource use with SDG targets.

The integration of AI into CE practices represents a paradigm shift in how resources are managed, products are designed, and waste is reduced. By addressing implementation challenges and leveraging emerging technologies such as blockchain, federated learning, and predictive analytics, organizations can enhance the resilience and sustainability of AI-driven CE systems. Continued research, policy development, and interdisciplinary collaboration are essential for bridging the gaps between innovation and practical implementation, ensuring that AI fulfills its potential to drive a secure and sustainable circular economy.

## III. RESULTS

*In what ways does the use of AI-driven solutions impact employee performance, productivity, and job satisfaction?*

Integrating AI technologies into circular economy models introduces several cyber risks due to the reliance on interconnected systems, data-driven decision-making, and automation. The primary risks are mentioned in Table 1.

TABLE 1. PRIMARY CYBER RISKS ASSOCIATED WITH AI INTEGRATION INTO CIRCULAR ECONOMY MODELS

| Category of cyber risk | Specific risks | Description |
|---|---|---|
| 1. Data security risks | Data breaches | Sensitive business and operational data can be exposed through AI vulnerabilities. |
| | Data poisoning | Malicious actors may tamper with training data, leading to incorrect AI outputs and decisions. |
| | Unauthorized data access | Improper access controls may lead to the theft or misuse of proprietary or consumer data. |
| 2. System vulnerabilities | AI algorithm exploitation | Attackers may exploit weaknesses in AI models, such as adversarial attacks, to manipulate outcomes. |
| | Integration vulnerabilities | AI systems often integrate with legacy infrastructure, creating potential security gaps. |
| | Supply chain attacks | Compromises in third-party AI solutions or software used in the circular economy ecosystem can introduce risks. |
| 3. Operational disruptions | Ransomware attacks | Circular economy systems, reliant on AI-driven automation, are vulnerable to ransomware that can halt operations. |
| | Denial of Service (DoS) Attacks | Cybercriminals may target AI systems to overload them, causing system downtime. |
| | Malware infiltration | Embedded malware can disrupt production cycles and supply chain continuity. |
| 4. Ethical and regulatory risks | Bias in AI Models | Cyber adversaries could exploit inherent biases in AI systems to create legal and reputational risks. |
| | Non-compliance | AI systems processing sensitive data may inadvertently violate data protection laws like GDPR, leading to penalties. |
| 5. IoT and edge device security | IoT Device Exploits | AI-driven IoT devices used in circular systems are often targeted due to poor security practices. |
| | Edge computing vulnerabilities | Real-time AI analytics at the edge could be exploited, disrupting operational efficiency. |

| Category of cyber risk | Specific risks | Description |
|---|---|---|
| 6. Intellectual property theft | AI model theft | AI algorithms and models represent valuable intellectual property that could be stolen or reverse-engineered by competitors or hackers. |
| | Data ownership conflicts | Disputes over data shared in circular ecosystems could expose businesses to legal challenges. |
| 7. Human factors | Phishing attacks | Employees interacting with AI systems may be targeted by phishing attacks to gain unauthorized access. |
| | Insider threats | Internal actors could exploit AI system vulnerabilities for personal or financial gain. |

These risks highlight the need for robust cybersecurity measures when implementing AI in circular economy models. Organizations must prioritize data protection, system security, and employee training to mitigate these risks and ensure the safe and efficient operation of their AI-driven systems.

To address these risks, organizations integrating AI into circular economy models should:

- implement robust cybersecurity frameworks and AI-specific security measures;
- use secure AI development practices to minimize vulnerabilities;
- conduct regular security audits of integrated systems and third-party software;
- deploy encryption and access controls for data protection;
- train personnel on cybersecurity best practices and potential AI-related threats.

Proactively addressing these risks can ensure that AI technologies enhance, rather than compromise, the sustainability goals of circular economy models.

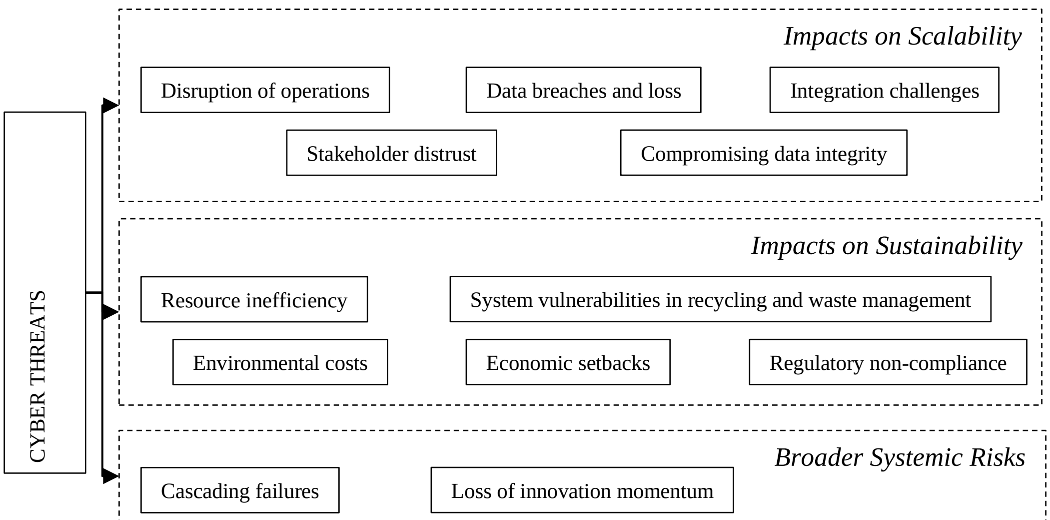
Organizations should also:

- leverage AI-driven anomaly detection to monitor for suspicious activities;
- deploy IoT-specific security protocols to secure interconnected devices;
- incorporate cyber insurance to mitigate financial risks associated with potential breaches.

By combining these best practices and frameworks, organizations can safeguard AI-driven circular systems, ensuring both resilience and sustainability.

Cyber threats can significantly impact the scalability and sustainability of circular economy initiatives, as these systems rely on interconnected AI-driven processes, large-scale data sharing, and automation (Fig. 4).

FIGURE 4. CYBER THREATS' IMPACT ON THE SCALABILITY AND SUSTAINABILITY OF CIRCULAR ECONOMY INITIATIVES




Source: author's development

To further explore the broader implications of AI adoption, it is important to consider how public perceptions align with the technological advancements and challenges discussed so far. While cybersecurity risks predominantly affect the scalability and sustainability of circular economy systems, the societal impact of AI reaches beyond technical considerations, influencing various aspects of daily life.

Fig. 5 illustrates public expectations regarding the impact of AI on various life aspects between 2025 and 2028. While most respondents foresee improvements in productivity and entertainment, concerns about negative effects on the job market highlight the need for proactive strategies to address societal challenges. Fig. 5 reveals varied public expectations regarding the impact of AI on aspects of daily life between 2025 and 2028. While the majority anticipate improvements in productivity (54%) and entertainment options (52%), concerns remain regarding the job market, where 36% of respondents fear potential negative effects. These perceptions underscore the need for balanced strategies to maximize AI's benefits while mitigating potential risks.

## IV. CONCLUSIONS

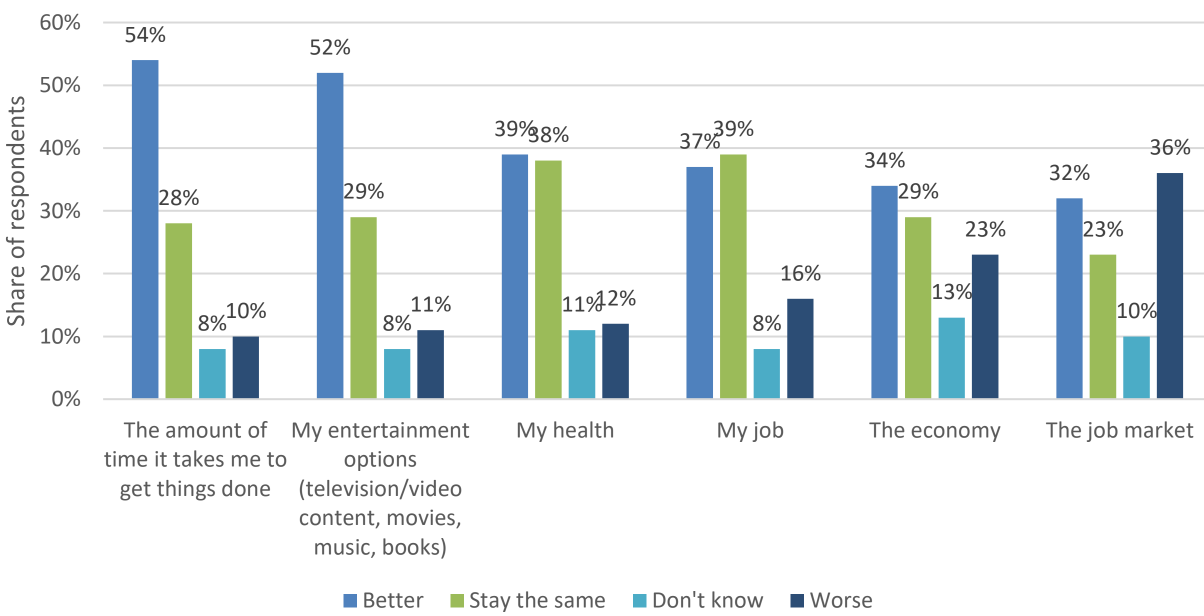
In conclusion, the integration of artificial intelligence into circular economy models presents unprecedented opportunities for optimizing resource use, reducing waste, and promoting sustainable practices. However, this transformation also brings new cyber risks that require a comprehensive approach to cybersecurity management.

This article examined the main cyber threats specific to AI-driven circular economy systems, such as attacks on product tracking systems, data manipulation, disruption of intelligent systems, and vulnerabilities of the Internet of Things. We also analyzed key strategies and frameworks that organizations can apply to enhance cybersecurity, including the NIST Cybersecurity Framework, ISO/IEC 27001, AI Risk Management Framework (AI RMF 1.0), and the EU AI Act.

Particular attention was paid to the impact of cyber threats on the scalability and sustainability of circular economy initiatives. Cyberattacks can undermine confidence in these initiatives, disrupt their operations, lead to financial losses, and negatively impact the environment. For the successful development of an AI-driven circular economy, it is crucial to implement robust cybersecurity measures, ensure data integrity, improve system resilience, and promote collaboration among stakeholders. This is the only way to guarantee the safe and efficient use of AI to achieve sustainable development goals.

In the future, research in this area should be aimed at developing specialized cybersecurity solutions that take into account the unique needs of the circular economy. It is also necessary to pay attention to the ethical aspects of using AI and to develop international standards for cybersecurity in this new paradigm. The integration of AI into circular economy systems represents a paradigm shift in how resources are managed and sustainability goals are achieved. While the journey is fraught with challenges, including cybersecurity risks and public apprehensions, the potential rewards are immense. By addressing these challenges through robust strategies, innovative technologies, and collaborative efforts, AI can serve as a cornerstone for a resilient and sustainable future. This strategic alignment of AI and CE principles not only enhances organizational efficiency but also contributes to broader environmental and societal well-being.

FIGURE 5. EXPECTED IMPACT OF ARTIFICIAL INTELLIGENCE (AI) ON THE WORLD BETWEEN 2025 TO 2028, BY LIFE ASPECT




Source: Statista, 2024c

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