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The Synergy Between Industry 4.0 and Circular Economy for Sustainable Performance in the Libyan Manufacturing Industry

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العلاقة بين الصناعة 4.0 والاقتصاد الدائري لتحقيق أداء مستدام في قطاع التصنيع الليبي

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Abstract:
This study explores the evolving landscape of the manufacturing sector, which faces increasing pressure to achieve sustainability amidst resource scarcity and rapid technological advancements. Industry 4.0 (I4) technologies offer solutions to optimize resource utilization and productivity, while the Circular Economy (CE) paradigm addresses environmental regulations, resource price volatility, and supply chain uncertainties. Despite their individual contributions, the synergistic relationship between I4 technologies, CE practices, and their combined impact on Sustainable Performance (SP) remains underexplored, particularly within the Libyan manufacturing industry. This research aims to address this gap through an empirical investigation. Data were collected from 110 Libyan manufacturing organizations via a questionnaire-based survey. The Statistical Package for the Social Sciences (SPSS) software was utilized for data analysis. The findings are expected to provide conceptual and empirical insights into how I4 technologies facilitate the transition towards CE practices and their joint impact on sustainable performance, identifying key drivers, enablers, and barriers within this context.

Keywords: Industry 4.0, Circular Economy Practices, Sustainable Performance, Manufacturing Industry, Libya.

الملخص
تستكشف هذه الدراسة المشهد المتطور لقطاع التصنيع، الذي يواجه ضغوطًا متزايدة لتحقيق الاستدامة في ظل ندرة الموارد والتقدم التكنولوجي السريع. تقدم تقنيات الصناعة 4.0 (I4) حلولاً لتحسين استخدام الموارد والإنتاجية، بينما يتناول نموذج الاقتصاد الدائري (CE) اللوائح البيئية، وتقلب أسعار الموارد، وعدم اليقين في سلسلة التوريد. على الرغم من مساهمات كل منها على حدة، إلا أن العلاقة التآزرية بين تقنيات الصناعة 4.0 وممارسات الاقتصاد الدائري وتأثيرها المشترك على الأداء المستدام (SP) لا تزال غير مستكشفة، لا سيما داخل قطاع التصنيع الليبي. يهدف هذا البحث إلى معالجة هذه الفجوة من خلال تحقيق تجريبي. تم جمع البيانات من 110 منظمة تصنيع ليبية من خلال مسح قائم على الاستبيان. تم استخدام برنامج الحزمة الإحصائية للعلوم الاجتماعية (SPSS) لتحليل البيانات. من المتوقع أن توفر النتائج رؤى مفاهيمية وتجريبية حول كيفية تسهيل تقنيات الصناعة 4.0 للانتقال نحو ممارسات الاقتصاد الدائري وتأثيرها المشترك على الأداء المستدام، مع تحديد العوامل الدافعة والممكنة والعوائق الرئيسية في هذا السياق.

الكلمات المفتاحية: الصناعة 4.0، ممارسات الاقتصاد الدائري، الأداء المستدام، الصناعة التحويلية، ليبيا.

Introduction

The manufacturing sector serves as a pivotal driver of economic development, particularly in nations like Libya, necessitating continuous innovation, learning, and research (Westkmper, 2014). For developing countries, industrial advancement is increasingly critical for achieving economic parity with developed nations and enhancing citizens' quality of life. Concurrently, the imperative of sustainability has gained significant traction, becoming a strategic priority for manufacturing firms (Naudé & Szirmai, 2012), (Gehrke et al., 2015). Sustainability is widely defined as 'development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs' (Brundtland, 1987). For industrial organizations, this translates into achieving substantial improvements in revenue, profitability, product development, market share, market expertise, working environment, and environmental footprint. These aspects are conventionally categorized into three dimensions: economic prospects, environmental protection, and social responsibility, collectively known as the triple bottom line of sustainability (Gimenez et al., 2012).

Despite the growing emphasis on sustainability, manufacturing firms continue to grapple with their adverse environmental and societal impacts. In response, researchers have proposed various approaches to foster an eco-friendlier industrial sector. Among these, the Circular Economy (CE) paradigm has emerged as a promising solution, offering a framework to decouple organizational growth from resource consumption. CE advocates for new production channels and strategies focused on minimizing resource consumption, enhancing efficiency, and reducing waste (Ellen Macarthur Foundation, 2015).

Simultaneously, advancements in industrial production systems have ushered in the digitalization era, characterized by increasingly connected, integrated, and decentralized manufacturing processes (Stock & Seliger, 2016). This shift defines the Fourth Industrial Revolution, or Industry 4.0 (I4.0), which aims to transform production systems into more flexible, efficient, and sustainable entities while maintaining high quality and low costs (S. Wang et al., 2016). I4.0 is recognized for its potential to contribute significantly to sustainability goals, guiding manufacturing organizations toward new avenues of growth (Carvalho et al., 2018). Smart products, a hallmark of the I4.0 environment, are anticipated to yield substantial economic, environmental, and social benefits (Erskin Blunck & Hedwig Werthmann, 2017), (Luthra & Mangla, 2018) .

While there is a general consensus on I4 technologies' role as enablers of CE, the precise mechanisms by which I4 technologies facilitate the transition to CE practices remain underexplored in the literature. Critically, the comprehensive relationship between I4 technologies, CE, and Sustainable Performance (SP) requires further conceptual and empirical investigation to fully understand their combined impact on SP (Lieder et al., 2017).

This study aims to address these identified literature gaps by empirically examining the extent to which I4 technologies and CE practices influence the SP of organizations within the Libyan manufacturing context. Specifically, this research seeks to answer the following questions:

RQ1: What is the theoretical framework of relationships between I4 technologies, CE practices, and SP ?

RQ2: How do I4 technologies and CE practices affect the SP?

Background

Sustainable Performance (SP)

Organizations are increasingly prioritizing sustainable operations to foster growth and market competitiveness. Recent academic interest has focused on developing robust assessments of corporate sustainability performance. Business sustainability performance primarily encompasses the social, environmental, and economic dimensions of sustainable development. Consistent with the Brundtland Report, sustainable development is defined as 'development that fulfills the needs of the present, without compromising the ability of future generations to meet their own needs' (Brundtland, 1987). This implies that current and future generations can leverage sustainability to address their needs. To achieve comprehensive sustainability, manufacturing firms must satisfy the diverse needs and expectations of clients, customers, suppliers, society, and governments. Consequently, manufacturing firms must holistically address the socio-economic and environmental dimensions, famously known as the triple bottom line of sustainability (Brundtland, 1987). Achieving a crucial balance among these three factors, social, environmental, and economic, is paramount for firms to attain true sustainability (Goyal et al., 2013) .

Industry 4.0 (I4.0) Technologies

The modern industrial landscape is characterized by a pervasive demand for the digitalization of manufacturing processes. As industries transition from mass production to customized production, there is an urgent need for rapid advancements in manufacturing capabilities. This imperative led to the conceptualization of Industry 4.0, representing the fourth industrial revolution. I4.0 technologies encompass various forms, including the Internet of Things (IoT), Big Data Analytics (BD), Cloud Computing (CC), Additive Manufacturing, Robotic Systems, and Augmented Reality. Within the I4.0 paradigm, manufacturing systems are elevated to an intelligent state, leveraging information and advanced technologies to optimize processes and enhance competitiveness.

Industry 4.0 is in a state of continuous evolution, paralleling the pervasive digitalization of technology across all domains. To remain competitive and relevant, firms are actively adopting I4.0 principles by integrating its technologies into their daily operations. This technological impetus, as described by (Lasi et al., 2014), has encouraged firms to employ innovative technologies in their routine activities. Key applications of Industry 4.0, as identified by (Lu, 2017), primarily include 'Smart Product,' 'Smart City,' and 'Smart Factory and Manufacturing.' The 'Smart Factory and Manufacturing' applications specifically aim to enhance corporate flexibility and intelligence by integrating cutting-edge technologies to optimally coordinate and connect processes (Albers et al., 2016), (Bibby & Dehe, 2018). The deployment of I4.0 technologies has been shown to reduce product costs, improve lead times, enhance product quality, and deliver numerous other technological benefits. Furthermore, I4.0 technologies are expected to propel industries towards developing extraordinary operational competencies and significant productivity improvements (Pfeiffer & Suphan, 2015), .

Circular Economy (CE) Practices

The Circular Economy (CE) primarily aims to achieve environmental quality, followed by economic prosperity, and subsequently considers its impact on social equity and future generations. Numerous definitions of CE exist in the literature, with the most widely recognized provided by the Ellen MacArthur Foundation, which defines CE as 'an industrial economy which is restorative or regenerative by intention and design'. The CE paradigm fundamentally seeks to facilitate the circulation of resources within a closed loop, thereby significantly reducing the need for new material inputs into production systems (Gusmerotti et al., 2019). Key principles of CE practices include recycling, remanufacturing, circular design, and circular manufacturing (Ghaithan et al., 2021).

In recent years, with the heightened focus on sustainability and firms' inclination towards innovative solutions, many researchers emphasize the '6R' principles of circularity (e.g., Reduce, Reuse, Recycle, Recover, Redesign, Remanufacture) (Kirchherr et al., 2018). These principles serve as operational and theoretical strategies, elucidating the functional mechanisms of CE and guiding the practical implementation of strategies to achieve CE objectives (Laidis, 2021).

Furthermore, the foundational elements of circular business models are derived from the core principles of the circular economy. Various business models have been proposed to translate CE principles into structured actions and responsibilities. A prominent example is the ReSOLVE framework, which outlines six business actions, Regenerate, Share, Optimize, Loop, Virtualize, Exchange, to operationalize CE principles and highlight major opportunities (Lewandowski, 2016). Studies suggest that CE has the potential to enhance resource utilization and minimize waste, thus fostering balanced, sustainable organizational growth (Ghisellini et al., 2016). However, some studies have raised concerns regarding the feasibility of CE implementation in organizations, citing high implementation costs, potential rebound effects, and questions about overall effectiveness" (Allwood, 2014), (P. Wang et al., 2018), (Pedersen & Hauschild, 2016).

Theoretical Framework and Hypothesis Development

Contemporary enterprises are increasingly concerned with achieving sustainability and are actively seeking solutions to reduce waste and, consequently, lower costs (Laidis, 2021). Industry 4.0 offers substantial support for the facilitation of Circular Economy principles. The adoption of I4.0 technologies enhances the transition toward a circular economy due to their advanced capabilities in tracking resource consumption and emissions. Indeed, I4.0 has empowered organizations to foster innovation, integrating material and machinery with data resources to realize circular economy principles, which directly contribute to sustainability objectives. The literature identifies CE as a critical organizational resource for addressing the challenge of escalating resource depletion rates (Jakhar et al., 2019). CE practices are designed to optimize existing resources, minimize waste generation, and cultivate an environment characterized by resource efficiency and regenerative models (Guo et al., 2017), (Mangla et al., 2018), (Jakhar et al., 2019). CE further contributes to business sustainability by fostering innovative production and consumption models, creating investment and job opportunities, reducing material and manufacturing costs, and enhancing supply chain resiliency (Lieder & Rashid, 2016), (Lopes de Sousa Jabbour et al., 2018).

Despite the evident potential, the comprehensive relationship between Industry 4.0 technologies, CE practices, and Sustainable Performance (SP) remains inadequately explored, demanding more rigorous conceptual and empirical investigation into how I4.0 technologies specifically facilitate the transition to CE practices and their collective impact on SP. Based on the foregoing discussion, we propose the following hypotheses, which form the core of our research model as depicted in Figure 1:

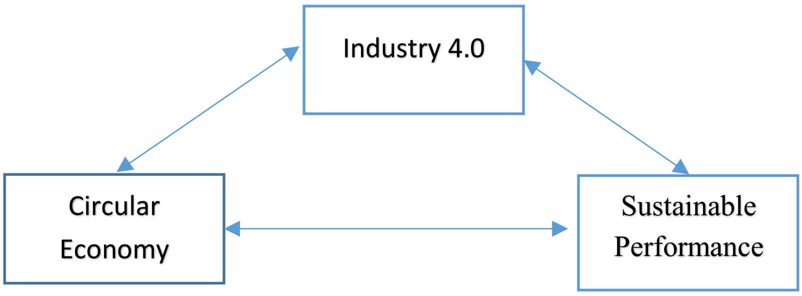

Figure (1): Study model.

- Hypothesis 1 (H1): There is a direct and positive relationship between Industry 4.0 technologies and Circular Economy practices .
- Hypothesis 2 (H2): There is a direct and positive relationship between Circular Economy practices and Sustainable Performance .
- Hypothesis 3 (H3): There is a direct and positive relationship between Industry 4.0 technologies and Sustainable Performance.

Material and methods

Research Design and Data Collection

This section details the research design, measurement scales, sampling strategy, and data collection procedures employed in this study. The study adopted a quantitative research approach, utilizing a questionnaire-based survey as the primary data collection instrument. This method was chosen for its efficiency, promptness, and cost-effectiveness in gathering data from a broad range of respondents".

Measurement Scale

The present study examined three primary constructs: Industry 4.0 technologies, Circular Economy Practices, and Sustainable Performance. Each construct was operationalized through specific sub-constructs and measured using multiple items.

- Industry 4.0 (I4.0) Technologies: This construct was measured by items related to the adoption and implementation of key I4.0 technologies, specifically Cloud Computing (CC), Big Data (BD), Cyber-Physical Systems, 3D Printing, Advanced Robotics, and the Internet of Things (IoT).
- Circular Economy (CE) Practices: This construct comprised three core sub-constructs: Reduce, Reuse, and Recycle.
- Sustainable Performance (SP): This construct was measured across its three established dimensions: Environmental Performance, Economic Performance, and Social Performance. Each of these sub-constructs was assessed using five measurement items.

- Procedures and Sample

Data for this study were collected from Libyan organizations, specifically targeting practitioners within the manufacturing sector. A convenience sampling method was employed, involving the collection of data from readily available respondents. This approach is widely used due to its simplicity, speed, and cost-effectiveness. The study utilized an online survey methodology, distributed via the SurveyMonkey website (http://www.surveymonkey.com). A total of 465 manufacturing practitioners from 110 manufacturing organizations, identified through the Libyap.com database, were approached for participation. The questionnaire was disseminated via email to employees of businesses and academic consultants affiliated with businesses.

To ensure data quality, only respondents with at least two years of experience in the manufacturing industry and demonstrable awareness of both I4.0 technologies and CE practices were invited to participate. Participation in the survey was entirely voluntary. Within a six-week period, 201 completed questionnaires were received, yielding a response rate of 43 percent. Incomplete submissions were automatically disallowed by the survey platform, ensuring that all received questionnaires were usable. The questionnaire design was adapted from (Laidis, 2021) to specifically fit the research context, covering questions related to the drivers, enablers, principles, and barriers of both circular economy and Industry 4.0, given their interacting roles in fostering corporate sustainability. Upon collection, the data were extracted from the SurveyMonkey platform and transferred to the SPSS (Statistical Package for the Social Sciences) software package for comprehensive analysis. Table 1 presents the demographic characteristics of the respondents and the profile of the participating manufacturing organizations.

Results and discussion

This section presents the empirical results derived from the analysis of the collected data. The findings are organized to first describe the sample characteristics, followed by descriptive statistics of the main constructs, and finally, the results of the hypothesis testing.

- **Sample Characteristics**

Table 1 provides a detailed overview of the sample characteristics, including the sector belonging to, company experience, and individual respondent experience.

Sector Belonging To: The majority of respondents (54.2%) were from the Manufacturing sector, which aligns with the study's focus. Other sectors included Construction (16.9%), Food Production (12.9%), Commerce (7%), Mining (4%), Services (2%), and Retail and Transportation/Automotive (both 1.5%). Company Experience: A significant proportion of participating organizations had substantial experience, with 45.8% reporting 15-19 years of operation, followed by 29.4% with 10-14 years, and 20.9% with 20-24 years. Only 4% of companies had 5-9 years of experience. This indicates a sample of established manufacturing entities. Respondent Experience: The individual respondents also demonstrated considerable experience, with 51.7% having 5-9 years of experience, 25.4% with 10-14 years, 18.4% with less than 5 years, and 4.5% with 15-19 years of experience. This suggests the data was collected from knowledgeable and experienced practitioners within the industry.

Table (1): Sample characteristics.

Variable	Level of Change	Frequency	Percentage
Sector Belonging To	Retail	3	1.5%
	Mining	8	4%
	Transportation and Automotive	3	1.5%
	Food Production	26	12.9%
	Construction	34	16.9%
	Commerce	14	7%
	Manufacturing	109	54.2%
	Services	4	2%
	Total	**201**	**100%**
Company experience	5–9 years	8	4%
	10–14 years	59	29.4%
	15–19 years	92	45.8%
	20–24 years	42	20.9%
	Total	**201**	**100%**
Experience	<5 years	37	18.4%
	5–9 years	104	51.7%
	10–14 years	51	25.4%
	15–19 years	9	4.5%
	Total	**201**	**100%**

Descriptive Statistics

Table 2 presents the descriptive statistics, including the mean and standard deviation, for the three main constructs: Circular Economy Practices, Sustainable Performance, and Industry 4.0 Technologies. Sustainable Performance showed the highest mean score (M = 3.995, SD = 0.521), indicating that respondents generally perceive their organizations as having relatively high sustainable performance.

Table (2): Descriptive statistics.

Variable	Mean	Std. Deviation
circular economy practices	3.357	0.748
Sustainable Performance	3.995	0.521
Industry 4.0 technologies	3.546	0.677

Industry 4.0 Technologies had a mean of 3.546 (SD = 0.677), suggesting a moderate level of adoption or awareness of these technologies among the surveyed organizations. Circular Economy Practices reported a mean of 3.357 (SD = 0.748), indicating a slightly lower perceived implementation

or emphasis on CE practices compared to SP and I4.0 technologies. The standard deviations suggest a moderate level of variation in responses for all constructs.

Hypothesis Testing

Table 3 presents the results of the Pearson Correlation analysis conducted to test the hypothesized relationships between the constructs.

- Hypothesis 1: "There is a direct and positive relationship between Industry 4.0 and Circular Economy". The Pearson Correlation coefficient was 0.601 (p < 0.001), indicating a strong, positive, and statistically significant relationship between Industry 4.0 technologies and Circular Economy practices. Thus, Hypothesis 1 is supported.
- Hypothesis 2: "There is a direct and positive relationship between Circular Economy and Sustainability Performance". The Pearson Correlation coefficient was 0.567 (p < 0.001), demonstrating a moderately strong, positive, and statistically significant relationship between Circular Economy practices and Sustainable Performance. Therefore, Hypothesis 2 is supported.
- Hypothesis 3: "There is a direct and positive relationship between Industry 4.0 and Sustainability Performance". The Pearson Correlation coefficient was 0.592 (p < 0.001), indicating a strong, positive, and statistically significant relationship between Industry 4.0 technologies and Sustainable Performance. Consequently, Hypothesis 3 is supported. All three hypotheses were supported at the 0.01 level of significance, suggesting robust positive relationships between the constructs as theorized.

Table (3): Hypothesis testing.

Hypothesis	Pearson Correlation	Sig
There is a direct and positive relationship between Industry 4.0 and Circular Economy	0.601**	0.000
There is a direct and positive relationship between Circular Economy and Sustainability Performance	0.567**	0.000
There is a direct and positive relationship between Industry 4.0 and Sustainability Performance	0.592**	0.000

Discussion

The findings of this study provide significant empirical insights into the relationships between Industry 4.0 technologies, Circular Economy practices, and Sustainable Performance within the Libyan manufacturing industry. All three proposed hypotheses were supported, demonstrating direct and positive relationships among these constructs. The strong positive correlation between Industry 4.0 technologies and Circular Economy practices (H1 :r=0.601$,p \< 0.001$) underscores the crucial role of advanced digital technologies in facilitating the transition towards circularity. This finding aligns with previous theoretical propositions that I4.0 capabilities, such as real-time data tracking, advanced robotics, and enhanced connectivity, enable better resource management, waste reduction, and optimized production loops inherent in CE principles. For instance, IOT and Big Data Analytics can provide granular insights into material flows and energy consumption, allowing for more precise 'reduce, reuse, and recycle' strategies. This empirically confirms the notion that I4.0 is not just an enabler but a significant driver for CE adoption.

Furthermore, the significant positive relationship between Circular Economy practices and Sustainable Performance (H2 :r=0.567$,p \< 0.001$) confirms the efficacy of CE in achieving broader sustainability goals. This result supports existing literature that posits CE as a paradigm capable of decoupling economic growth from resource consumption, leading to improved environmental quality, economic prosperity through waste reduction and resource optimization, and positive social impacts. The adoption of CE principles like recycling, remanufacturing, and circular design directly contributes to economic savings, reduced ecological footprint, and potentially enhanced social equity through new business models and job opportunities.

Finally, the strong positive relationship observed between Industry 4.0 technologies and Sustainable Performance (H3 : r=0.592 $,p \< 0.001$) highlights the direct contribution of digital transformation to organizational sustainability. This outcome is consistent with previous research suggesting that I4.0 technologies foster more flexible, efficient, and sustainable production systems. Smart factories and manufacturing systems, powered by I4.0, can lead to reduced product costs, improved quality, and optimized resource use, all of which contribute to economic, environmental, and social dimensions of sustainable performance. The ability of I4.0 to provide real-time monitoring and control allows for proactive adjustments to production, minimizing waste and energy consumption, thus directly improving environmental performance.

Collectively, these findings demonstrate a synergistic effect. While I4.0 technologies directly contribute to sustainable performance, they also foster an environment conducive to the adoption and effectiveness of circular economy practices, which in turn further enhance sustainable performance. This suggests that a holistic approach integrating both I4.0 and CE is crucial for manufacturing firms aiming for comprehensive sustainability. The results specifically within the Libyan context provide valuable empirical evidence, addressing the previously identified research gap regarding these relationships in developing countries' manufacturing sectors.

- **Implications for Theory and Practice:**

The findings contribute to the theoretical understanding of the interplay between I4.0, CE, and SP by empirically validating their positive interconnections, especially within a less-explored geographical context like Libya. For practitioners, these results emphasize the strategic importance of investing in I4.0 technologies not only for operational efficiency but also as a foundational element for transitioning towards CE practices and achieving long-term sustainable performance. Manufacturing firms in Libya and similar developing economies should consider integrating I4.0 roadmaps with their sustainability strategies, recognizing the transformative potential of digital technologies in fostering a circular and sustainable future.

- **Limitations and Future Research:**

Despite the valuable insights, this study has limitations. The reliance on convenience sampling and a self-reported questionnaire may introduce biases. Future research could employ longitudinal studies or case studies to gain deeper insights into the dynamic implementation challenges and benefits. Additionally, exploring specific I4.0 technologies and their differential impact on various CE principles could provide more granular understanding. Investigating the moderating or mediating roles of other organizational or contextual factors would also enrich the research.

Conclusion

This study set out to investigate the intricate relationships between Industry 4.0 technologies, Circular Economy practices, and Sustainable Performance within the Libyan manufacturing industry, a domain previously lacking comprehensive empirical exploration. Our findings conclusively demonstrate significant direct and positive relationships among all three constructs. Specifically, Industry 4.0 technologies are strongly associated with the adoption of Circular Economy practices, and both Industry 4.0 technologies and Circular Economy practices are significantly and positively linked to enhanced Sustainable Performance.These results highlight the profound synergy between advanced digital technologies and circularity principles in driving organizational sustainability. For the Libyan manufacturing sector, this implies that strategic investments in Industry 4.0 are not merely technological upgrades but fundamental enablers for developing robust Circular Economy frameworks, ultimately leading to improved economic, environmental, and social performance. The study provides empirical evidence that adopting Industry 4.0 is a vital step towards achieving a more sustainable and resilient manufacturing future, especially in economies undergoing industrial development. By integrating these two transformative paradigms, manufacturing organizations can effectively address the pressing challenges of resource scarcity, environmental regulations, and the global demand for sustainable practices, thereby contributing to both national economic development and global sustainability goals.

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