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ENVIRONMENTAL PERFORMANCE AND DIGITIZATION: THE ROLE OF INDUSTRY 4.0 IN THE ECOLOGICAL TRANSITION OF COMPANIES

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A B S T R A C T

*'his study explores the intersection of digitization and sustainability, focusing o
ow Industry 4.0 technologies can enhance companies' environmentc
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ıdustry 4.0 offers innovative solutions to reduce carbon emissions, optimiz
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ansformative potential of these technologies while acknowledging th
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-waste management. Through a review of contemporary research and cas
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1. INTRODUCTION

In order to face climate change's issues, companies are pushed increasingly to adopt environmentally friendly practices. The international treaty such as the Paris Agreement, consumer's expectations for sustainable products, and Investors' integration of ESG (environmental, social, and governance) criteria are encouraging companies to rethink their economic and industrial models (Frimousse & Peretti, 2023). However, this transition cannot be limited to minor adjustments; it requires a complete overhaul of production processes and supply chains (Zimon et al., 2022).

The emergence of Industry 4.0, described often as the fourth industrial revolution, offers innovative solutions to these challenges. Based on advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, and Blockchain, Industry 4.0 promises to transform production systems by making them more intelligent, interconnected, and efficient. For example, IoT enables real-time monitoring resources used in production, while AI and Big Data optimize industrial processes by analyzing massive datasets, reducing inefficiencies, and limiting environmental impacts (Cantuarias et al., 2020).

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Recent research confirms that these technologies play a crucial role in improving companies' environmental performance. The integration of cyber-physical systems and digital platforms can reduce carbon emissions, minimize industrial waste, and improve energy efficiency while promoting process transparency through tools such as Blockchain (Alix et al., 2024; Tite, 2022; Knapcikova et al., 2024). However, this transformation comes with significant challenges, especially high implementation costs, the increasing demand for specialist skills, and concerns about managing the e-waste generated by these new technologies (Luthra & Mangla, 2018).

Issues and objectives

Given the increasing environmental challenges, a main question arises: To what extent can Industry 4.0 technologies be used to improve companies' environmental performance while supporting their transition to sustainable ecological models?

In this perspective, this article pursues several objectives:

- To analyze how digital technologies are transforming industrial practices, in particular, to reduce environmental impact;
- To explore the opportunities and limitations of these technologies by examining case studies and recent theoretical models;
- To provide concrete recommendations for maximizing their potential whilst overcoming the challenges of implementation.

Based on contemporary academic research and emerging conceptual frameworks, this paper aims to provide an integrated perspective on the relationship between digitization and sustainability. The conclusions reached will enrich the scientific literature while offering practical paths for decision-makers engaged in the ecological transition.

2. LITERATURE REVIEW AND CONTEXTUAL ANALYSIS

In this section, we analyze the global and local factors that influence corporate environmental performance, highlighting the elements that favor ecological transition. We begin with a review of key concepts relating to this topic, such as the ecological transition of companies and Industry 4.0. Next, we will explore the link between digitalization and environmental performance by examining how digital technologies, such as the Internet of Things (IoT), artificial intelligence (AI), and cyber-physical systems, can help reduce companies' ecological footprints while optimizing their industrial processes. (Sy, 2023). This analysis will provide a better understanding of how digitalization, particularly through Industry 4.0, represents a crucial lever in the transition to a more sustainable, environmentally friendly economy.

2.1 Corporate Ecological Transition

The ecological transition of companies refers to a process of transformation aimed at reducing environmental impact while maintaining economic competitiveness. This evolution is diven by factors such as the effects of climate change, the increasing scarcity of natural resources, and the growing demands of stakeholders. The major challenges that companies must face include the reduction of greenhouse gas (GHG) emissions, the sustainable management of natural resources, the adoption of the circular economy, and the integration of environmental, social, and governance (ESG) criteria into their strategies. These challenges require profound adjustments to industrial processes and business models to balance environmental and economic performance (Walker-Jones, 2021, Frimousse & Peretti, 2023).

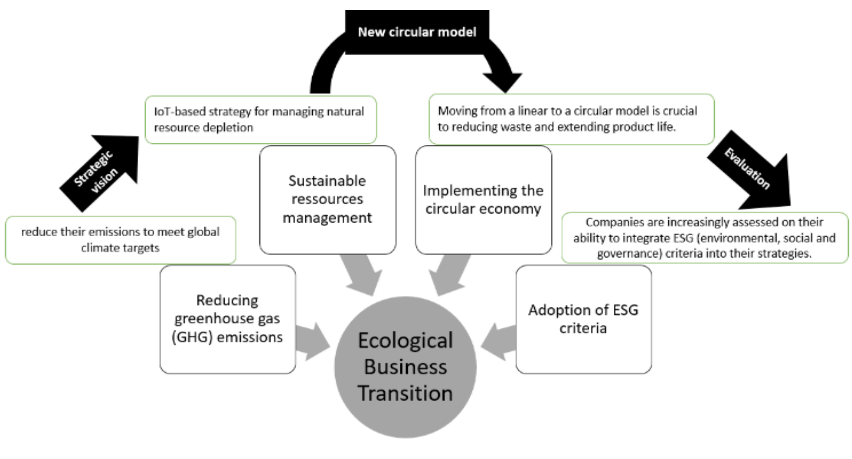

Figure 1. Processes for the Ecological Transition of Companies. (Authors)

The Figure 1 presents an in-depth analysis of the scientific problems and obstacles associated with each dimension of the ecological transition. It examines the technical, environmental, and social aspects while highlighting innovative solutions aimed at ensuring a successful ecological transition for businesses.

Recent literature highlights several key factors in the corporate green transition process. Firstly, emerging technologies such as information systems and digital platforms play a key role in efficient resource management and emissions reduction. For example, Blockchain technology ensures the traceability of raw materials within supply chains, enhancing transparency and guaranteeing compliance with environmental standards (Mullet, 2022). Secondly, cross-sector collaboration among companies, governments, and academic institutions is proving essential for developing sustainable solutions. Initiatives such as the Green Supply Chain Alliances in Europe demonstrate how this cooperation not only reduces the environmental footprint but also encourages innovation (Ashraf & van Seters, 2020).

However, as we will attempt to address in Table 1, despite the many advantages offered by technological solutions, their adoption remains hampered by various obstacles, including high initial costs, a lack of specific skills, and inadequate existing infrastructure. In addition, cultural and organizational challenges are also identified as major obstacles to ecological transition (Adoue et al., 2014; Hacene, 2024).

Table 1. The scientific challenges of the ecological transition for companies (Authors)

Reducing greenhouse gas (GHG) emissions		**Sustainable resource management**	
Problem: The industrial sector, accounting for around 24% of global greenhouse gas (GHG) emissions, is a major obstacle to decarbonization efforts (IPCC, 2022).	**Obstacle 1:** Companies are struggling to reduce their GHG emissions to meet the international targets, due to economic and regulatory constraints. **Obstacle 2:** The adoption of sustainable technologies, such as energy efficiency and renewable energies, remains limited by financial and technical challenges. **Obstacle 3:** The optimization of resources and the reduction of emissions are hampered by the complexity of production chains and resistance to change. -	**Problem**: The progressive depletion of natural resources, such as water and essential minerals, raises the need to devise strategies to improve their management and use more efficiently**.**	**Obstacle 1:** Although resource management via the Internet of Things (IoT) is promising, its implementation remains limited by technical challenges, high costs, and a lack of suitable infrastructure. **Obstacle 2:** Although real-time monitoring of resource consumption via the IoT offers advantages, widespread adoption is hampered by difficulties with integration, data management, and effective solutions for identifying areas of inefficiency.
Solution: Reduce the environmental impact of the industrial sector by implementing sustainable practices and integrating innovative technologies to minimize greenhouse gas emissions (Rockström et al., 2023).		**Solution:** Minimize waste and ensure sustainable management of natural resources, particularly in high-consumption sectors, to promote their long-term conservation (Zhao et al., 2022; Zhang et al., 2021).	
Implementing the circular economy		**Adoption of ESG criteria**	
Problem: The linear economic model fails to limit waste production and extend product lifetimes, resulting in increased pressure on natural resources and inefficient waste management.	**Obstacle 1**: Large-scale implementation of recovery, recycling, and reuse strategies is hampered by technical, economic, and logistical challenges. **Obstacle 2**: Adoption of closed-loop models remains limited, despite successful initiatives in certain sectors such as the automotive industry, slowing the transition to more sustainable practices. (Ellen MacArthur Foundation, 2021; Geissdoerfer et al., 2020).	**Problem:** The lack of uniform standards for ESG practices is a major obstacle to consistent assessment and transparent communication of companies' environmental, social, and governance performance.	**Obstacle 1**: Companies are under increasing pressure to integrate environmental, social, and governance (ESG) criteria into their strategies, presenting significant challenges in adapting their operational structures and processes. **Obstacle 2**: The lack of uniform standards for ESG practices makes it difficult to compare companies' sustainability efforts, thereby restricting stakeholders' ability to accurately and effectively assess their performance. (Bansal & DesJardine, 2022; Eccles et al., 2014).
Solution: Implementing a circular economic model, based on sustainable resource management, reduces environmental impact while generating economic benefits. This model is based on the reuse of recovered materials, promoting a more efficient and sustainable economy.		**Solution:** ESG (environmental, social, and governance) assessment takes into account ecological, social, and governance dimensions, thereby promoting an integrated and sustainable approach to assessing corporate performance.	

By integrating resource management, decarbonization, and circular approaches, companies can not only reduce their environmental impacts but also benefit from sustainable economic advantages, such as cost savings and greater resilience to market fluctuations. As mentioned in Table 1, research emphasizes the need for strategic alignment between environmental objectives and corporate technological capabilities to maximize these long-term benefits.

2.2 Industry 4.0

Definition

Industry 4.0, referred often to as the fourth industrial revolution, marks a digital transformation of production and industrial management systems. It is based on the integration of advanced technologies to connect, automate, and optimize industrial processes, resulting in efficiency benefits and reducing the environmental impact. One of the key technologies of Industry 4.0 is the

Internet of Things (IoT). It enables real-time communication between equipment and systems via sensors and intelligent networks. For example, IoT-equipped machines can continuously monitor production performance, detecting anomalies to avoid breakdowns and improve process reliability (Xu & Ouyang, 2022). At the same time, Big Data and analytical tools play a crucial role in optimizing operations. By processing vast amounts of data from sensors and machines, these technologies can predict failures, reduce waste and improve energy efficiency in factories (Wang et al., 2023). Artificial intelligence (AI) is also used to automate decision-making and optimize processes. It is particularly effective for predictive maintenance, anticipating necessary repairs, and optimizing supply chains real time (Zhang et al., 2023). Cyber-Physical Systems (CPS), which combine physical and digital elements interacting via intelligent networks, enable more flexible manufacturing management, where machines can adjust their performance in response to changing conditions (Teiar, 2018). Blockchain, a distributed ledger technology, ensures the transparency and traceability of raw materials and products in supply chains, making it easier to verify the sustainability of materials and environmental compliance (Wang et al., 2023).

In addition, additive manufacturing, particularly 3D printing, enables custom parts to be produced with less waste, reducing material consumption compared with traditional manufacturing methods. Finally, Augmented Reality (AR) and Virtual Reality (VR) are used to enhance employee training, but also to facilitate remote-assisted maintenance, making industrial processes more flexible and less polluting. These technologies are converging to transform the industry into a more sustainable sector, optimizing resources, reducing ecological footprints, and contributing to a circular economy.

Industrial Applications of Industry 4.0 Technologies

Industry 4.0 technologies offer a wide range of practical applications in industrial processes, helping to improve efficiency, sustainability, and competitiveness. Automated production line, facilitated by the Internet of Things (IoT) and cyber-physical systems, represents a breakthrough. These technologies enable machines to operate autonomously, reducing the need for human intervention and thus increasing the precision as well as the efficiency of industrial operations (Sharma et al., 2024). Optimizing energy efficiency is also a key concern for smart factories. The use of artificial intelligence (AI) and Big Data enables companies to monitor and adjust their energy consumption in real-time, generating substantial savings. Some studies show that these technologies can reduce energy costs by up to 30% in certain industrial sectors (Rissman et al., 2020).

In addition, predictive maintenance, made possible by IoT sensors, gathers crucial data on the condition of equipment, anticipating breakdowns and thereby minimizing downtime and repair costs. Supply chain management also benefits from these technologies, notably with blockchain, which enables full traceability of materials throughout the chain. This enhances sustainability and logistical transparency, particularly in sectors such as food and automotive (Sharma et al., 2024). Finally, technologies help optimize recycling process and reduce waste, by facilitating the tracking of material flows, supporting the principles of the circular economy, and improving resource management more responsibly.

These innovations converge to make industries not only more efficient but also more sustainable while responding to contemporary environmental challenges.

Limits and Challenges

Although Industry 4.0 offers significant potential for improving business efficiency, sustainability, and competitiveness, its adoption faces several major challenges. One of the main obstacles is the high initial cost associated with implementing advanced technologies. Integrating complex systems such as IoT sensors, big data platforms, and artificial intelligence requires considerable investment, which is a hindrance for many small and medium-sized enterprises (SMEs), which often lack the financial resources to make these costly transformations (Ustundag & Cevikcan, 2018). This cost includes not only the purchase of equipment but also the staff training and the adaptation of existing infrastructures.

Another crucial challenge lies in data security

The interconnection of industrial systems makes companies more vulnerable to cyber-attacks. These attacks can disrupt production and compromise sensitive data, such as information related to manufacturing processes or personal customer details. It is therefore imperative to strengthen cybersecurity to protect systems against these threats. This requires the implementation of advanced security measures, such as data encryption, reinforced firewalls, and ongoing employee training programs on best security practices. (Sharma et al., 2024).

As illustrated in Figure 2, the adoption of Industry 4.0 requires specialized skills, which is another major challenge for companies. To fully exploit emerging technologies, employees need to receive training in technical skills such as data analysis, IoT systems management, and the use of artificial intelligence. However, the shortage of qualified talent in these fields represents a major obstacle. Companies must invest in the ongoing training of their workforce or recruit experts, a process that can be both costly and time-consuming (Kılıç & Atilla, 2024).

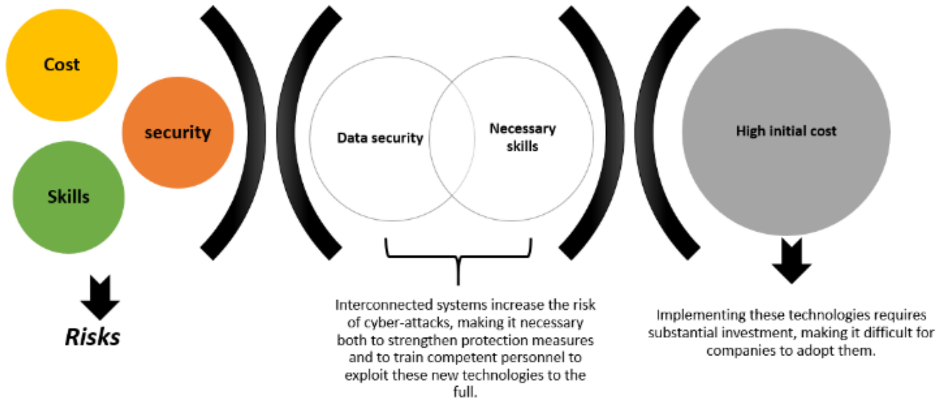

Figure 2. Industry 4.0 risk analysis (Authors)

Contemporary literature highlights the importance of Industry 4.0 in redesigning industrial processes, enabling them to become more intelligent, efficient, and sustainable. Advanced digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), Big Data, and blockchain offer solutions for optimized resource management, helping to reduce the environmental impact of businesses (Jagtap et al., 2023; Zhang et al., 2023). However, although these technologies have considerable potential for improving environmental performance, their successful adoption depends on several determining factors.

Firstly, favourable public policies are essential to support the integration of these technologies, particularly for small and medium-sized enterprises (SMEs), which often face significant financial constraints (Bai et al., 2023). Secondly, significant investment in employee training is necessary to ensure that the skills required to use and manage these emerging technologies are effectively acquired. (Jagtap et al., 2023). Finally, close collaboration between the various economic actors, such as companies, governments, and academic institutions, is essential to overcome the technological, regulatory, and financial challenges that are slowing down the adoption of Industry 4.0. This cooperative framework is crucial to establishing synergies between digitalization and environmental performance, thereby facilitating a successful and sustainable ecological transition.

2.3 Link between Digitization and Environmental Performance

Digitization, through the integration of digital technologies into industrial processes, is a major strategic lever for improving a company's environmental performance. The adoption of tools such as the Internet of Things (IoT), artificial intelligence (AI), and blockchain can optimize resource management, increase transparency, and reduce carbon footprints while streamlining operational costs. These technologies offer not only more precise resource management but also solutions that improve energy efficiency, track materials throughout their lifecycle, and minimize waste.

Recent research on the impact of digital technologies on environmental performance reinforces this perspective, identifying concrete mechanisms by which digitalization supports companies' ecological objectives, as detailed in Table 2.

Table 2. An Overview of Different Approaches to the Impact of Digitalization on Business Performance (Authors)

Impact	Authors	Main Idea
Optimizing energy consumption	(Kamble et al., 2022)	Integrating IoT smart sensors in production systems enables the detection and automatic correction of energy inefficiencies, reducing both energy costs and CO2 emissions
Waste reduction and resource management	(Zhao et al., 2023)	Real-time inventory tracking technologies help reduce surpluses and losses, contributing to the reduction of industrial waste
Circular economy and traceability	(Saberi et al., 2019)	Blockchain enhances material and recycled product traceability, ensuring supply chain transparency and tracking resources for reuse and recycling.
Predictive maintenance and cost reduction	(Bhambri et al., 2024)	Adopting these technologies can reduce maintenance costs by 20-30%, optimize resource use, and extend machine life
ESG transparency and reporting)	(Sandberg et al., 2023	Companies using digital tools for collecting and analyzing ESG data demonstrate better environmental performance and more agile management of their ecological footprint

For example, by facilitating real-time analysis of production data, digitization makes it possible to predict and anticipate failures, thereby contributing to reduced losses and more efficient resource management (Wang et al., 2023; Zhang et al., 2023). This direct connection between digitization and environmental performance clearly shows how companies can achieve their sustainability goals while gaining a competitive edge in a market that is increasingly geared towards environmental responsibility.

The impact of digital technologies on corporate environmental performance has been widely explored in the scientific literature. These studies highlight various ways in which digitalization can support environmental objectives, such as reducing energy costs, minimizing waste, and optimizing the supply chain, thereby promoting a circular and sustainable approach (Bai et al., 2023; Sharma et al., 2024).

Digitization represents a significant opportunity to optimize companies' environmental performance, particularly through the integration of cutting-edge technologies such as the Internet of Things (IoT), Big Data, Artificial Intelligence (AI), and Blockchain. These technologies enable more efficient resource management, improved operational processes, and a reduced carbon footprint. However, to fully leverage these technologies, several challenges must be addressed, including high initial implementation costs, the management of large datasets (Big Data), and increased cybersecurity risks (Kamble et al., 2022).

By integrating appropriate digital solutions, companies not only have the opportunity to improve their environmental performance but also to move towards more sustainable and transparent business models. These approaches ensure compliance with environmental regulations, while meeting the growing demands of stakeholders for responsible and sustainable business practices (Bai et al., 2023; Zhang et al., 2023).

3. INTEGRATED ENVIRONMENTAL PERFORMANCE MODEL AND GREEN TECHNOLOGIES: TOWARDS SYNERGY BETWEEN GREEN IT AND GREEN MANUFACTURING

The Green IT/Green Manufacturing Theory focuses on the integration of digital technologies, particularly those arising from Industry 4.0, to improve corporate sustainability. This theoretical framework is based on two main pillars: Green IT, which encompasses practices such as optimizing data center energy management and reducing e-waste, and Green Manufacturing, which aims to make production processes greener by reducing waste and optimizing resource use. The adoption of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), and additive manufacturing enables companies to reduce their ecological footprint while improving operational efficiency. This model demonstrates how the transition to a more sustainable industry can be facilitated by the use of smart technologies, creating a dual benefit for the environment and industrial competitiveness (Kamble et al., 2022; Zhang et al., 2023).

3.1 Green IT (Green Information Technology)

Green IT encompasses a set of practices and technological solutions aimed at reducing the environmental footprint of human and industrial IT activities. As an essential element of digital sustainability, Green IT focuses on optimizing IT infrastructures and systems to reduce energy consumption, limit the production of electronic waste, and promote innovative solutions such as cloud computing and virtualization. This concept is based on three main axes: improving the energy efficiency of IT systems, reducing e-waste through responsible practices, and adopting modern technologies, such as cloud computing and virtualization, to manage technological resources more sustainably. These practices are summarized in Table 3. These approaches allow IT to be redefined from an environmental perspective while maintaining business performance and competitiveness (Zhao et al., 2023).

Table 3. Key Aspects of Green IT and the Essential Elements of Each Concept(Authors)

Energy Efficiency Optimization	• Reduction of energy consumption through management algorithms. • Virtualization of servers to reduce the need for physical hardware. • Contribution to sustainable management of technological resources.
Reducing electronic waste	• Reduce electronic waste through Green IT. • Encouraging longer life for electronic devices. • Promote the reuse and recycling of components. • Reduce the environmental impact of technological obsolescence.
Cloud Computing and Virtualization	• More efficient, centralized management of resources through cloud computing. • Pooling of infrastructures to reduce energy consumption. • Reduced energy consumption compared with decentralized systems. • Energy optimization through server virtualization. • Reduce hardware requirements by using a single physical server for multiple systems.

Leading companies such as Microsoft and Google exemplify the application of Green IT principles to reduce their environmental impact. Microsoft, for example, has invested heavily in “green” data centers, incorporating innovative cooling technologies to reduce energy consumption. Google, for its part, uses artificial intelligence to optimize the energy management of its data centers, which not only improves energy efficiency but also contributes to a substantial reduction in CO_2 emissions. These practices are illustrated in Figure 3. These approaches demonstrate these companies' commitment to achieving their environmental sustainability goals while increasing their operational performance (Zhang et al., 2023).

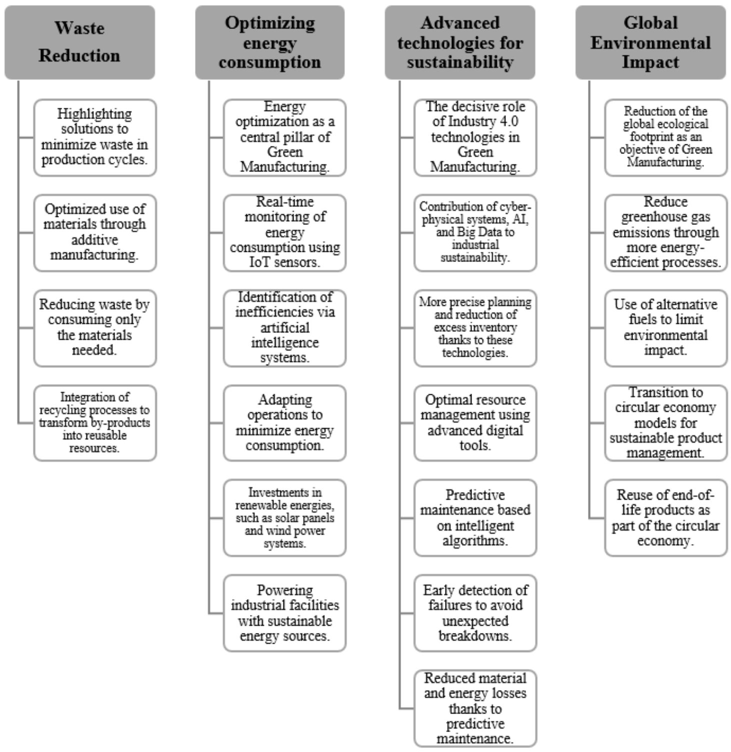

Figure 3. Key Aspects of Green Manufacturing and the Fundamental Elements of Each Concept (Authors)

3.2 Green Manufacturing

The concept of Green Manufacturing involves integrating advanced technologies and environmentally friendly practices into industrial processes. The aim is to reduce waste, optimize energy consumption, and minimize the overall environmental impact of production operations. This approach is a proactive response to the growing pressure on companies to adopt more responsible production methods while ensuring their competitiveness in a globalised economic environment. It not only meets regulatory requirements and societal expectations in terms of sustainability but also generates long-term economic gains by reducing resource and waste management costs (Cao et al., 2021).

3.3 The Impact of Industry 4.0 on Environmental Performance

ndustry 4.0, often referred to as the fourth industrial revolution, incorporates a range of advanced technologies, such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, cyber-physical systems, and additive manufacturing. These innovations are profoundly changing industrial processes, optimizing the use of resources and significantly reducing the environmental impact of economic activities. These technologies and their applications are summarized in Table 4. The application of these technologies enables companies to make their operations more efficient, notably by reducing energy consumption and minimizing waste, while promoting more environmentally friendly production (Kamble et al., 2022). These advances thus contribute to the goal of achieving sustainable and competitive industrial production, by aligning economic and ecological interests.

Companies such as Siemens, Bosch, and Unilever exemplify the crucial role of Industry 4.0 technologies in improving industrial sustainability and environmental performance. Siemens, for example, uses its MindSphere IoT platform to monitor and optimize the energy efficiency of its facilities, contributing to a significant reduction in its carbon footprint (Cao et al., 2021). Bosch, for its part, applies artificial intelligence in its production lines to identify and correct inefficiencies in real-time, thereby enhancing its operational sustainability (Matin et al., 2023). Unilever, meanwhile, integrates additive manufacturing to minimize its plastic consumption, using only the exact amount of material needed to produce bespoke packaging, therbey contributing to the reduction of plastic waste (Stark & Matuana, 2021). These examples illustrate how the adoption of advanced technologies enables companies to reinvent their industrial processes to make them both more efficient and ecologically responsible.

Table 4. Analysis of the Impact of Industry 4.0 on Environmental Performance (Authors)

Optimized Resource Management	• Real-time data collection on production lines thanks to IoT. • Fine-tuned resource management based on analysis of collected data. • Detection of equipment wastage and malfunctions. • Reduce energy consumption by optimizing processes. • Reduce material losses through more efficient use of resources. • Continuous monitoring of machine performance via IoT sensors. • Reduced downtime to limit the environmental impact of processes. • Contribute to reducing the carbon footprint of industrial activities.
Industrial Waste Reduction	• Key role of AI and Big Data in reducing industrial waste. • Analysis of manufacturing processes using machine learning algorithms. • Identification of inefficiencies and sources of waste production. • Real-time adjustments to minimize waste and optimize resources. • Reduction of wasted materials and defective products thanks to these technologies. • Contribution of additive manufacturing, such as 3D printing, to material savings. • Use the appropriate amount of material to minimize surpluses and rejects. • Aligning industrial practices with sustainability objectives.
Transition to a Circular Economy	• Contribution of blockchain to transparency in supply chain management. • Promoting sustainable practices through greater visibility of processes. • Tracking the origin of materials to ensure traceability. • Promoting reuse and recycling as part of the circular economy. • Reduce the ecological footprint of products through more transparent management. • Contribute to sustainability throughout the product life cycle.
Improving energy efficiency	• Integration of physical and digital technologies in cyber-physical systems. • Optimization of energy management through these systems. • Adjustment of energy consumption via smart grids. • Reducing energy wastage through dynamic management of needs. • Integration of renewable energies to enhance the sustainability of industrial processes. • Improving energy performance and sustainability through the use of advanced technologies.
Towards a more responsible industry	• Industry 4.0 technologies for sustainable resource management. • Aligning companies with the Sustainable Development Goals (SDGs) thanks to these technologies. • Transforming traditional production models to meet environmental expectations. • Responding to the growing demands of consumers and regulators in terms of environmental responsibility. • Industry 4.0 as an opportunity to improve corporate environmental performance. • Reducing the ecological footprint while increasing competitiveness in a market focused on sustainability.

4. EXPLORATORY STUDY OF THE ROLE OF INDUSTRY 4.0 IN ECOLOGICAL TRANSITION: CASE STUDY OF SEVEN MOROCCAN COMPANIES AND THEIR ENVIRONMENTAL PERFORMANCE

4.1 Morocco Facing Ecological and Industrial Transitions: The Impact of Industry 4.0 in This Evolution

In Morocco, several recent initiatives demonstrate the progressive integration of Industry 4.0 technologies aimed at improving companies' environmental performance. A striking example is the collaborative project initiated by the Ministry of Industry, the Digital Development Agency (ADD), and the Fez Smart Factory (FSF) consortium. This project aims to encourage the adoption of advanced technologies in industrial sectors, by creating an environment that fosters resource optimization and reducing carbon emissions, notably through the development of smart factories and the training of local actors (Ministry of Industry and Commerce, 2021).

Another major initiative is the introduction of the “TATWIR” platform as part of Morocco's industrial recovery plan. It actively supports the decarbonization of industrial processes and the improvement of energy efficiency, with a focus on the integration of Industry 4.0 technologies (The Ministry of Industry and Commerce, 2024). Tools such as the Internet of Things (IoT), artificial intelligence (AI), and blockchain are now being used to refine industrial processes, optimize resource management, and reduce greenhouse gas emissions.

Moroccan companies are beginning to adopt these technologies not only to address environmental challenges but also to enhance their competitiveness on a global scale. These initiatives are part of a broader national strategy to promote energy transition, with increasing investment in renewable energies, particularly solar and wind power, and intelligent energy management.

In short, although these projects are still in the development phase, they show a growing awareness of the crucial role of digitalization in achieving ecological objectives, while strengthening the competitiveness of Moroccan companies on the global stage.

To assess the impact of Industry 4.0 technologies on Moroccan companies and their role in improving environmental performance, we propose an in-depth study of seven Moroccan companies. This analysis aims to determine how the adoption of these technologies influences sustainable practices and environmental outcomes. Through this research, we aim to identify the benefits, challenges, and strategic implications of integrating these innovations into Morocco's industrial context.

4.2 Methodology

In order to study the motivations of Moroccan companies to adopt Industry 4.0 technologies in their processes of ecological transition and environmental performance improvement, an exploratory study was carried out among seven companies operating in various sectors. These companies were selected through a national network of key actors, including researchers, sustainability experts, and private sector representatives. This network aimed to develop practical tools to facilitate the integration of digital strategies aligned with sustainability principles.

The study was conducted over several months and included 14 interviews, each lasting an average of one hour. These sessions enabled direct exchanges with decision-makers from the companies concerned, providing valuable qualitative data. The companies, their characteristics, and their ISO 14001 certification status are presented in Table 5. All selected companies were already using Industry 4.0 technologies in their management and production processes. This approach aimed to gather information based on concrete practices rather than abstract theories.

To ensure confidentiality, company identities were anonymized. The sample included companies of varying sizes and sectors, offering a representative overview of current initiatives in Morocco. The study's results highlight the opportunities as well as the specific challenges associated with integrating Industry 4.0 technologies into companies' green transition.

Table 5. List of companies interviewed (Authors)

Company	**Sector**	**Interview number**	**ISO 14001 certification**
CIM	cement industry	1 and 2	YES
SOT	pharmaceutical sector	3 and 4	YES
OGP	phosphate sector	5 and 6	YES
EMO	water bottling	7 and 8	YES
DLM	industrial equipment manufacturing	9 and 10	YES
MAT	telecommunications	11 and 12	YES
COM	sugar extraction, refining, and packaging	14 and 14	YES

In order to analyse the motivations of Moroccan companies to adopt Industry 4.0 technologies in their ecological transition, a mixed methodology was deployed, combining various data collection techniques: semi-directive interviews, on-site observations, the study of internal documents, and online research on company websites. The interviews involved two categories of stakeholders: (1) environmental managers and (2) operational managers (such as industrial site managers and production managers). A total of 14 interviews were carried out among the selected companies.

To guarantee the rigor of the results, data triangulation was applied. This involved comparing primary data (from interviews and observations) with secondary data (internal documents, online information), enabling us to check the consistency of information gathered using multiple methods. This approach strengthened the reliability of the conclusions while minimizing bias, in accordance with the methodological principles established by Miles and Huberman (Miles & Huberman, 2003).

Data analysis was carried out using a thematic approach, following the steps proposed by Bardin (Bardin, 1977, 2013). The coding process was carried in two phases: deductive coding, based on theoretical concepts derived from the literature, and inductive coding, enabling the emergence of new themes directly from the data (Strauss & Corbin, 1990). To facilitate the processing of qualitative data, NVivo software was used, in addition to manual coding to ensure the validity and accuracy of the results.

The data collected was organized in the form of analytical matrices, allowing us to visualize the main motivations behind the adoption of digital technologies, as well as their specific applications within companies. This structure enabled both vertical analysis, which examined each case individually, and horizontal analysis, which compared common trends across companies. A systematic count of recurring themes was carried out to identify shared priorities and obstacles.

This methodological approach provided detailed insights into the motivating factors, observed practices and barriers encountered when integrating Industry 4.0 technologies, offering a comprehensive view of their role in the ecological transition of Moroccan companies.

4.3 Towards Dual Use of Green Technologies in Morocco: Environmental Legitimacy and Performance Management

In this study, we explored the application of the Integrated Environmental Performance and Green Technologies approach, based on the synergy between Green IT and Green Manufacturing, in seven Moroccan companies operating in various sectors. The results obtained highlight that the adoption of green technologies and associated measurement tools meets two main objectives:

-Strengthening environmental legitimacy: Audits, environmental indicators and the integration of Green IT and Green Manufacturing practices are used to improve the legitimacy of companies in the eyes of their stakeholders. In a context where Moroccan companies are seeking to comply with international standards and meet growing expectations in terms of sustainability, this legitimization is crucial. In particular, it enables companies to position themselves favourably in international markets and attract foreign partnerships.

-Improving environmental performance: the application of Industry 4.0 technologies, such as the Internet of Things (IoT), artificial intelligence (AI) and additive manufacturing, has enabled the optimization of resource management (energy, water, materials) and reduction of environmental impacts. These technologies are being used to improve companies' operational efficiency while meeting their environmental objectives. For example, the use of IoT sensors for real-time monitoring and data analysis by AI algorithms have led to a substantial reduction in industrial waste and energy consumption in several of the cases studied.

Adapting Green IT Practices

- **Optimizing Data Centers and Digital Infrastructures**

The optimization of data centers and digital infrastructures represents a key strategic lever for the seven Moroccan companies to reduce both their ecological footprint and their operating costs. For example, companies such as MAT and CIM have integrated virtualization solutions and adopted modular architectures to limit their energy consumption. Others, such as SOT and the OGP group, have migrated to cloud computing solutions, enabling them to reduce their dependence on physical resources and promote more flexible management of their infrastructures. As for COM, the company has opted for energy-efficient servers to optimize the management of its IT systems. These actions not only improve environmental sustainability, but also strengthen the competitiveness of Moroccan companies in a global economic environment that is increasingly demanding in terms of sustainability and innovation.

- **Electronic Waste Management**

The environmental managers at SOT and OGP Group confirmed that “an effective strategy for managing end-of-life IT equipment could involve partnerships with local players specializing in recycling or reconditioning. This process would not only reduce electronic waste, but also enable the reuse of certain components, thus contributing to the circular economy” (interview 3, 5). This is confirmed by a study of the International Labour Organization (ILO), which highlights the importance of responsible e-waste management. According to this study, a sustainable, structured approach could significantly reduce the environmental impact of the annual production of over 50 million tonnes of electrical and electronic waste. By adopting such practices, it would be possible to mitigate associated emissions and promote better management of these materials (International Labour Organization (ILO), 2019).

In addition, incentives such as tax credits or reductions could encourage companies to invest in recycling. Moroccan legislation, notably law no. 28-00 on waste management, imposes strict standards for the treatment of electronic waste and offers subsidies to companies adopting environmentally-friendly technologies (Houdaïfa, 2021). Benefits, such as tax credits or reductions on the cost of importing recycled materials, can be offered to companies engaging in recycling practices.

This regulatory framework would enable both SOT and OGP to significantly reduce their ecological footprint while optimizing their costs. As confirmed by the two companies' environmental managers: “The aim is to reduce the need to acquire new equipment on a regular basis and to reduce the space required to store obsolete equipment, while reinforcing our image as a responsible company. It could also help to build greater loyalty among our customers and partners.” (interview 3, 5)

- **Improving the Industry's Environmental Footprint**

CIM and OGP have adopted ambitious strategies to reduce their environmental footprint and improve energy efficiency. CIM has set itself a target to reduce its CO_2 emissions by 30% by 2025, compared to 1990 levels. In addition, the company aims to reduce its CO_2 emissions to less than 500 kg per tonne of cement by 2030. It also plans to reduce its electricity consumption by 65% by 2030, while increasing the use of alternative fuels by 43% (interview no. 2, official company website).

For its part, OGP uses advanced technologies to minimize its environmental impact. The company focuses on optimizing its energy-intensive production lines and integrating solutions to improve the efficiency of its irrigation systems, thereby contributing to water and energy conservation. “We have deployed various technologies to support the decarbonization of our industrial processes, as part of a global approach to ecological transition” (interview no. 6).

- **Integration of Green Manufacturing**

The integration of Green Manufacturing is a major strategic lever for the seven Moroccan companies studied to improve their environmental performance and support their transition to sustainable production. The following examples of the application of energy efficiency, waste reduction, and process optimization practices in these companies are treated in Table 6.

Table 6. Application of Data Center Optimization and its Impact on Energy Reduction (Authors)

Company	contexts	applications	impacts
CIM	The cement sector is very energy-intensive, particularly for its production monitoring, management and control systems.	▪ Server virtualization: Reducing the number of physical servers for internal operations (production site management and logistics). ▪ Environmentally-friendly cooling: Use of evaporative or closed-circuit cooling systems to optimize data centers.	Potential 25% reduction in IT-related energy consumption, while optimizing costs
SOT	As a leader in the pharmaceutical industry, SOT requires reliable data centers to manage its research, manufacturing and distribution processes.	▪ Migration to the cloud: Outsourcing certain IT functions to energy-optimized cloud environments. ▪ Energy-efficient monitoring: Implementation of software to monitor and reduce IT system consumption.	Save 30% in energy costs while increasing system resilience.
OGP	OGP, a major actor in the phosphate industry, uses extensive digital infrastructures for mine management and international logistics.	▪ Private cloud computing: Pooling resources across subsidiaries to reduce duplication and waste. ▪ Heat recycling: Recovery of heat from data centers to heat nearby industrial facilities.	Optimize data center energy requirements by 35%, and make the most of secondary resources
EMO	Quality control and product traceability require sophisticated digital infrastructures.	▪ Adoption of modular data centers: Able to adapt to fluctuating needs while minimizing energy consumption. ▪ Centralized management: consolidate IT systems from different plants on a common platform to reduce duplication.	20% reduction in IT-related carbon footprint.
DLM	As a specialized industrial supplier, its processes require reliable IT for project and supplier management.	▪ IoT systems integration: Reduce energy consumption by monitoring IT equipment consumption in real time. ▪ Renewable energies for IT: powering local data centers with solar panels.	15% reduction in IT-related operating costs.
MAT	A key player in telecommunications, its data centers are at the heart of its operations.	▪ Massive virtualization: Reduce hardware requirements by optimizing data management software. ▪ Passive cooling: Implementation of systems using natural cooling sources (free cooling).	30% reduction in energy consumption by main centers.
COM	COM manages a complex production chain and uses digital systems to optimize its logistics processes.	▪ Energy optimization of servers: To improve production chain and inventory management, the company deploys energy-efficient servers. ▪ Collaborative cloud computing: Adoption of cloud solutions, SaaS (Software as a Service) platforms, to reduce dependence on physical infrastructures.	IT costs reduced by 20-30% thanks to rationalization of resources and the use of new technologies. .

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Table 7. Application of Energy Efficiency Practices and their Impact on Environmental Footprint and Waste Reduction (Authors)

Company	**environmental footprint reductions**	**Tools used for energy optimization**	**waste reduction through additive manufacturing**
CIM	Reduce CO2 emissions by up to 20%.	• Iot sensors • Alternative fuels	15% on average
SOT	20% energy savings	• Iot sensors • Alternative fuels	Chemical waste reduced by 25%.
OGP	reduce energy consumption by up to 30%.	• More efficient irrigation systems energy optimization technologies	No information
EMO	reduce energy consumption at production sites by 20%.	• Iot sensors	More sustainable building materials thanks to additive manufacturing
DLM	reduce the energy consumption of its production lines by 10 to 15%,	• Iot sensors	Optimizing organic waste management
MAT	save up to 30% energy on IT infrastructures	• Virtualization solutions • Cloud computing	Passive cooling solutions could reduce data center energy consumption by 25%.
COM	20% energy savings	• Organic waste recycling technologies • Iot sensors	No information

• The Use of Advanced Technologies (Industry 4.0)

This section examines how seven Moroccan companies are using Industry 4.0 technologies to reconcile industrial efficiency and environmental responsibility. The analysis of their initiatives, observed impacts, and prospects is treated in detail in Table 8. Particular attention is paid to advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, and the integration of renewable energies, which are transforming industrial processes. For these companies, the integration of these solutions represents a strategic opportunity to maximize their economic performance while minimizing their ecological footprint, illustrating the convergence between industrial modernization and sustainability objectives.

Table 8. The Impact of Technology Used by Companies on Environmental Performance(Authors)

CIM	**Technologies used**	• IoT: Real-time optimization of energy use in cement kilns. • AI: Maintenance forecasting to reduce breakdowns and extend equipment life. • Renewable energies: Increasing use of solar and wind power in production processes.
	Environmental impact	• Reducing CO_2 emissions through energy efficiency systems. • Optimized waste management to promote a circular economy.
SOT	**Technologies used**	• Automation and robotization: Precise control of pharmaceutical processes to minimize raw material losses. • Blockchain: Complete traceability of pharmaceutical products to ensure regulatory and ecological compliance.
	Environmental impact	• Reduced chemical waste. • Reduced energy consumption thanks to modern, connected equipment.

OGP	**Technologies used**	• IoT: Intelligent systems to monitor and optimize water use in phosphate treatment processes. • AI: Data analysis to optimize the supply chain and reduce transport-related emissions. • Renewable energies: Deployment of large-scale solar installations at mining sites.
	Environmental impact	• Conservation of Water Resources through recycling and desalination. • Contribution to carbon neutrality through the integration of green energies.
EMO	**Technologies used**	• IoT: Smart sensors to monitor water quality and optimize bottling processes. • Renewable energies: Transition to solar-based energy solutions.
	Environmental impact	• Reducing plastic waste through sustainable packaging initiatives. • Reducing energy consumption in plants.
DLM	**Technologies used**	• Additive manufacturing and 3D printing: Reducing wastage of metallic materials. • IoT and AI: Optimizing industrial processes to improve energy efficiency.
	Environmental impact	• Reducing the carbon footprint of manufacturing. • Reduction of industrial waste through specific technologies.
MAT	**Technologies used**	• Green IT: Optimizing data centers with artificial intelligence systems to reduce power consumption. • Blockchain: Improving traceability in digital services, particularly for renewable energy projects in telecommunications infrastructures.
	Environmental impact	• Lower overall energy consumption. • Contribution to the recycling of electronic equipment.
COM	**Technologies used**	• IoT: Intelligent monitoring of agricultural resources used for sugar production. • Blockchain: Traceability of agri-food products to guarantee sustainability and compliance. • Renewable energies: Integration of solar energy into refining processes.
	Environmental impact	• Reduced water and energy consumption in production. • Reduction of CO_2 emissions through the use of green energy.

In Morocco, the implementation of Industry 4.0 technologies is transforming several sectors, using tools such as the Internet of Things (IoT) and artificial intelligence (AI) to optimize the management of essential resources. In sectors such as agriculture and agri-food, the COM company is using these technologies to improve precision irrigation and predict yields (interview no. 14). In heavy industry, CIM and OGP apply these tools to perfect their production processes (interviews 2 and 4).

Block chains have been adopted by SOT and COS, with the two companies' operational managers asserting that: "Transparent supply chains guarantee the ecological conformity of products, which is a crucial aspect for exports" (interview no. 4 and 6).

In addition, the renewable energies integrated by EMO, notably through solar and wind power projects, help to reduce the carbon footprint of their industrial facilities. Finally, the combination of Green IT and Green Manufacturing technologies, implemented by MAT and DLM, enables digital optimization and sustainable production to be combined, maximizing resource efficiency while reducing environmental impact (official company websites).

• Transition to a Circular Economy

The Moroccan companies studied are implementing various strategies to integrate the circular economy, thereby valorising waste and optimizing the resources use.

CIM Maroc, for example, converts waste into solid recovered fuel (SRF), achieving a 30% waste recovery rate by 2023, with a target of 50% by 2030 (official company website). SOT, meanwhile, not only recycles surplus raw materials, but also recycles 60% of its glass packaging, enabling it to reduce its waste by 18% (official company website). OGP Group recycles waste into by-products, reclaiming 2.4 million tonnes of Phosphogypsum by 2022 (official company website).

As for EMO, it recycles part of its plastic packaging an d plans to reach 30% recycled plastic by 2025 (interview no. 8). DLM, meanwhile, reuses scrap metal and has succeeded in reducing its industrial waste by 25% by 2023 (interview no. 10). MAT also participates in the circular economy by collecting and recycling electronic equipment, recovering 40% of its rare metals (interview no. 12). Finally, COS recovers bagasse from sugar cane to produce biogas and distributes compost, reducing its fossil fuel consumption by 40% (official company website).

• Capacity-building and awareness-raising

The seven Moroccan companies studied are actively investing in training and awareness-raising initiatives to support the transition to a sustainable economy. CIM has set up green technology training programs in partnership with local institutions, aimed at improving energy management and reducing CO_2 emissions in its plants (interview No. 1).

SOT, for its part, offers its employees training in sustainable resource management and recycling, and benefits from tax incentives for its green innovation projects (interview No. 3). OGP trains its employees and local farmers in the use of sustainable technologies, collaborating with universities to develop skills in waste management and renewable energies (interview no. 5).

EMO invests in internal training for efficient water management and reducing environmental impact reduction of its production, while raising awareness in local communities (interview 7). DLM, in the construction sector, trains its teams in the use of recycled materials and ecological technologies, while benefiting from subsidies for its sustainably projects (interview no. 9). MAT supports educational programs on green technologies and energy management in its data centers, while carrying out awareness campaigns to encourage local businesses to adopt eco-friendly solutions (interview no. 11).

Finally, COM trains its employees and partner farmers in sustainable agricultural practices and agricultural waste recycling, while enjoying tax benefits for its green investments. These initiatives illustrate a strong commitment by Moroccan companies to developing the skills needed to adopt sustainable technologies, supported by government programs and awareness-raising initiatives to promote the transition to a circular economy (interview no. 13).

- **Measuring Environmental Performance**

As part of the transition to a circular economy and the integration of cutting-edge technologies, MAT and COM have demonstrated a strong commitment to environmental performance: “We have set up dashboards and environmental indicators to assess and improve our performance on an ongoing basis. These tools make our actions measurable and adjustable, thanks to precise monitoring systems and performance indicators specifically adapted to our environmental objectives. This approach guarantees proactive management aligned with best practice in sustainability” (Interview 11 and 13). However, the environmental managers of both CIM and OGP assert that “Our main objective is to significantly reduce our carbon footprint and improve our energy efficiency. To achieve this, we use sector-specific indicators, which enable us to rigorously monitor our progress towards set targets, particularly in terms of reducing greenhouse gas emissions and waste recovery. This approach is part of a global strategy aimed at integrating sustainability principles into all our operations.”

Benchmarking is also an essential tool in this dynamic, enabling Moroccan companies to compare themselves with international best practices. This stimulates continuous improvement, as can be seen at MAT and DLM, who have adopted global standards to optimize their resource management and mitigate their environmental impact. These approaches illustrate that a quantitative assessment of environmental performance is crucial to adjusting the strategies put in place and maximizing the benefits associated with the circular economy (official company website).

In this way, these companies are not only deploying environmentally friendly technologies and practices; they are also implementing monitoring mechanisms that ensure their actions are measurable and aligned with global standards, thereby strengthening their competitiveness and commitment to environmental sustainability. This approach demonstrates that quantified environmental performance, benchmarked against international standards, is a strategic lever for continuous improvement in the ecological impact of Moroccan companies.

- **Constraints on Corporate Environmental Performance in the Context of Ecological Transition and Industry 4.0**

The companies studied encounter a series of constraints in their ecological and digital transition, constraints that are mainly influenced by sector specificities and gaps in regulatory frameworks. CIM, operating in an energy-intensive sector, points out that “we are struggling to reduce our dependence on fossil fuels and modernize our infrastructure, due to the high cost of the necessary investments and the lack of incentives to encourage the use of renewable energies” (interview N°1 and 2). For its part, SAT faces the additional challenges of complying with strict quality and safety standards, while also having to manage pharmaceutical waste in a context where regulations favouring sustainable practices are still insufficient. According to company managers: “regulatory frameworks for promoting sustainable practices remain underdeveloped” (interview 3).

For OGP, regulatory issues are particularly focused on the management of water resources and tailings. The company notes that “we are facing major regulatory challenges concerning the management of water resources and tailings, which requires substantial investment to integrate digital and ecological technologies on a large scale” (interview 6). In the agri-food sector, EMO encounters difficulties linked to the management of plastic waste, pointing out that recycling infrastructures are underdeveloped and regulations on their application remain limited (interview no. 8). In the metallurgy sector,

DLM suffers from a lack of regulations favouring the energy transition, thus hindering the implementation of greener solutions in a traditionally energy-intensive and polluting sector. As for MAT, a leader in telecommunications, the company faces major challenges in managing its energy-hungry data centers, compounded by insufficient regulations on the sustainable management of electronic waste. “We are facing obstacles due to the high energy consumption of our data centers, exacerbated by insufficient regulations on the sustainable management of electronic waste, despite the growing environmental challenges” (interview 12).

Finally, COS has to cope with high water and energy consumption, in a context where regulatory incentives to promote sustainable production practices remain limited.

As its manager points out, "we have to reduce our high water and energy consumption, in a context where regulatory incentives to adopt sustainable production practices remain limited" (interview no. 14).

These obstacles -whether economic, technical or regulatory- are significantly slowing the transition to Industry 4.0 and the improvement of environmental performance, while exposing companies to competitive and social challenges in an increasingly demanding global environment

5. DISCUSSION AND CONCLUSION.

This research aimed to apply the Integrated Environmental Performance and Green Technologies Model, highlighting the interaction between digital technologies (Green IT) and sustainable manufacturing practices (Green Manufacturing), as part of the ecological transition of Moroccan companies. The study revealed how the integration of Industry 4.0 technologies enables companies not only to measure and improve their environmental performance, but also to optimize their production processes while reducing their ecological footprint.

The companies analysed have shown that the adoption of strategies to measure environmental performance, particularly via digital tools, responds to internal sustainability imperatives as much as to external constraints. Tools such as indicators for energy consumption, CO_2 emissions reduction, and waste management enable these companies to rigorously track their efforts to reduce natural resources and implement circular economy models. This approach is particularly evident in industrial recycling and waste recovery practices, where green technologies such as Green IT facilitate real-time data collection and analysis, improving resource management and operational efficiency.

Application of the Integrated Model has demonstrated that the combination of green technologies and sustainable manufacturing goes far beyond mere regulatory compliance, contributing to business competitiveness and resilience in the face of environmental challenges. For example, practices such as the use of biogas in COS plants or the recycling of industrial waste at CIM bear witness to ongoing innovation in product lifecycle management, helping to reduce dependence on non-renewable resources.

In addition, these companies illustrate how green technologies, in synergy with Industry 4.0, enable more proactive and precise management of environmental impacts. For example, the use of benchmarking, as observed in OGP, enables them to compare themselves with global best practices and stimulate continuous improvement. This dynamic illustrates the synergy between digital transformation and ecological technologies, positioning the latter as a key lever for ecological transition.

Through the adoption of Industry 4.0 technologies, these companies are successfully integrating environmental sustainability into their production strategies. This integration goes beyond mere compliance with external requirements, and becomes a driver of innovation and competitiveness in an economic context increasingly focused on sustainability. The results of this study underline the importance of accurate assessment of environmental performance, as well as the impact of digital tools that not only promote internal efficiency, but also the transparency and legitimacy of companies vis-à-vis their stakeholders.

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