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ADOPTION OF INDUSTRY 4.0 TECHNOLOGIES TO PROMOTE SUSTAINABLE PRACTICES

ADOÇÃO DE TECNOLOGIAS DA INDÚSTRIA 4.0 PARA PROMOVER PRÁTICAS SUSTENTÁVEIS

ADOPCIÓN DE TECNOLOGÍAS DE LA INDUSTRIA 4.0 PARA PROMOVER PRÁCTICAS SOSTENIBLES

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ABSTRACT

Objective: To analyze the adoption of industry 4.0 technologies to promote sustainable practices, in the last five years, in a chemical industry that manufactures adhesives.

Methodology: Single case study, with a qualitative approach, collecting empirical data through four in-depth interviews, systematic participant observation and documentary survey, submitting the data to content analysis.

Results: It was identified that the company uses some I4.0 technologies to reduce environmental impact, such as big data and IoT. Due to the size of the company and limited resources, investments in new technologies and incorporation of sustainable practices are restricted.

Limitations: As this is a case study, the results obtained cannot be generalized.

Practical implications: The results provide managers of organizations that wish to adopt industry 4.0 technologies with elements for analysis and reflection, to develop their own plans and guide operational procedures.

Theoretical implications: The results provide the advancement of knowledge about the adoption of industry 4.0 technologies in small companies and similar economic sectors.

Originality/value: The study can be considered original, as a search was carried out in the SCOPUS database in March 2024, selecting articles in English between 2019 and 2023, obtaining only 15 articles, which highlights the scarcity of research on the topic.

Keywords: Chemical industry. Industry 4.0. Sustainability. Technologies.

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RESUMO

Objetivo: Analisar a adoção das tecnologias da indústria 4.0 para promover práticas sustentáveis, nos últimos cinco anos, em uma indústria química fabricante de adesivos.

Metodologia: Estudo de caso único, com abordagem qualitativa, coleta de dados empíricos por meio de quatro entrevistas em profundidade, usando roteiro com dez perguntas, observação sistemática participante e levantamento documental, submetendo os dados à análise de conteúdo.

Resultados: Identificou-se que a empresa utiliza algumas tecnologias da I4.0 visando a redução do impacto ambiental, como a big data e IoT. Devido ao porte da empresa e cenário de limitação de recursos, os investimentos em novas tecnologias e incorporação de práticas sustentáveis, são restritos.

Limitações: Por se tratar de um estudo de caso os resultados obtidos não são generalizáveis.

Implicações práticas: Os resultados fornecem aos gestores das organizações que desejam adotar tecnologias da indústria 4.0 elementos para análise e reflexão, para elaborar seus próprios planos e orientar procedimentos operacionais.

Implicações teóricas: Os resultados facultam o avanço do conhecimento sobre adoção das tecnologias da indústria 4.0 em empresas de pequeno porte e setor econômico similares.

Originalidade / valor: O estudo pode ser considerado original, pois foi realizada uma busca na base SCOPUS, em março de 2024, selecionando artigos em inglês entre 2019 e 2023, obtendo apenas 15 artigos, o que evidencia a escassez de pesquisas sobre o tema.

Palavras-Chave: Indústria 4.0. Indústria Química. Sustentabilidade. Tecnologias.

RESUMEN

Objetivo: Analizar la adopción de tecnologías de industria 4.0 para promover prácticas sustentables, en los últimos cinco años, en una industria química fabricante de adhesivos.

Metodología: Estudio de caso único, con enfoque cualitativo, recogiendo datos empíricos a través de cuatro entrevistas en profundidad, observación participante sistemática y encuesta documental, sometiendo los datos a análisis de contenido.

Resultados: Se identificó que la empresa utiliza algunas tecnologías I4.0 para reducir el impacto ambiental, como big data e IoT. Debido al tamaño de la empresa y recursos limitados, las inversiones en nuevas tecnologías y la incorporación de prácticas sustentables están restringidas.

Limitaciones: Al tratarse de un estudio de caso, los resultados obtenidos no se pueden generalizar.

Implicaciones prácticas: Los resultados proporcionan a los directivos de organizaciones que desean adoptar tecnologías de la industria 4.0 elementos de análisis y reflexión, para desarrollar sus propios planes y guiar procedimientos operativos.

Implicaciones teóricas: Los resultados proporcionan el avance del conocimiento sobre la adopción de tecnologías de la industria 4.0 en pequeñas empresas y sectores económicos similares.

Originalidad/valor: El estudio puede considerarse original, ya que se realizó una búsqueda en la base de datos SCOPUS en marzo de 2024, seleccionando artículos en inglés entre 2019 y 2023, obteniendo solo 15 artículos, lo que resalta la escasez de investigaciones sobre el tema.

Palabras clave: Industria 4.0. Industria química. Sostenibilidad. Tecnologías.

INTRODUCTION

The chemical sector has been considered very important for global economy, as it encompasses several other industrial sectors with their production and supply of various products and services. Falkenroth-Naidu et al. (2023), through McKinsey consulting, show that the global chemical industry has evolved considerably in recent years, with almost 25% growth in 2021, as a result of the high demand for chemical products in the automotive, construction, electronics and other sectors. Brazil ranks sixth in the ranking of the largest revenue generators in the global chemical industry, with the chemical sector being extremely important for the Brazilian economy, with a turnover of 187 billion dollars in 2022. For the industrial chemical products sector (which is the case of the company analyzed), more than 88 billion dollars were invoiced, showing a growth of almost 24.6% compared to 2021 (Abiquim, 2022).

According to Sebrae (2023), investment in innovation to foster and sustain the competitive capacity of the Brazilian chemical sector is essential for companies to remain active in the market. Galembeck (2017) adds that companies and managers must increasingly observe trends practiced abroad, in order to then propose changes in Brazilian business operations and gradually further improve the scenario of the sector in the country.

Industry 4.0 is revolutionizing the industrial sector by integrating advanced technologies to improve efficiency and sustainability. In the context of the chemical industry, the adoption of these technologies can offer innovative solutions to reduce environmental impacts. By adopting production processes that are less harmful to the environment, through Industry 4.0 technologies, companies can transform their operations by combining manufacturing and sustainability (Silva, Silva & Ometto, 2016). According to the authors, sustainability seeks to balance the environment, economy and society, while manufacturing involves the use of labor, tools and equipment in the production of goods or services for use or sale. Sustainable manufacturing, or "green manufacturing", focuses on environmental issues, evolving with new environmental management practices. This approach promotes cleaner production, better use of natural resources and less waste generation (Silva, Silva & Ometto, 2016).

Industry 4.0 technologies contribute to the sustainability of companies, whether in the development of sustainable products which are harmless the environment or in operational processes with greener and more responsible practices, in addition to the perception that the implementation of new technologies in operations facilitates the development of different ways of achieving results, through the restructuring of their processes (Hayes, 2006; Schreiber, 2022). Within this context, the term Industry 4.0 encompasses the set of emerging and innovative digital connectivity technologies, the purpose of which is to modify the operations of traditional companies, not referring to an industry itself (Schreiber, 2022). According to the author, successfully implementing Industry 4.0 integration in the company's operations is possible, as long as there is prior preparation and a careful study of the changes that may or may not happen.

This study was conducted, thus, in a chemical industry, which, for safety reasons, is identified in this study with the code name Company W. The company is located in the Vale do Rio dos Sinos region, in Rio Grande do Sul, and its main activity is the manufacturing of adhesives and solvents. This study aimed to analyze the adoption of Industry 4.0 technologies to promote sustainable practices in a chemical adhesives industry. This focus is crucial due to the potential of these technologies to mitigate environmental impacts and improve competitiveness. First, we analyzed which Industry 4.0 technologies were adopted to extenuate environmental impacts of the operation, within a period of five years, and then we related them to the vision of industry experts, added to theory, aiming to present actions that can contribute to the implementation of new technologies and more sustainable practices.

Although literature has extensively explored Industry 4.0, there is a significant gap in the application of these technologies in small companies in the chemical sector, especially regarding to sustainability. Therefore, choosing this particular topic is justified for the academic and scientific community, as well as for the chemical sector in general, as it contributes to the advan-

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ce of knowledge about the operation of a small company in the segment, highlighting the innovations made in the last five years and the Industry 4.0 technologies implemented in the period, which resulted in greener practices and the mitigation of environmental impact. Furthermore, the study can be considered original, as a search was carried out in the SCOPUS database in March 2024. Using combined keywords, such as Technologies AND industry 4.0 AND sustainability, Industry 4.0 chemical AND Industry AND sustainability and Industry 4.0 chemical AND Industry AND green manufacturing, applying the business and environmental science filters to them, selecting only articles in English and published between 2019 and 2023, resulting in 15 articles, highlighting the scarcity of research on the topic.

The results indicate the use of technologies such as big data and IoT, although resource constraints limit wider adoption. Regarding the body of this study, it is structured into sections that discuss the theoretical framework used, the methodology, the results and practical and theoretical implications, the conclusions and, finally, the bibliographical references.

THEORETICAL FRAMEWORK

One topic that has been calling attention in Industry 4.0 is sustainable manufacturing (Javaid et al., 2022), which seeks to integrate the fundamental values of sustainable development into the industrial sector, contributing to increased environmental, social and economic efficiency. Sustainable digital, transformation and the development of intelligent solutions, offered by Industry 4.0, offer companies the possibility of creating innovative business models that are less harmful to the environment (Javaid et al., 2022; Ivanov, 2018; Villar et al., 2020).

Therefore, Industry 4.0 innovations must be implemented with a view to establishing a sustainable environmental foundation. With the growing number of organizations directing their efforts to reconcile sustainability objectives imposed by the market or by legislation, I4.0 is transforming the established traditional scenario and challenging existing practices, offering the expertise and guidelines necessary to improve sustainability efficiency, especially in the context of industrial production (Ghobakhloo, 2020; Javaid et al., 2022; Oláh et al., 2020).

According to Javaid et al. (2022), the fundamental stages in the process flow sectors of Industry 4.0, towards sustainability, begin with I4.0 tools, go through integration processes and end with sustainable results. This process begins with the adoption of intelligent and digital dimensions, promoting an efficient and sustainable culture. Intelligent innovations in methods and procedures are crucial components for the production of goods that promote environmental preservation; therefore, in the integration stage, the interaction between humans and machines is addressed, as well as the adequate management of time and virtualization, characterized by smart factories. Finally, sustainable results are reflected in the economy, safety, health of workers and environmental preservation (Ingaldi & Ulewicz, 2019; Javaid et al., 2022; Machado, Winroth & Silva, 2020).

In order to establish sustainable environments, one of the focuses of I4.0 is to change the current architecture of companies' processes. According to Javaid et al. (2022), the main developments of I4.0 to create a sustainable environment are as follows:

a) Smart production using Industry 4.0 technologies, characterized by the convergence of technology, working in an integrated manner and in real time, with the understanding that human work and technological procedures are perfectly combined, making it necessary to integrate them;

b) Industry 4.0 for the water industry, offering possibilities for improved asset control, such as real-time tracking, smart water metering and alarm-triggered preventive maintenance. It can facilitate climate response times, improve community responses and contact networks, as well as ensure continuous water availability;

c) Industry 4.0 to reduce energy consumption, using IoT technology, for example, to build smart cities that aim to improve quality of life and reduce energy consumption. With the vision of smart cities, infrastructure and resource delivery capacity would be improved;

d) Information transparency through Industry 4.0, with the interconnection and transparency of information enabling decision-making inside and outside production facilities, improving efficiency. With big data, for example, it is possible to implement smart factories, where data from production machine sensors is analyzed to anticipate the need for maintenance and repair operations. Optimization of the supply chain, improving prices, predicting failures and creating products, are also examples.

e) Industry 4.0 to improve air quality, where a stable power supply network can be linked to virtual power from renewable energy infrastructure plants, such as solar panels. These facilities use smart grid-based technologies, and automated solutions can significantly reduce city gas emissions and air quality indices. With smart traffic management and less congestion on the roads, energy consumption, waste and carbon emissions in cities are reduced;

f) Interconnection of the supply chain using Industry 4.0, because without the appropriate sensors, decisions can be made incorrectly through inaccurate results.

Thus, the integration of sustainability with Industry 4.0 presents a promising perspective for companies to move towards more responsible and efficient practices. Significant applications of Industry 4.0 for the development of a sustainable environment include: (i) improved environmental innovation capacity, using I4.0 technologies to transfer knowledge between people and machines and improved automated processes, increasing efficiency and reducing waste production, including technologies such as IoT, digital twins and cyber-physical systems; (ii) minimizing waste, using lean thinking to buy less, from packaging to raw materials and energy, since the response to climate change can also be considered an opportunity to increase profitability and develop a green image and sustainable development. Big data is one of the technologies that could be used; and (iii) waste recycling, based on practices such as the expansion and reuse of raw materials through recycling, internal use of waste and interdependence of markets for by-products. Robotic analysis can be used as a technology. (Chen et al., 2021; Di Carlo et al., 2021; Sołtysik-Piorunkiewicz & Zdonek, 2021; Upadhyay et al., 2021).

Javaid et al. (2022) also highlight that one of the main challenges faced by companies when adopting both Industry 4.0 and Sustainability 4.0 is related to the need for substantial investments in technologies and infrastructure. The implementation of advanced monitoring, data collection, and analysis systems requires a considerable investment in financial and human resources. The growing implementation of industrial automation and reverse logistics, driven by cost reduction benefits, for example, already serves to highlight the potential of I4.0 technologies to make organizations more sustainable (Fatorachian & Kazemi, 2018; Schreiber, 2022). Oliveira, França, and Rangel (2018) add that reducing environmental impact by combining the smart factory model with the integration of physical and virtual systems, integrating them with product life cycle analysis and ecodesign practices, can bring many benefits to companies. Moeuf et al. (2017) corroborate such statements with the concept that the adoption of Industry 4.0 facilitates the implementation of environmentally sustainable practices, resulting in products and operations that do not harm the environment.

Ghobakhloo (2020) points out that sustainability and the impacts of Industry 4.0 are intrinsically related in the business scenario, with I4.0 technologies, which are characterized by the digitalization and automation of processes, not being perceived only as a technological revolution, but also as an opportunity to promote more sustainable practices. The search for innovative and sustainable solutions in the implementation of Industry 4.0 in companies is essential to ensure economic and technological development without compromising natural resources and the well-being of future generations (Beier et al., 2020; Ghobakhloo, 2020; Kamble, Gunasekaran & Dhone, 2019).

In this way, Ghobakhloo (2020) highlights the impacts that Industry 4.0 technologies can have on the business environment, in terms of sustainability:

a) Energy and resource sustainability: Industry 4.0 supports environmental sustainability through sustainable energy and resource

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transformation, changing the way society produces, trades, consumes and lives. The sustainability implications are not limited to energy sustainability alone, but may include more efficient production systems, the emergence of advanced digital manufacturing technologies (CPPS, additive manufacturing and smart robotics) and intelligent resource planning and allocation systems;

b) The development of environmental responsibility: The development of reactive and proactive “environmentally friendly” practices are implications that Industry 4.0 and digitalization offer. Additive manufacturing technologies, for example, can facilitate the development of new environmentally friendly products, in addition to benefiting environmental management practices, such as life cycle assessment and data integration and management (IoT) capabilities. In addition, the productivity impacts of I4.0 generated by collaborative production management, knowledge management capabilities in the supply chain and production flexibility, can offer several opportunities for environmental sustainability in terms of waste reduction and material efficiency;

c) Job creation: Industry 4.0 projects a reduction in low-to medium-skilled jobs, but compensates for this loss related to automation by creating new opportunities in the areas of information technology, mechatronics, process engineering and systems integration. The implications of I4.0 for social sustainability are not limited to the creation of job opportunities, but contribute to a greener and more sustainable economy, leading to the creation of opportunities related to sustainable production;

d) Improving social welfare: Technologies and digitalization can offer opportunities for the depolarization of income and wealth, as opportunities and rising minimum wages due to skill-intensive use in new jobs in the context of I4.0 can positively address the issue of economic inequality. New marketing and distribution models, as well as the material, resource and production efficiencies offered by smart digitalized production, are expected to improve the global accessibility and affordability of goods and services.

The transition to Industry 4.0 and subsequent industrial digitalization have the potential to open doors to sustainability, such as resource optimization and global economic growth. However, for I4.0 to fully play its role in promoting sustainability, digital transformation needs to reach a more advanced level of maturity, which can be achieved through the development of human resources capable of dealing with the demands of digitalization (Jabbour et al., 2018; Ghobakhloo, 2020; Wang & Shen, 2016; Xu, Xu & Li, 2018).

The challenges of sustainable development can be considered a starting point for most innovations in industries, which are intensifying efforts to incorporate Industry 4.0 technologies into their operations to overcome global environmental challenges such as climate change, water shortages, environmental pollution, and resource depletion. In this context, it is clear that the global chemical industry is entering a new phase of development, the pace and direction of which will be defined as I4.0 technologies are implemented in companies. With the increasing pressure of environmental demands from the global community, the chemical sector needs to find ways to make its business greener and more sustainable, and through the digitalization of business processes and the implementation of I4.0 technologies, for example, the creation of new values and new opportunities for the industry is accelerated (Gawel & Herweijer, 2020; Shevtsova, Shvets & Kasatkina, 2020).

METHODOLOGICAL PROCEDURES

This study uses a qualitative approach, with a descriptive method, with a single case study strategy, data collection techniques through in-depth interviews, systematic participant observation and documentary survey. Content analysis was used as the data analysis technique (Bardin, 2011; Gil, 2008; Malhotra, 2019; Prodanov & Freitas, 2013). A small-scale chemical industry of adhesives and solvents, identified in this study with the codename Company W, located in the Vale do Rio dos Sinos region, in Rio Grande do Sul, was studied. The company has been in the market for over 30 years in Brazil, serving various segments.

The interviews sought to understand how the operation currently works, the technologies used in the operational process and the incentives

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for the use of new technologies. The interviewee who works at the company was chosen based on the criteria of length of service and participation in strategic decisions, as well as having higher education. Therefore, it was defined that the interviewee would be the responsible chemist, who has been involved in strategic decisions for more than ten years and has extensive knowledge about the operation. The interviewee is identified throughout the study by the acronym P1.

In addition to the chemist (P1), three other people from outside the company were interviewed, i.e., without any employment relationship and who are not employees. These interviewees are identified by the acronyms P2, P3, P4. Interviewee P2 is the owner and chemist responsible for a chemical industry of similar size to the company studied, operating in the market for over 25 years manufacturing cleaning products, located in the same region as Company W. The objective of the interview was to obtain information about another chemical industry of very similar size and activity, aiming to relate it to the answers of interviewee P1, in order to verify similarity in the processes.

The other interviewees are two experts in the field, the first being a higher education professor of industrial chemistry at the Lutheran University of Brazil (ULBRA), in Canoas-RS, who has worked in the chemistry field for almost 40 years and is identified by the acronym P3. The third is a higher education professor of Chemical Engineering at Feevale University, in Novo Hamburgo-RS, who has worked in the chemical sector for over 20 years and is identified by the acronym P4. With interviewees P3 and P4, the objective was to gather the views of experts on the sector, to understand what a chemical industry operation would be like, the particularities, trends and challenges faced, as well as to verify what the alternatives would be for adopting I4.0 technologies in the operational processes of industries in the sector. Table 1 summarizes the information provided by the interviewees.

Table 1
Interviewees' Profiles

INTERVIEWEE	COMPANY W	EDUCATION AND WORK	EXPERIENCE
P1	Collaborator	Industrial Chemist and Technical Manager at W Company	10 years
P2	Not a collaborator	Industrial chemist and owner of a chemical industry of similar size to the company studied	Aprox. 25 years
P3	Not a collaborator	Specialist, industrial chemist, consultant in the field and higher education professor	Aprox. 40 years
P4	Not a collaborator	Specialist, chemical engineer, consultant in the field and higher education professor	Aprox. 20 years

Source: Research Data (2024).

To conduct the interviews, a script with ten questions was developed based on the concepts presented in the theoretical review, as well as on their adherence and greatest importance for achieving the objectives. The script was validated with two experts, with doctoral degrees and training in administration, in relation to the content, and with three employees of the analyzed company, who hold management and sales positions, in relation to the understanding of the wording of each of the questions. This validation is indicated by the scientific literature, by authors who deal with scientific methods (Gil, 2008; Malhotra, 2019). The interviews were recorded using the researcher's smartphone and later transcribed within 48 hours after execution.

On April 4, 2024, the first interview was conducted with P2, in person at the company where he works, lasting approximately 40 minutes. On April 5, 2024, the interview with P3 was conducted virtually, using the Google Meet digital meeting platform, for approximately 30 minutes. Finally, on April 8, 2024, the interviews with P1 were conducted in person at the company studied, for approximately 30 minutes, and with P4, virtually, also using the Google Meet platform, for approximately 35 minutes. The data collected in the interviews were analyzed according to the content analysis techniques, according to Bardin (2011).

For the document survey, a checklist of documents was prepared to support the verification of existing tools and documentation that could be used for data collection. The company provided documents that were in its internal records, such as the management system, production control reports, permanent archives, and other administrative documents. For the systematic participant observation, this stage was carried out by the author of this study, who is an employee of the company studied and has access to information, company facilities, contact with employees, internal archives, and also operational routines. A new checklist was created containing the items that were not validated in the document survey checklist, and that do not exist or were not found in the documents provided. The observation, according to Malhotra (2019), was structured, undisguised, natural, and, finally, personal.

For the data analysis of this study, the content analysis technique was used, according to Bardin (2011), with the researcher being guided by three stages: pre-analysis, on the elaboration of the question scripts for the interview and checklist for document collection and systematic observation and with the structuring of the main ideas; analysis stage, with the organization of the charts, tables and synthesis of the responses obtained and, the definition of the categories, which are: (i) mapping of the technologies used in the operation; (ii) assessment of the environmental impacts of the operation and; (iii) possibility of implementing new technologies in the operational process. Finally, the data processing stage, with the delimitation of the results, interpretations and suggestions for improvements.

OUTCOMES AND DISCUSSIONS

The first question asked which Industry 4.0 digital and connectivity technologies are currently used in business processes and in the chemical sector, in a more generalized way. This question identified a difficulty for the interviewees in understanding which technologies belonged to the I.40 group. It can be seen that in some cases the company already uses the technology, but without knowing that it was part of the group. In order for the interviewees P1 and P2 to better understand and evaluate the technology, it was necessary to briefly introduce some concepts about what Industry 4.0 technologies are, their applications and practical examples. Table 2 illustrates the answers.

Table 2

I4.0 Technologies Used

Interviewee	Technologies Used	I4.0 technologies identified
P1	Cloud data storage, alarm monitoring system and cameras with access via cell phone, remote switching of lights on and off, online website for content generation, water tank level sensor with alarm and lamp activation.	*Big Data*, IoT, AI e CPS
P2	ERP system, solar energy panels, alarm monitoring system and cameras with access via cell phone, machine sensors.	IoT
P3	Robots and mechanical arms, automation, central panels, SDCD, remote actuation of machines and valves, large data processing and storage.	*Big Data*, IoT, CPS, robótica e automação
P4	Large-scale data processing, internet of things, data storage, remote access, remote device activation, machine learning, integration, sensors	*Big Data*, IoT, learning machine, CPS, AI.

Source: Research Data (2024).

Conforme a figura 2, para o entrevistado P1, apAccording to Figure 2, for interviewee P1, after the previous examples provided, technologies such as cloud data storage (big data), remote monitoring and activation systems via application (IoT), level and warning sensors (IoT), and artificial intelligence (AI) are used. For interviewee P2, a lack of mastery of the concept of Industry 4.0 was noted, having cited, for example, the company's ERP system and solar energy panels. The use of sensors in machines and a remote access application via cell phone for the company's monitoring system (IoT) were also mentioned. For interviewees P3 and P4, considering an overview of the chemical sector and the technologies most used in the sector, it is clear that the two answers are very similar and support the understanding of the similarity of companies in the segment, citing technologies such as robotics, process automation by autonomous robots (IoT), mechanical arms, central control panels, remote actuation

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of machines, valves and other equipment (IoT), cloud storage, big data processing, machine and computer integration (CPS) and machine learning. Therefore, the main technologies identified in the answers are: (i) internet of things (IoT); (ii) big data; (iii) artificial intelligence (AI); (iv) cyber-physical systems (CPS); (v) machine learning and; (vi) robotization.

Technology can be represented in three categories: physical, such as machines and equipment; human, by skills and experiences; and organizational, by production systems and quality procedures. As mentioned by the interviewees, there is a concern in mentioning the physical category, trying to find technologies in machines and equipment, mainly. Adopting I4.0 techniques and tools that increase connectivity and automate processes can allow greater flexibility in chains, increase production capacity, and bring financial, sustainable, and safety impacts to processes (Fatorachian & Kazemi, 2018; Moeuf et al., 2017; Oliveira, França & Rangel, 2018; Schreiber, 2022).

Systems driven by artificial intelligence (AI) and cognitive computing (CPS) can transform industrial connectivity, information, and perceptions about processes and their interactions. In view of this, the production principles of increasing efficiency, reducing human errors, optimizing costs, and better use of resources can be redirected to another level, based on autonomous systems such as CPS, IoT, and big data (mentioned in the responses), and are fundamental for the efficient and large-scale production process. In addition, machine learning capabilities, as identified in the responses, through the application of machine cognition and interaction with the Internet of Things, end up emerging as alternatives to assist or even replace human decision-making (Fatorachian & Kazemi, 2018; Oliveira, França & Rangel, 2018; Schreiber, 2022).

The next question asked which stages of the operational process would benefit from the adoption of Industry 4.0 technologies, from the perspective of greater efficiency, productivity, cost reduction and sustainability. The answers can be seen in Figure 3.

Figure 3

Process Steps Benefited

Interviewee	Which stages of the operational process would benefit from the adoption of Industry 4.0 technologies, from the perspective of greater efficiency, productivity, cost reduction and sustainability?
P1	Use IoT to turn on, turn off and program reactors, organizing night shifts to optimize production and consumption of energy and water; Real-time production monitoring system, through panels and integration with the system, optimizing time and increasing productivity; Greater assertiveness in the stages of chemical processes and product development through greater data processing; Reduction in the generation of solid office waste, with greater storage space in the cloud; Production operations would gain more speed through the automation of some manual processes, such as bottling, for example;
P2	The interviewee understands that he would not benefit from the implementation of any of the technologies presented;
P3	The implementation of big data processing systems would facilitate decision-making and assertiveness in processes; The automation of processes through autonomous machinery and robotization could reduce human risk in more dangerous operations; The integration of intelligent machinery via the internet would allow greater speed in processes; The final logistics of the process would benefit through the implementation of more automated processes; Control of inventory, inputs, machine loading.
P4	Mainly manual processes that today use human operators, logistics stages, transportation and loading of raw materials, internal organization of production layout, space optimization and agility in activations and decision-making.

Source: Research Data (2024).

This question reveals the difference in understanding the technologies, the concept of Industry 4.0 and its application in companies between interviewees P1 and P2, whose focus is on the company in which they work. According to P1, I4.0 through IoT would allow the implementation of a remote and automated machinery activation system, reducing labor, electricity and water consumption costs. Real-time monitoring systems of the production process could also be implemented in order to optimize time and increase productivity. Big data can be enforced for greater data processing, with the aim of receiving accurate information and increasing assertiveness in the process as a whole. The automation of manual processes through autonomous equipment, such as product packaging, could also reduce time

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and increase process accuracy.

Interviewee P2 had a different answer, saying that no I4.0 technology would make a difference in the process, since the operation is working and producing satisfactory results. Interviewees P3 and P4, industry experts, said that in the chemical industry in general, I4.0 technologies are very useful and would certainly transform industry operations, citing examples such as big data and large volumes of data processing to improve information and decision-making, process automation via robotics and autonomous robots, aiming to maintain standards, reduce waste and prevent accidents with people, as well as optimizing internal and external space and logistics.

The opportunities offered by Industry 4.0 technologies, through machine learning, IoT and big data, are alternatives for producing more with fewer people, in addition to offering greater security and reducing business risks, as well as increasing productivity, reducing time and providing greater integration of production stages. Simplified decision-making, assertiveness facilitated by I4.0 technologies, interaction between computers and machines and the least possible amount of human interference are other aspects that can be implemented and improved through the use of technologies. (Ghobakhloo, 2020; Jabbour et al., 2018; Kamble, Gunasekaran & Dhone, 2019; Moeuf et al., 2017; Wang & Shen, 2016; Xu, Xu & Li, 2018).

There are also sustainability and environmental control issues, which can be improved and benefited by companies through the adoption of I4.0 technologies, with many companies including sustainability issues as a fundamental objective in their operational strategy. Sustainability 4.0, a term designated to the important role of technology in achieving sustainability goals, involves the use of technologies such as IoT and AI to improve environmental performance and drive innovation in companies. Therefore, when the interviewee mentions IoT as a solution for remotely operating machines and valves, the benefits are both energy savings, reduced gas emissions, savings in machinery cooling water, and also reduced risks to human health. Therefore, this is a technology being used for environmental and sustainable purposes (Chen et al., 2020; Di Carlo et al., 2021; Sołtysik-Piorunkiewicz & Zdonek, 2021; Upadhyay et al., 2021).

The following question asked about the technologies that have been adopted by companies in the last five years to reduce their environmental impact. The answers are shown on Table 4 below.

Table 4

Adopted Technologies

Interviewee	Technologies adopted that resulted in reduced environmental impact
P1	Cloud data storage, LED lights and sensors.
P2	LED lights and solar energy panels.
P3	One could look for more affordable alternatives, develop "entry-level" technologies and think of small solutions to problems compatible with the size of companies.
P4	Technologies related to energy issues and clean energy, green energy. Lithium batteries, solar panels and waste-to-energy transformation processes.

Source: Research Data (2024).

The technologies adopted by the companies of interviewees P1 and P2, aiming to reduce environmental impacts, financially accessible initiatives were provided, such as the replacement of LED lights, implementation of sensors to activate lights by presence, installation of solar energy panels and the implementation of cloud storage to reduce the use of boxes and paper. For interviewee P3, thinking about the chemical sector in general, more accessible alternatives could be sought and some low-cost technology developed, thinking of solutions for problems compatible with the sizes of the companies. In the view of P4, major technological developments are being directed at the energy and green energy issue, such as the implementation of lithium batteries, solar energy panels and the development of production processes to transform waste into energy.

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According to the responses of interviewees P3 and P4, highlighting the importance of improvements in the flow of processes and integration of the factory, the process towards sustainability begins with the implementation of I4.0 tools, with the adoption of intelligent dimensions, and the promotion of an efficient and sustainable corporate culture. Integration addresses issues such as the relationship between machines and humans and time management, reflecting the results in economy, safety, worker health and environmental preservation. (Ingaldi & Ulewicz, 2019; Ivanov, 2018; Javaid et al., 2022; Machado, Winroth & Silva, 2020; Oláh et al., 2020; Villar et al., 2020).

Water consumption control through measurements and preventive maintenance using sensors is an example of the implementation of I4.0, aiming at a sustainable environment. Reducing energy consumption, with IoT being used for machine programming, is also an example. The use of big data to improve the efficiency of information and data processing, allowing more assertive decision-making, anticipating needs and optimizing processes, is another example of environmental improvement provided by I4.0. Waste recycling and reuse of raw materials through recycling and remanufacturing, related to analysis by autonomous robots, for example, are mentioned by the interviewees and are also related to the concepts of I4.0 for sustainability. (Chen et al., 2021; Di Carlo et al., 2021; Ivanov, 2018; Javaid et al., 2022; Oláh et al., 2020; Sołtysik-Piorunkiewicz & Zdonek, 2021; Upadhyay et al., 2021; Villar et al., 2020).

Furthermore, as a result of systematic participant observation and documentary research based on analysis of internal records of organizations, it was possible to verify, as a practical example, that among the technologies adopted to promote sustainable practices, the installation of sensors connected to the internet stands out for the automated control of water, electricity, as well as stocks of inputs and waste generated. This preference is due both to the relevance of the environmental impact and to the reduction in the value of the investment required for its implementation. These preferences, in the use of technologies to promote sustainable practices, in organizations from different economic sectors, have already been noted and mentioned in other studies, such as those by Villar et al. (2020), Sołtysik-Piorunkiewicz & Zdonek (2021) e Javaid et al. (2022).

The final question was about actions that could be taken by companies and by the chemical sector in general to reduce environmental impact with the support of new technologies. Table 5 below illustrates the response of each of the interviewees.

Table 5

Future actions to reduce environmental impact

Interviewee	What actions, in your opinion, could be adopted by the company to reduce the environmental impact of its activities, with the support of new technologies?
P1	*Implementation of devices for remote machine activation; *Use of big data technology to analyze data faster and make faster decisions in the product formulation and development process; *Automation of final production processes, such as bottling, for example, through robotization or equipment automation; *Increase in cloud storage capacity to increase digital files and reduce paper and boxes;
P2	*Robotization and autonomous processes would be interesting, aiming to gain speed in processes and assertiveness; *Systems with greater data processing and faster information; *More advanced formulation systems and; *Integration of systems and machinery.
P3	*Invest in research and development of new products, less harmful to the environment and from renewable and biodegradable sources;
P4	*Mainly, raising awareness at senior management levels of companies about the environment, sustainability and greener practices.

Source: Research Data (2024).

The interviewees' responses show their concern with optimizing processes and managing resources, in addition to providing better conditions for the team. The chemical industry can improve, with the use of I4.0 technologies, operations through digitalization, bringing these benefits. Digitalization in the production process enables the adoption of three main strategies: the digitalization of existing processes, the implementation of a data-centric operating model, and the integration of a digital business model. These strategies can provide returns of between 5% and 20%, depending on the company, overcoming financial barriers as identified in the response of interviewee E2, who rejects the difficulty

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of implementation due to high costs. (Jabbour et al., 2018; Gawel & Herweijer, 2020; Ghobakhloo, 2020; Shevtsova, Shvets & Kasatkina, 2020).

Furthermore, the implementation of I4.0 technologies, with a sustainable bias, is based on three pillars: environmental, maintaining a balance in consumption and replenishing resources; economic, with long-term economic growth; and social, with the management of impacts on people. (Beier et al., 2020; Ghobakhloo, 2020; Kamble, Gunasekaran & Dhone, 2019; Moeuf et al., 2017).

The transition to I4.0 drives sustainability in industries. However, a higher level of maturity is required from the team and the corporate culture, which can be achieved through the development of human resources and training to deal with the demands that may arise with digitalization. The transition and implementation of connectivity concepts require not only technological changes, but also cultural and institutional ones, and management must establish action priorities, prepare for challenges and complexities, and think about partnerships and collaborations that assist in the transition. (Jabbour et al., 2018; Ghobakhloo, 2020; Wang & Shen, 2016; Xu, Xu & Li, 2018). Such statements are related to the response of interviewee P4, which indicates the need for a change in hierarchical level in the chemical sector, which must happen from top to bottom, that is, being driven and organized by the highest levels of command.

Finally, the need for research and development is highlighted, involving everything from the acquisition of new suppliers and more innovative and sustainable raw materials, to internal processes and management tools. The growing pressure for more sustainable practices has been transforming the way companies view their processes, increasingly seeking alternatives to make the business greener. Changing the company's culture, values and macro thinking must be essential for the transition to greener manufacturing to be possible and to occur naturally, without major operational impacts. (Jabbour et al., 2018; Gawel & Herweijer, 2020; Ghobakhloo, 2020; Shevtsova, Shvets & Kasatkina, 2020).

CONCLUSION

The objective of this study was to analyze the adoption of Industry 4.0 technologies to promote sustainable practices in the last five years in a chemical company that manufactures adhesives. The study is justified by its contribution to the themes of Industry 4.0 and organizational sustainability, especially in the chemical sector and in small-scale industries. Therefore, in addition to benefiting the company itself, based on the evidenced data and the analysis of possible technologies that could be used in the company's operations aiming to mitigate environmental impacts, the study is also justified for other companies of similar size in the region, and the methodology can serve as a model to be followed.

In order to achieve the goal, besides the single case study strategy option, a qualitative approach was used: data collection through in-depth interviews with the responsible chemist and three external experts who do not work in the company, documentary analysis of files and records received by the company and systematic participant observation, considering that one of the authors of this study is an employee. The data were subjected to content analysis.

According to the analyses, the Industry 4.0 technologies used in the current operation were identified, concluding that the company was already using certain technologies even without knowing that they belonged to the group, and the reasons for the implementations were aimed at both cost reduction and mitigation of the environmental impacts of the operation. Furthermore, despite the scenario of limited resources that was evidenced, and which corroborates the experts' view that the chemical sector suffers from the high cost of technologies, the company sought affordable alternatives that fit the current reality, demonstrating the interest of managers in monitoring and addressing issues related to the environment. Finally, suggestions for new technologies and improvements were highlighted by the interviewees, aiming at the possibility of future implementation both in the company and for the chemical sector in general.

Since the results originate from a single case study, limiting their generalizability, it is suggested that further research on the topic be conducted in companies with similar realities in the region, adopting both a qualitative and quantitative approach, with the aim of relating the content of the responses to theory and identifying possible similarities in industrial operations of companies of similar size and activity to the company studied. From this perspective, it is recommended that such research analyze not only the environmental and economic impacts, but also the role of organizational culture and regional policies in advancing sustainability.

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