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Nemzetközi tudományos konferencia a Magyar Tudomány Ünnepe alkalmából

International Scientific Conference on the Occasion of the Hungarian Science Festival

Sopron, 2023. november 23.

23 November 2023, Sopron

FENNTARTHATÓSÁGI ÁTMENET: KIHÍVÁSOK ÉS INNOVATÍV MEGOLDÁSOK

SUSTAINABILITY TRANSITIONS: CHALLENGES AND INNOVATIVE SOLUTIONS

Szerkesztők / Editors:

OBÁDOVICS Csilla, RESPERGER Richárd, SZÉLES Zsuzsanna, TÓTH Balázs István

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Potential Effects of Industry 4.0 Technologies on Environmental Sustainability - A Systematic Literature Review

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Abstract:
Industry 4.0 and its potential impact on different aspects of environmental sustainability have been analysed from different perspectives in the existing literature. However, Industry 4.0 collects different technologies that are not necessarily combined. It is clear that the combination of different technologies is the core value of Industry 4.0, but the examination of each technology separately is crucial for determining the right combination of technologies for each specific case. For that reason, the following research provides a systematic literature review (SLR) of each technology included in Industry 4.0 and its effects on environmental sustainability aspects based on 52 research papers. 417 articles from the SCOPUS database, which contain the word Industry 4.0 in the title, abstract, and/or in the indexed keywords, were scanned by the command-line program Astrogrep to find the most common Industry 4.0 technologies. First, the study reviews the potential effects of the six technologies on different aspects of environmental sustainability, and later on, the challenges faced by organizations when applying these technologies for environmental purposes were reviewed and new research scopes and future research directions were highlighted.

Keywords: environmental sustainability, industry 4.0, digital transformation, IoT, CPS
JEL Codes: O14, Q56

1. Introduction

More than 24.000 papers were available in the SCOPUS database that contained the word Industry 4.0 (or fourth industrial revolution or I 4.0) either in the abstract, title and/or indexed key words by May 2022. After the first industrial revolution in the 18th century, the world has struggled to create additional commodities from limited and diminishing natural resources to meet the growing demand for consumption while minimizing negative environmental and social consequences. (Müller et al., 2018). The significance of Industry 4.0 is broad, ranging from mass production to satisfying customers through product customization. The adoption rate of Industry 4.0 in the last couple of years has been extremely high (Dev et al., 2020). There is a trend toward the use of Industry 4.0 for economic purposes only, despite the high potential that the technological facilities have for environmental aspects. Industry 4.0 can play a significant role in balancing the cost/reward of environmental sustainability commitment if presented in the "right way" (El Merroun, 2022). The primary goal of environmental sustainability is to preserve the earth's environmental systems' equilibrium, the balance of natural resource use and replenishment, and ecological integrity (Glavič & Lukman, 2007). While the first industrial revolutions resulted in substantial and unexpected environmental shifts, the long-term implications of Industry 4.0 require extensive academic research. The effects of Industry 4.0 and digital transformation on environmental sustainability are predicted to be significant (Kamble et al., 2018; Lopes de Sousa Jabbour et al., 2018). The potential impact of industry 4.0 technologies on sustainability, supply chain management, and manufacturing sustainability is a well-discussed topic in the literature; however, not many review papers have investigated the application of Industry 4.0 tools for reaching environmental sustainability, and none of them examined the effect of each technology on the environment.

2. Literature review

The high level of stochastic uncertainty in the numerous components of the system, as well as the reality that many stakeholders have completely conflicting perspectives, make it difficult to create environmental policy. According to market statistics and scientific studies, customers will only act environmentally friendly if green purchases do not incur additional costs (Farjam et al., 2019; Gleim et al., 2013). According to many studies, one of the most significant barriers to the adoption of environmentally friendly practices is a lack of awareness (O'Neill & Oppenheimer, 2002). In the past few years, at least on paper, the integration of digital transformation and sustainable practices has become visible in European legislation. Political guidelines presented as part of Von Der Leyen's campaign included six "headline aspirations," two of which were "A European Green Deal" and "A Europe fit for the digital era" (Floridi, 2020). Since Von Der Leyen's nomination, Commission texts have begun to refer to the "twin transitions" – environmental and digital – that will determine Europe's medium- to long-term future. To ensure a more sustainable future, the fourth industrial revolution has the potential to address many of the environmental limits of traditional industrial practices (Morrar & Arman, 2017). Industry 4.0 technologies can result in a reduction in the amount of energy and resources consumed by the detection and analysis of data across all stages of manufacturing and supply chain activities (Shrouf et al., 2014). Based on the availability of footprint data and traceable analysis, Industry 4.0 can decrease the environmental impact of a product, process, or service (Peukert et al., 2015). The implementation of AI, robotics, and other advanced technologies across numerous economic sectors, such as the supply chain, distribution channels, and manufacturing, has a significant impact on the natural environment, resulting in a reduction in pollution, a decrease in greenhouse gas emissions, a decrease in energy consumption, and an increase in profits, simultaneously (Ejsmont et al., 2020).

3. Methodology

The current paper synthesises accessible material on the relationship of various technologies featured in I4.0 and the environmental sustainability element, and it provides an academic critique of the theory via a systematic literature review (SLR). Tranfield et al. (2003) defined SLR as a rigorous process that aims to minimize bias through exhaustive literature searches of published and unpublished research and an audit trail of the reviewers' decisions, methods, and findings. The accessibility to literature that provides information about new technologies and research possibilities in industries is low. SLR can help to identify research trends and new potential in a specific research area (Antony et al., 2021).

The paper followed the structure illustrated in the Figure 1:

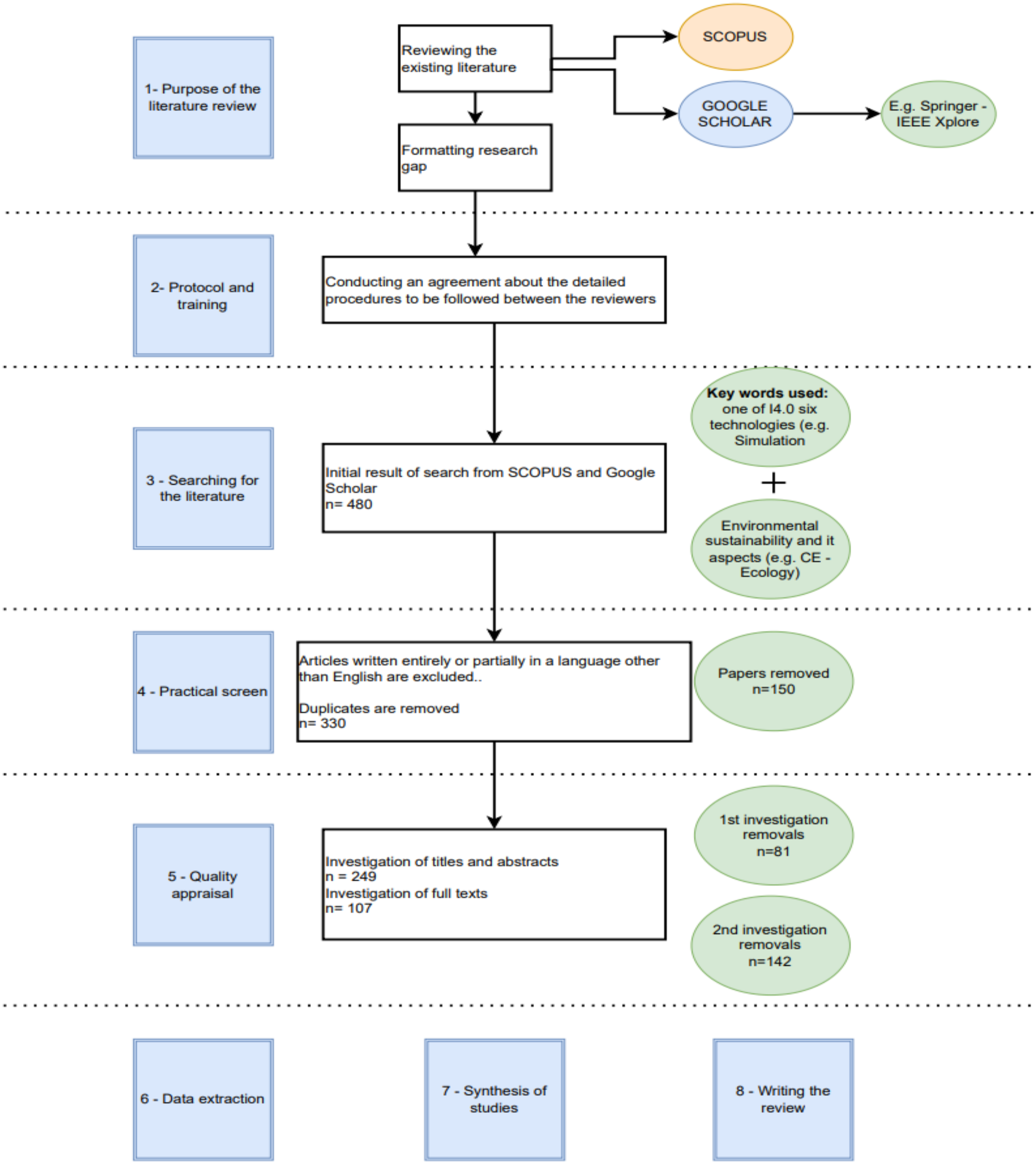

Figure 1: The systematic literature review guideline and selection process
Source: Proposed by Okoli and Schabram (2010)

3.1. Research gap and research questions

The research bridges the gap of investigating the potential implications of each Industry 4.0 technology on environmental sustainability. To fill this void, the following questions were posed:

- *Q1: What are the environmental sustainability benefits of the technology facilities provided in I4.0?*
- *Q2: What are the hurdles and limitations that must be overcome in order to use I4.0 technologies for environmental purposes?*

3.2. Search and selection process

The literature review search was conducted between January 2022 and April 2022. SCOPUS and Google Scholar were the main sources of data, taking into consideration that GS journals are indexed in a well-known databases (e.g., IEEE Xplore, Web of Science, Springer). The new papers were prioritized, as most of the articles were published in the last four years.

The keywords used in the search process are:

- IoT or Internet of Things,
- AI/ML or Artificial intelligence or Machine learning or Deep learning,
- 3D printers or 3D printing or Additive manufacturing or AM,
- Blockchain,
- Simulation,
- Augmented Reality or AR,

and

- Environmental sustainability/protection/preservation/restoration,
- Circular economy,
- Ecology/Ecosystem,
- Waste management,
- Energy management/efficiency,
- Climate change,
- Natural resources management.

4. The benefits of Industry 4.0 technologies on environmental sustainability

Industry 4.0 offers enormous environmental sustainability potential. This combination is projected to increase energy and material efficiency, as well as the use of renewable energy sources in industrial manufacturing (Ghobakhloo & Fathi, 2021). However, it is becoming increasingly evident that sustainability benefits are not a foregone consequence but must be carefully integrated into each company's digitization objectives (Renn et al., 2021). In the following paragraphs, we will discuss how each Industry 4.0 technology can help to improve environmental sustainability while promoting green actions.

4.1. Iot and environmental sustainability

The Internet of Things (IoT) is the fabric that facilitates the flow of data between people, things, and processes, resulting in a growing data sphere and complex traffic models based on a variety of data sources (Ibrahim et al., 2022).. As the IoT's main feature is tracking, and waste management has the largest share in the literature in this regard, the internet of things is the most practical way to enhance the effectiveness of municipal hazardous waste management with minimal waste and an efficiency of 95.09% (Xu & Yang, 2022). The IoT benefits for the environment are not limited to waste management; Parvathi Sangeetha et al. (2022) implemented a hybrid remote-controlled device based on the Internet of Things and Global Positioning System (GPS) with Radial Function Network (RFN), to manage the pump for storing and transporting groundwater to a farmer's field, as well as monitoring soil humidity, pressure, and temperature in a farm field. Furthermore, a survey conducted by Hu et al. (2022), based on 355 manufacturing employees in China to measure the impact of eco-sustainability motivational factors on organizations’ adoption of the Green Industrial Internet of Things (GIIoT).

4.2. AI/ML and environmental sustainability

In most cases, artificial intelligence and machine learning go hand in hand. Until recently, artificial intelligence (AI) algorithms were mostly employed in the industry and enterprise sectors for low-level activities (Emmert-Streib et al., 2020). Urbanization and civilization, as well as unsustainable practices and procedures, have led to the rise of artificial intelligence-based solutions that help with environmental sustainability (Saheb et al., 2022). Optimization of resource and energy management is one of the most acknowledged uses of AI (Zendehboudi et al., 2018). The ML now detects the features and produces accurate predictions without the need for human intervention. Increasing need for larger data sizes for various energy system applications, such as predicting photovoltaic (PV) generation (Wang et al., 2020), calculation of the battery's state of charge (Chemali et al., 2018), energy management of households (Coelho et al., 2017), the estimation of energy requirements for the distribution and individual appliances, as well as the planning and management of building energy consumption (Mocanu et al., 2016).

AI/ML has great potential in the waste management field. As organizations are pressured to produce recyclable goods, there are still many products that are recyclable by nature, but they are not treated and eventually become waste. At the top of the list, we can find textiles. In principle, 95 percent of waste textiles may be recycled, but in fact, recycling rates are quite low worldwide, with just 10–15 percent in China, 15.2 percent in the US, and 25 percent in the European Union (Li et al., 2021). According to Du et al. (2022), textile waste may be identified and sorted with the use of artificial intelligence technologies. The authors presented an AI solution based on an online near-infrared (NIR) qualitative identification model based on NIRS technology for 13 different types of waste textiles.

Third, fourth, and fifth on the list of the world's top 10 environmental risks based on effect are the water shortages (Harper, 2020). To fulfil the increased need for clean drinking water, experts have resorted to renewable and ecologically acceptable sources of energy such as solar power (Pandey et al., 2021). Based on an artificial intelligence system, (Salem et al., 2022) demonstrated a deep learning model with an accuracy of 82.64 percent for inspecting the quality of cooling water in terms of the renewable water concept.

4.3. Additive manufacturing and environmental sustainability

Additive manufacturing (AM), also known as three-dimensional (3D) printing, is a revolutionary technology that produces complex-shaped, multi-material parts in a single process (Dvorak et al., 2018). Consequently, additive manufacturing has emerged as a direct digital production technique in the age of industry 4.0 (Bueno et al., 2020). Several studies have highlighted the potential sustainability benefits of additive manufacturing processes in different fields (Liu et al., 2022), which is supported by the increasing number of studies analyzing the environmental effects of AM (Saade et al., 2020). Additive manufacturing has the potential to reduce energy consumption, and eliminate waste, including waste that affects the environment or threatens long-term sustainability (Ghobadian et al., 2020). When creating lightweight components, the product geometries may be improved, resulting in a reduction in the amount of material required during fabrication and the amount of energy utilized in operation. Due to the simple manufacturing of on-demand parts, transportation and inventory waste are reduced in the supply chain (Mani et al., 2014).

The construction sector has an important share of the literature regarding the impact of 3D printers on environmental sustainability (Khan et al., 2021; Lu et al., 2019). (Adaloudis & Bonnin Roca, 2021) applied grounded theory to analyze the potential effects of 3D printers within the construction business over the three elements of sustainability. Regarding the environmental aspect, the 3D printer can reduce waste and failures resulting from better quality control and reduce the environmental impact of concrete production and transportation. With a holistic design approach, it has the potential to improve energy efficiency and other performance parameters. Weng et al. (2020) studied the economic cost, environmental effects, and productivity of a concrete bathroom unit. When compared to a precast counterpart, a 3D printed bathroom unit may save 34.1%, 85.9%, and 87.1% on overall cost, CO_2 emissions, and energy use, respectively.

4.4. Blockchain and environmental sustainability

Blockchain technology was first introduced as a revolutionary tool that will make financial transactions without the involvement of a third party (e.g. Bank) possible by Satoshi Nakamoto, a pseudonymous developer. The currency used for these kinds of transactions is called Bitcoin, which is referred to as a cryptocurrency. By March 2022, more than 18.000 cryptocurrencies were on the market (Hayes, 2022). In 2013, a Russian developer named "Vitalik Buterin" published a white paper in which he said that Satoshi's blockchain was the first credible decentralized solution. And now, attention is rapidly starting to shift toward this second part of the blockchain, and how the technology concept can be used for more than just money (Buterin, 2014).

Blockchain technology provides the ability for transparency that allows producers to share the production process step by step in a reliable way. Since green practices are not optional for corporations anymore, the tractability of processes has become more crucial than ever. Based on document analysis, field research, interviews, and focus groups, Varavallo et al. (2022) designed, developed, and implemented a Blockchain-based traceability platform to ensure traceability in the agricultural and food industries with less environmental impact and lower costs for each transaction sent through the supply chain. According to Dey et al. (2022), food waste and loss account for nearly 6% of total greenhouse gas emissions worldwide. To overcome the food waste problem, the authors proposed a multi-layered Blockchain-based framework utilizing machine learning, cloud computing, and QR code in a decentralized Web 3.0 enabled smart city called SmartNoshWaste. The application focuses on the consumption of potatoes in the United Kingdom since it is one of the most common food items that is wasted. Erol et al. (2022) studied the potential of Blockchain to mitigate the effects of barriers to successfully implementing a circular economy. The results showed that the most important functions of blockchain in overcoming CE adoption barriers are transparent supply chain traceability management, improved collaboration and coordination in supply chain ecosystems; superior trust in supply chain ecosystems; and enhanced business models through cooperation and prosumerism.

4.5. Simulation and environmental sustainability

Process simulation is a software-based representation of physical, chemical, biological, and other unit operations (Pasha et al., 2021). Simulation models offer considerable potential for adjusting and predicting energy use, material consumption, and reducing rework to improve the performance of sustainable manufacturing (Turan et al., 2022).

Simulation has become an important tool in the construction business to create a more productive, safer, and higher-quality construction process with less negative environmental impact (Teng & Pan, 2019). According to global resource data, the construction industry consumes 32% of resources, generates 40% of greenhouse gas emissions, and creates 40% of construction waste (Han et al., 2020). The construction industry has increased massively and, simultaneously, prefabricated building destruction has also risen, resulting in massive carbon emissions (Luo et al., 2021). Building energy performance simulation software such as EnergyPlus, Ecotect, and eQuest is commonly used to simulate existing building energy performance and evaluate retrofit possibilities (Yudelson, 2010).

The construction business is not the only sector that can be environmentally friendly relying on simulation; several other cases in different sectors are spotted in the literature. Naseri-Rad et al. (2022) presented a sustainability assessment by simulating the clean-up of contaminated sites that are associated with health, environmental, economic, and social problems. The model enables site managers to understand the dynamics affecting the sustainability of each remediation scenario throughout the decontamination process's full life cycle. Burinskiene et al. (2018) simulated the warehouse's daily operations to make the flow as efficient as possible. The analysis demonstrates tremendous possibilities for reducing waste and achieving economy of distance. Yeomans and Imanirad (2012) used simulation-driven optimization (SDO) to produce diverse, maximally different, near-optimal policy solutions for waste treatment and disposal.

4.6. Augmented Reality and environmental sustainability

Augmented reality (AR) is a type of reality approximation in which physical items are connected to a virtual equivalent via contextual computer-generated information. AR has progressed from a science-fiction fantasy to a well-established scientific subject (Çakıroğlu et al., 2022).

Based on Energy Performance Augmented Reality (EPAR) modelling, Ham and Golparvar-Fard (2013) assessed and illustrated the differences between real and simulation results of the predicted energy performance of buildings. Bekaroo et al. (2018) developed an Android augmented reality-based application named ARGY to help people better understand the energy use of electronic devices at home and in the workplace. (Alonso-Rosa et al., 2020) developed an IoT energy device using augmented reality to easily visualize the power quality (PQ) parameters and energy usage of household appliances in real-time. Mylonas et al. (2019) introduced a prototype that incorporates augmented reality into a classroom exercise to help students learn about school buildings' energy conservation.

5. The challenges of the integration of Industry 4.0 and environmental sustainability

Industry 4.0 offers several features and capabilities that can be used to change industries into ecologically friendly and green practices. Nonetheless, there are numerous challenges connected with Industry 4.0 adoption, particularly in terms of sustainability (Verma et al., 2022). These difficulties differ from case to case and cannot be examined in separation.

5.1. IoT and environmental sustainability challenges

Connecting a large number of devices from any location at any time is made possible by the Internet of Things (IoT) (Khatua et al., 2020). However, IoT in energy systems has its own set of issues and barriers. Almalki et al. (2021) acknowledge that Internet of Things (IoT) development requires significant energy, they also acknowledge that it generates unintentional e-waste and pollution emissions. According to Ruan et al. (2019) green IoT system deployment raises several new financial, operational, and management (FOM) concerns, such as how to pay for network nodes to be recharged and repaired as well as how to handle IoT data.

5.2. AI/ML and environmental sustainability challenges

Through artificial intelligence, it is possible to develop systems of intelligence that will generate the knowledge required to preserve life (Nishant et al., 2020), but the AI for sustainability is challenged by over-reliance on historical data in machine learning models, the unpredictability of human behavioural reactions to AI-based interventions, increased cybersecurity concerns, negative consequences of AI applications, and difficulty assessing the results of interventions. Palomares et al. (2021) conducted a SWOT analysis on the AI effects on environmental sustainability. The most critical challenges of AI in this context are that the wide range of AI approaches makes it difficult to pick the optimal one or ones.

5.3. Additive manufacturing and environmental sustainability challenges

The usage of AM for sustainability reasons has been noticed since the technology's introduction (Gutowski et al., 2009). With all the great benefits come several challenges. Ford and Despeisse, (2016) highlighted the benefits of additive manufacturing in a sustainability context, but because AM technologies for direct production are still in their infancy, their widespread acceptance and realization of these benefits are dependent on overcoming considerable difficulties. Wu et al. (2022) explained that additive manufacturing has some bottlenecks as the industry has been hesitant to embrace it due to a lack of reliable standards for transitioning from prototyping to mass production. As a result, scale, speed, and size may be disadvantages that delay the adoption of AM in manufacturing.

5.4. Blockchain and environmental sustainability challenges

According to Dey et al. (2022), one of the most complicated aspects of implementing blockchain in a smart city from an environmental point of view is prioritizing citizen privacy and data security.

By using the fuzzy Delphi method, Rejeb et al. (2022) generated a list of the most relevant barriers when adopting the Blockchain to significantly alter aspects of circular economy activities and overcome environmental sustainability problems. To effectively rank these barriers, the best-worst method (BWM) was used. The results showed that lack of knowledge and management support, reluctance to change, and technological immaturity are the most relevant barriers, while investment cost, security risk, and scalability issues are the least impactful barriers to blockchain adoption in the CE.

5.5. Simulation and environmental sustainability challenges

According to Turinsky and Kothe (2016), modeling and simulation capabilities help to increase nuclear energy's economic competitiveness and reduce the volume of spent nuclear fuel per unit of energy while maintaining nuclear safety. However, to achieve that, advanced modeling and simulation capabilities in radiation transfer, thermal-hydraulics, fuel performance, and corrosion chemistry are required. The simulation modeling approach makes it nearly impossible to analyze massive amounts of sustainability data since it contains a lot of variables that have to be taken into consideration (Gbededo et al., 2018).

5.6. Augmented Reality and environmental sustainability challenges

The daily usage of AR is still complicated in a way that users' interactions with digital overlays that are placed in front of their vision create the requirement for smooth and lightweight user engagement with such overlays (LaViola Jr et al., 2017). Garzon et al. (2020) developed and evaluated an AR-based educational application to promote aquaponics-based sustainable agricultural practices. According to the evaluation process, the impact of the AR-based application is similar to what was discussed in the AR benefits section, which is mainly increasing awareness. However, the results also showed that the most critical challenge faced in this context is the accessibility of AR applications.

6. Conclusion

This study contributes to the literature by addressing the most significant publications on the integration of Industry 4.0 and environmental sustainability; the possible benefits of this combination, in addition to the likely obstacles are examined. If there is one lesson to be learned from any new technology that arrives in the modern world, it is that as many benefits as it may deliver, it also brings with it a set of obstacles and various consequences. Industry 4.0 is an unavoidable reality at this point. Even if certain groups continue to dispute its vastness and relevance, market leaders have already invested heavily in it, and most organisations will soon either hop on it or be left behind. However, it is critical for policymakers to closely watch the projected effects of I4.0, as these technologies can quickly get out of control and harm the environment more than the previous industrial revolutions did.

Discloser

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