

ASSESSING THE DETERMINANTS OF PERFORMANCE IN WASTE RECYCLING COMPANIES IN THE CONTEXT OF INDUSTRY 4.0: AN ANALYTICAL APPROACH.

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Abstract: This article analyzes the key factors that influence the performance of a production process in recycling plants as well as the unexpected results obtained by integrating advanced technologies. The adoption and adaptation of smart technologies in companies operating in the recycling area has led to a revolution in the adaptation of those using such technologies. The specialized literature has a number of researches on the integration of technologies that are part of the industrial revolution also called Industry 4.0, but it does not abound in having ver vercetări in the area of factories dedicated to recycling, which leads us to the conclusion that this type of research is not advanced. Based on a critical review of the existing literature, the article provides a detailed insight into the interplay between the adoption of smart technologies in a manufacturing process and how firms utilize these technologies in order to increase company performance. What is gratifying for the existing activity in companies in the recycling area in our country is that major investments are being made in all aspects of retooling as well as the

impact they have on the environment, from reducing pollution to recreating raw materials used in other industries.

JEL classification: C61, M15, M41, P41

Key words: Industry 4.0, ERP, SAP, waste management, circular economy, AI, PP – Production Planning,

1. INTRODUCTION

In today's era, characterized by increased competitive pressures and strict regulations on sustainable production, digitalization plays an important role in the waste sector as it helps to develop a sustainable global economy through the way companies organize their business. Adopting best practices and strategies has become essential, revolutionizing manufacturing industries and production processes. In recycling plants, practical solutions with long-term benefits for society and the environment are being implemented with digitization as a consequence of technological progress. Digitization involves the use of advanced technologies such as smart sensors, Big Data, artificial intelligence to streamline every step of the recycling process materials (Cucchiella, F. et al, 2015). Using advanced technologies in the sorting process and analyzing the data collected by sensors installed on the equipment removes impurities and increases the value of recycled materials (Zanelli, C et al, 2021).

Industries are facing challenges related to improving productivity and competitiveness but also how to realize processes to keep pace with technological progress. The study examines the integration of Industry 4.0 technologies in production processes, providing the tools needed to achieve sustainable production, with recycling representing a priority for every organization (Liu, X. et al, 2023). The performance of production processes in a recycling plant can be improved by applying Industry 4.0 concepts such as interconnectivity, intelligence and intelligent automation (iRPA or RPA).

The use of these technologies can provide innovative solutions that can help recycling plants to overcome efficiency challenges, such as automating the sorting and processing process by using advanced industrial robots to increase the accuracy in separating and identifying recyclables, thus automatic sorting systems based on AI, computer vision and optical sensors identify and separate recyclables such as plastic, metal, paper based on characteristics such as weight, chemical composition (Gabrys, K., 2023). Artificial intelligence develops sorting algorithms by learning from the collected data, minimizing the waste of recyclable materials and reducing the contamination of recycled materials (García, LCH, 2024).

If in an ordinary factory the performance of the production process is measured by the volume and quality of the products obtained in order to satisfy the market requirements, in a recycling factory the main goal is related to the efficiency of the recycling processes and the optimization of the recovery process by minimizing the non-recyclable waste (Knickmeyer, D., 2020).

The operational flows within a recycling plant are structured in several stages, each stage having an essential role, as it transforms waste into reusable resources, contributing to the sustainability of the recycling process (Torkelis, A et al, 2024).

2. LITERATURE REVIEW

In order to integrate the literature of specialties related to this scientific article we made an analysis of how a number of authors wrote using their appearance in WOS, using the following criteria:

- for keywords found in articles we used the combination
 - „waste recycling performance” OR
 - „factors affecting recycling industry 4.0” OR
 - „waste recycling efficiency industry 4.0”;
- we used the range 2020 – 2024;
- as „document types” we used:
 - „review article” OR „open access”;
- we used as search for „web of science categories”:
 - „Environmental Sciences” OR
 - „Engineering, Environmental” OR
 - „Green & „Sustainable Science & Technology” OR
 - „Materials Science, Multidisciplinary” OR
 - „Chemistry, Multidisciplinary” OR
 - „Energy & Fuels” OR „Biotechnology & Applied Microbiology”
 - OR „Public, Environmental & Occupational Health”,

as shown in figure 1, below:

Web of Science infographics

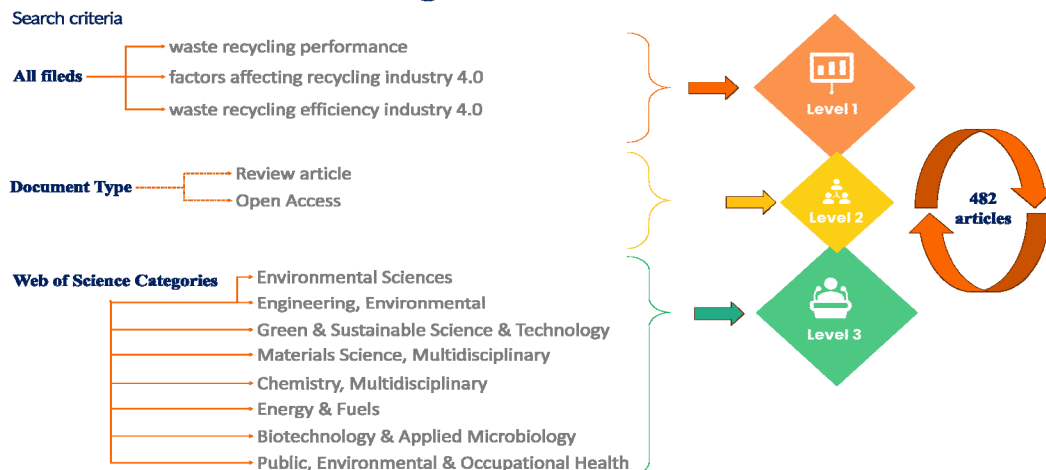


Figure no. 1 – WoS articles criteria Infografic

This resulted in 482 articles, which we analyzed using the R software application together with their graphical interface - biblioshiny - this interface is based on the bibliometrix package of the R software, which helped us to perform a bibliometric interpretation using data extracted from Web of Science databases. As can be seen in the image below, Figure 2, we have an exemplification of the keyword trend from 2018 to 2024, with words such as strategies or recovery, degradation or performance, waste or

construction being frequently found in the published articles, thus the interest in such topics is increasing.

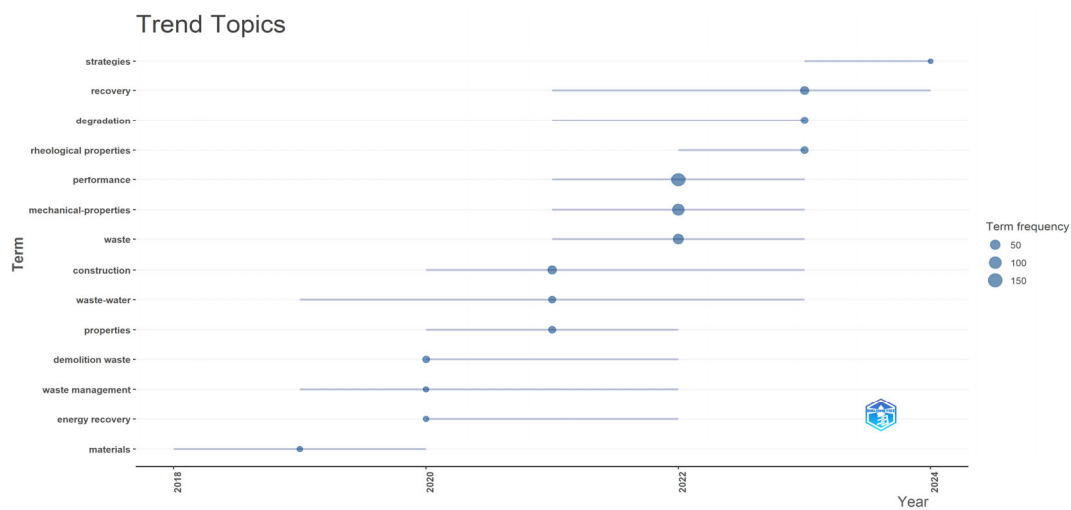


Figure no. 2 – Trend topic

A different approach regarding the co-citation network, as shown in the figure below, figure 3, shows a certain difference of research directions regarding waste management, which is to be appreciated, due to the fact that it is a very sensitive topic in terms of the evolution of our society.

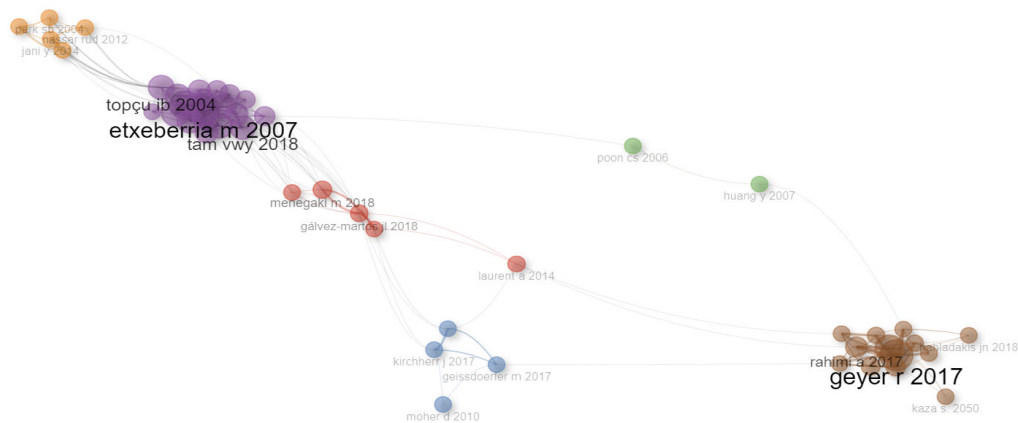


Figure no. 3 – Co-citation Network

3. ADDRESSING FACTORS INFLUENCING COMPANY PERFORMANCE IN THE CONTEXT OF INDUSTRY 4.0

The approach of how the concepts found in Industry 4.0 are adopted and adapted has had and still has an important role in shaping the business processes found in most all companies using these types of smart technologies. In Figure no. 4 (Figure no. 4) the

authors of this article detail a number of factors that influence the approach discussed above, from technological, operational, to organizational.

Key performance drivers for waste recycling companies in the context of Industry 4.0

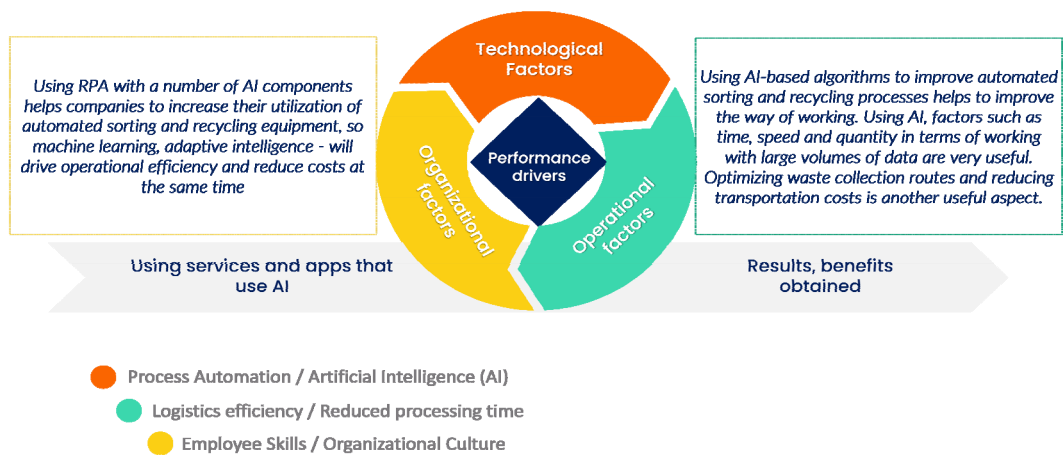


Figure no. 4 – Key performance drivers – Industry 4.0 – waste recycling company

An approach from the point of view of process automation and the degree of use of automated sorting and recycling equipment highlights the fact that such action found in recycling companies is one of the most important technological factors influencing their performance. This involves the use of advanced, intelligent equipment and technologies, which minimize human intervention, increase operational efficiency and improve the quality of processes found in the recycling area. In terms of the technologies used, these can be optical sorting systems, industrial sorting robots, intelligent conveyor belts, automatic compacting and pressing systems or shredding and granulation technologies.

5. CONCLUSIONS

This article analyzes the factors that have influenced the performance of waste recycling companies in the context of the Industry 4.0 revolution, highlighting the impact of emerging technologies (adoption and adaptation of smart technologies) on business processes, operational and strategic areas. The results underline that the adoption of smart technologies, such as the Internet of Things (IoT), process automation and Big Data analytics, play a key role in optimizing recycling activities, reducing costs and increasing sustainability. One of the main conclusions of the presented paper is that the implementation of Industry 4.0 technologies significantly improves the efficiency and quality of recycling processes, contributing to a more sustainable and circular economy-oriented value chain. However, success depends on multiple factors, with the authors of this article bringing to the forefront how data is organized in terms of organizational structure, employee skills and the degree of integration of technologies into existing processes. The study also highlighted the challenges faced by companies, including the high costs of implementing new technologies and the need for continuous staff training. These issues underline the importance of financial and strategic support from government institutions and public-private partnerships to accelerate the digital transformation in the

recycling sector. From a managerial point of view, the results suggest that the adoption of an innovation-centered model, accompanied by a clear strategy for integrating Industry 4.0 technologies, can provide companies with significant competitive advantages, contributing to the achievement of sustainability and performance targets. In conclusion, this study provides valuable insights into how recycling companies can harness the potential of digital technologies to improve organizational performance.

Future research could explore in more detail the impact of these technologies in different geographical regions or in relation to different environmental policies, in order to develop customized solutions to support a sustainable and efficient transition towards Industry 4.0, more recently integration with Industry 5.0.

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