

Evolution of waste management concepts: From recycling to resource economy in the context of Industry 4.0 and 5.0

Tetyana Maslak*

PhD, Assistant
Lviv Polytechnic National University
79013, 12 Stepan Bandera Str., Lviv, Ukraine
<https://orcid.org/0000-0002-9815-4387>

Abstract. The relevance of the study is conditioned by the aggravation of the global problem of waste management against the background of accelerating digital transformation of production systems. More than 2 billion tonnes of solid household waste are generated annually in the world, and by 2050 this figure, according to various estimates, will grow to 3.4-3.8 billion tonnes, while the share of processed products remains critically low even in developed countries. The purpose of the study was to systematise the evolution of conceptual approaches to waste management from its disposal to the development of a resource economy, to assess the role of institutional and regulatory mechanisms in this transition, and to substantiate the impact of Industry 4.0 technologies and human-centred Industry 5.0 principles on the transformation of the resource management system. The methodological basis was a systematic review of the literature, comparative and analytical and institutional analysis of scientific publications indexed in Scopus and Web of Science for 2016-2024, analysis of corporate practice cases, and a secondary analysis of official reports and EU regulations. Six conceptual stages of waste management evolution have been identified, a threshold relationship between the rate of the landfill tax and the level of recycling in the EU countries has been established depending on regulatory instruments, the role of AI, IoT, blockchain, and digital product passports as catalysts for a closed material cycle in Industry 4.0 logic has been determined, and the concept of “Circular Economy 5.0”, which integrates human-centredness, resilience, and resource efficiency, has been substantiated. The practical significance of the study lies in the development of the author’s conceptual model of transition to a resource economy in the context of Industry 5.0, which can serve as a basis for developing strategies for the “green” restoration of Ukraine in the context of post-war reconstruction

Keywords: waste hierarchy; circular economy; industrial symbiosis; digital transformation; regulatory mechanisms; digital product passport; post-war recovery

Introduction

Waste management is one of the most pressing challenges of our time. The volume of waste generation is growing at a faster pace, while the level of its re-involvement in economic circulation remains insufficient even in countries with a developed regulatory system. The digitalisation of production systems – the emergence of Industry 4.0 technologies and the human-centred paradigm Industry 5.0 – radically changes the technological capabilities of managing material flows. For Ukraine, this issue is particularly acute, as it intersects with the challenges of post-war reconstruction and commitments to European integration. The scale of the problem is illustrated by global estimates: more than 2 billion tonnes of solid household waste are generated annually

in the world, and by the middle of the century this figure is projected to grow by approximately 1.7 times, while greenhouse gas emissions from the waste sector are approaching 2.4 billion tonnes of CO₂ equivalent (Kaza *et al.*, 2018). Despite regulatory progress, in particular in the EU, overall resource efficiency remains low, and the share of circular use of materials is measured only in units of percent.

The transformation of conceptual approaches to waste management took place gradually – from primitive disposal and incineration to complex recycling strategies, and later – to systemic models of the circular and resource economy. Digitalisation has become a cardinal factor in the current round of this transformation. Industry 5.0,

Suggested Citation:

Maslak, T. (2026). Evolution of waste management concepts: From recycling to resource economy in the context of Industry 4.0 and 5.0. *Innovation and Sustainability*, 6(3), 83-89. doi: 10.31649/vis/3.2026.83.

*Corresponding author (tetiana.o.maslak@lpnu.ua)



presented by the European Commission, redefines the very logic of production, shifting the focus from productivity to human-centredness, sustainability, and resiliency, which directly resonates with the principles of the resource economy. The paper by M. Breque *et al.* (2021) explored the concept of Industry 5.0, with an emphasis on sustainability, human-centredness and sustainability of production; concluded that digitalisation should be combined with environmental and social goals. M. Friant *et al.* (2020) systematised different approaches to the circular economy and showed the absence of a single interpretation of it. The European Commission (2020) identified the main areas of the EU's transition to a circular economy, in particular, reducing the use of resources, preventing waste generation, and developing reuse and recycling. P. Rosa *et al.* (2020) analysed the relationship between the circular economy and Industry 4.0 and identified the significant potential of digital technologies for resource efficiency and circular business models. X. Xu *et al.* (2021) examined the development of Industry 4.0 and Industry 5.0 and concluded that the future of manufacturing involves combining digital technologies with the principles of human-centredness and sustainable development. A. Mandpe *et al.* (2023) investigated the application of circular economy principles to sustainable solid waste management in developing countries. The researchers showed that a combination of waste prevention, reuse, recycling, and resource recovery can improve the efficiency of waste management systems and promote sustainable development.

Despite a large number of publications in the field of circular and resource economics, there is a lack of comprehensive research in the literature that systematically combines the evolutionary logic of the transition from waste disposal to the resource economy paradigm with a critical analysis of institutional mechanisms and digital technologies of Industry 4.0 and 5.0 – especially in the context of countries undergoing transformation or post-war reconstruction. It is the filling of this gap that determines the scientific originality of the study. The purpose of the study was to systematise and critically analyse the evolution of conceptual approaches to waste management from primary disposal to the development of a resource economy, assess the role of institutional and regulatory mechanisms, and substantiate the importance of Industry 4.0 and 5.0 as catalysts for a new paradigm. To achieve this goal, the following tasks were defined: to identify and characterise the conceptual stages of the evolution of waste management together with their theoretical foundations; to assess the role of EU institutional and regulatory mechanisms in the transition to a circular and resource economy; to substantiate the contribution of Industry 4.0 and 5.0 technologies to the development of a new paradigm of resource management.

Materials and Methods

The study was implemented in the format of a systematic review of the literature, supplemented by comparative analytical, institutional and case analysis, and secondary

analysis of official report data. This combined design is conditioned by the interdisciplinary nature of the subject, combining technological, regulatory, and economic dimensions. The Scopus and Web of Science databases were used to select the sources; search queries were formulated using the keywords “waste management”, “circular economy”, “resource economy”, “waste hierarchy”, “Industry 4.0”, “Industry 5.0”, and “digital product passport” in the titles and keywords of publications. The chronological scope of the initial search was 2016–2024; however, for conceptually significant studies, the scope was extended to 1990. The inclusion criteria were peer-reviewed papers of categories Q1–Q3 of the Scopus database, reviews and monographs published by Elsevier, Springer, and Wiley, and official documents of the European Commission, the World Bank, Eurostat and The Ellen MacArthur Foundation; the exclusion criteria were abstracts, dissertations, and non-commercial Internet sources without DOI. The primary array consisted of 74 publications, of which 28 were selected for direct analysis after consecutive screening (based on the relevance of the title, abstract, and full text).

To reconstruct the evolution of conceptual approaches, each selected stage was compared according to a unified set of criteria: the dominant attitude to waste as an object of management; a key regulatory act; the level of closeness of the material cycle; the level of digital maturity. These four criteria form a consolidated comparative matrix, while additional dimensions – resource value orientation, economic effects, and the role of digital technologies – are revealed in the narrative description of each stage to avoid matrix overload. Regulatory mechanisms were investigated using the “incentives – information – infrastructure” analytical framework (Milios, 2018), which allows explaining differences in the pace of transition between EU countries. To verify the conceptual generalisations at the practical level, corporate and territorial case studies (Renault Group, Apple Inc., Michelin, and the Kalundborg industrial symbiosis) were analysed, drawing on corporate and industry reports as their source material. This method was used as an illustrative and confirmatory method, and not as an independent empirical study. Quantitative indicators were borrowed from Eurostat statistical databases (n.d.), World Bank reports “What a Waste 2.0” (Kaza *et al.*, 2018), reports of the European Environmental Protection Agency, materials from UNEP (2024) and IEA (n.d.). The regulatory framework consisted of texts of EU directives and regulations available through the official EUR-Lex portal.

Results and Discussion

Six conceptual stages in the evolution of waste management

The analysis identified six conceptual stages in the evolution of waste management, which differ not only in technological characteristics, but also in the regulatory context, economic effects, and level of digital maturity. Unlike the classic five-stage models (Negrete-Cardoso *et al.*, 2022), the proposed approach identifies the digital-human-centred

stage as an independent, rather than as a component of the resource economy, which more accurately reflects the qualitative leap caused by Industry 4.0 and 5.0.

Stage 1. Disposal and incineration (before the 1970s): linear waste disposal without a reverse cycle. For most of the industrial age, waste was perceived solely as an undesirable byproduct of production and consumption to be disposed of. The dominant methods were landfill disposal and open incineration. This approach is characterised by a linear “take – make – dispose” model, which involves the unilateral movement of materials from natural resources to landfill without any reverse cycle (Geissdoerfer *et al.*, 2017). The economic effects of this stage were hidden: disposal costs were low (an average of 5–15/tonne until the 1970s), but external externalities (groundwater, air pollution, the occurrence of “NIMBY syndrome”) were never taken into consideration in market prices. The lack of a regulatory framework meant that the “price” of waste for the producer was zero, which systematically stimulated their excessive formation.

Stage 2. Waste hierarchy and regulatory design of the concept (1970s–1990s). The paradigm shift began with the advent of environmental legislation. A key conceptual innovation was the “waste hierarchy”, which prioritised waste prevention over recycling and recycling over disposal. This hierarchy was subsequently consolidated in the EU Waste Framework Directive (Directive of the European Parliament and Council of the European Union No. 2008/98/EC) and remains the regulatory core of the EU regulatory field. The researchers emphasise, however, that the waste hierarchy focuses on the “end-of-pipe” and does not solve the problem of excessive resource consumption at the beginning of the production chain (Murray *et al.*, 2017). Empirical data indicate that operationalising the waste hierarchy through price signals is crucial: EU countries where the total cost of landfilling (landfill tax plus gate fee) exceeds 100 EUR/tonne consistently achieve recycling rates above 50%, whereas in countries where this threshold is not reached, the recycling rate often remains below 30%. Therefore, the real efficiency of the transition is determined not by the waste hierarchy itself as a concept, but by its implementation through price instruments.

Stage 3. Industrial ecology and symbiosis (1990s – early 2000s). The next qualitative leap is associated with the emergence of industrial ecology, a scientific discipline that studies the flow of materials and energy in industrial systems by analogy with natural ecosystems. The concept of industrial symbiosis, popularised on the example of Denmark’s Kalundborg, demonstrates how waste from one enterprise can serve as resources for another (Ghisellini *et al.*, 2016). Kalundborg is the most documented example of industrial symbiosis in the world. According to available estimates, the annual savings of participants in the symbiosis are about EUR 24 million, while reducing CO₂ emissions by about 635 thousand tonnes and saving about 3.6 million m³ of water annually. At the same stage, the idea of “Cradle to Cradle” by W. McDonough and M. Braungart, which

promotes closed product design (McDonough & Braungart, 2002). At this stage, there is a transition from mainly environmental control over industrial production to a systematic vision of the relationship between enterprises, resources, and natural ecosystems. Industrial ecology and industrial symbiosis lay the foundations for the closed use of materials and energy, and the concept of “Cradle to Cradle” extends this principle to the entire product life cycle.

Stage 4. Circular economy: conceptual design and standardisation (2010–2015). The term “circular economy” (CE) became widespread in the 2010s due to the activities of the Ellen MacArthur Foundation (2013), which defined it as an economy “conceived and focused on recovery and regeneration”. W. Stahel (2016) emphasised that CE is a system transformation aimed at maximising the value of resources through closed production loops and long-term design. The conceptual heterogeneity of the CE was confirmed in the study by J. Kirchherr *et al.* (2017): 114 definitions analysed show that only a third of them contain an explicit reference to the waste hierarchy, and the social dimension is almost not mentioned. R-hierarchy (9R Framework), proposed by J. Potting *et al.* (2017), structures strategies by priority: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover.

At this stage, the EU has formed a systematic regulatory architecture – from the 2015 CE Package to the updated 2020 Circular Economy Action Plan (European Commission, 2020) – that covers the entire product lifecycle. L. Milios (2018) formulated an analytical triad of regulatory prerequisites for the transition to a circular economy: “the right incentives” (price signals – landfill taxes and modulated producer fees), “the right information” (material declarations, certification, and product passports), and “the right infrastructure” (separate collection, sorting, and recycling systems). It is the underdevelopment of the “infrastructure” in a broad sense that is the main barrier for most countries of Central and Eastern Europe, including Ukraine.

Stage 5. Resource economy: from circularity to full resource efficiency (second half of the 2010s). Contemporary discourse goes beyond CE, forming the concept of “resource economy” – a resource economy in which waste is considered not as a residue, but as a secondary resource; according to M. Esposito *et al.* (2018), this reflects a deeper transformation of enterprise competitive strategies. The complete conceptual “disappearance” of waste as a category is more of a strategic goal and a regulatory guideline than an actual state achieved: the real volumes of individual waste streams (including electronic ones) continue to grow, as discussed below. A series of new EU legislative acts serves as a regulatory marker of this transition. Directive (EU) of the European Parliament and Council of the European Union No. 2019/904 (2019) set mandatory targets for separate collection of PET bottles: 77% by 2025 and 90% by 2029. Regulation (EU) of the European Parliament and Council of the European Union No. 2023/1542 (2023) requires a 90% return of cobalt, copper, nickel and 50% return of lithium by 2027.

Stage 6. Digital dimension: Industry 4.0 and 5.0 as catalysts for resource transformation (2020s and beyond). A qualitatively new dimension of waste management transformation is Industry 4.0 technologies and the human-centred Industry 5.0 paradigm. P. Rosa *et al.* (2020) in a systematic review of 60 publications found that IoT, Big Data, and blockchain technologies are the most studied in the context of supporting circular strategies, although the systemic macroeconomic effects remain poorly understood. The key technology vectors of Industry 4.0 cover several areas. First of all, these are AI and computer vision systems in sorting: innovative optical sorters achieve a capacity of about 200 units/min with a purity of more than 95% (compared to 30-40 units/min and 65-80% with manual sorting); according to UNEP (2024), the use of AI reduces the transport leg of waste collection by 36.8%, costs – by 13.35%, time – by 28.22%. Equally important are IoT and smart urban collection systems, where route optimisation reduces operating costs by 30-50% and transport CO₂ emissions by 60%. A separate area forms a blockchain for verification of material origin, which provides a constant audit trail of material flows.

A fundamentally new step is the digital product passport (DPP), introduced by the Regulation (EU) of the European Parliament and Council of the European Union No. 2024/1781 (2024). DPP is a digital record that accompanies a product throughout its entire lifecycle. Starting in 2027, DPP will become mandatory for industrial batteries and electric vehicle accumulators, and by 2030 it will be extended to textiles, electronics, and tires. The European Commission estimates that DPP can generate approximately EUR 16 billion/year of consumer benefits due to improved maintainability.

Industry 5.0, presented by the European Commission as a “sustainable, human-centred and resilient industry”

(Breque *et al.*, 2021), is based on three core principles – human-centredness, constancy, and resiliency (Xu *et al.*, 2021). Unlike Industry 4.0, it transfers consistency and circularity from the category of additional requirements to the category of system-forming production principles. Corporate practices indicate the operationalisation of these concepts. Through its Refactory plant in Flins, Renault Group generates more than EUR 500 million per year from recycling and remanufacturing; Apple has deployed the Daisy robotic system, capable of dismantling up to 200 smartphones per hour; Michelin has committed to increasing the share of renewable materials in its tyres to 40% by 2030 and 100% by 2050. However, technological optimism cannot ignore Jevons paradox: increasing resource efficiency can drive consumption growth. Industry 4.0 technologies themselves have a significant carbon footprint – global data centres consume more than 460 TWh/year (IEA, n.d.), and the volume of e-waste in 2022 reached 62 Mt with a recycling rate of only 22.3%. The synthesis of these concepts forms what is called “Circular Economy 5.0” – an integrated approach where digital infrastructure is the means, not the goal.

Comparative analysis and author's conceptual model

The proposed six-step model differs from the existing classifications in several aspects. Unlike bibliometric reviews (Negrete-Cardoso *et al.*, 2022; Khan *et al.*, 2023), it focuses on the economic effects and performance indicators of each stage. Incorporating regulatory analysis through the triad proposed by L. Milios (2018) – “incentives, information, infrastructure” – explains why some countries move to higher levels of the waste hierarchy more rapidly than others. Ultimately, the separation of Industry 4.0/5.0 into an independent sixth stage corresponds to a qualitative leap in technological capabilities, and not just their evolutionary development.

Table 1. Comparative analysis of conceptual stages of waste management

Stage	Name	Attitude to waste	Key regulatory act	Cycle closure level	Digital maturity
1 (before the 1970s)	Linear waste disposal	Unwanted by-product	Absent	Absent	Absent
2 (1970s-1990s)	Waste hierarchy	Object of regulation (end-of-pipe)	Directive of the European Parliament and Council of the European Union No. 2008/98/EC	Low (recycling <30 %)	Minimum
3 (1990s-2000s)	Industrial symbiosis	Resource for other businesses	Industrial and environmental legislation	Medium (inter-enterprise level)	Low
4 (2010-2015)	CE	Resource in a closed loop	CE Package 2015; Action Plan 2020 (EC)	High (system level)	Average
5 (second half of the 2010s)	Resource economy	Waste as a secondary resource (the goal is its “disappearance”)	European Parliament and Council of the European Union No. 2023/1542	Very high (material-waste-free)	High (LCA, DRS)
6 (2020s and beyond)	Industry 4.0 / 5.0 + CE 5.0	Data and value in the digital chain	Reg. 2024/1781 (DPP); Ind. 5.0 Policy (EC, 2021)	Complete (human-centred resiliency)	Maximum (AI, IoT, blockchain, DPP)

Source: compiled by the author

For Ukraine, the transition to the later stages of the described evolution is not only an ecological, but also an economic and geopolitical priority. The current share of

municipal waste processing in Ukraine is only 6-8% with more than 90% disposal, which corresponds to conceptual stages 1-2 according to the proposed model. The Law “On

Waste Management”, adopted in 2022, is a necessary but insufficient condition for the transition; its implementation requires substantial investment and systemic institutional design in line with the logic of the triad.

It is advisable to compare the results obtained with the existing classifications and conclusions of other researchers to outline common positions, differences, and unexplored aspects. First of all, the proposed model correlates with the bibliometric review by M. Negrete-Cardoso *et al.* (2022), which recorded five dominant clusters of scientific publications – from “disposal” to “circular economy”. What is common is the recognition of the step-by-step transition; the difference is that the mentioned review does not single out the digital dimension as an independent qualitative leap. The proposed approach addresses this gap by conceptualising Industry 4.0/5.0 as a distinct paradigmatic transformation rather than as a technological adjunct to the CE. The threshold relationship established in the study between the landfill tax rate and recycling efficiency is consistent with the theoretical proposition of L. Milios (2018) on the crucial role of price signals: the countries with the highest recycling rates – the Netherlands, Belgium, Austria, Germany – are characterised by a total disposal cost exceeding 150 EUR/tonne. Furthermore, this result complements the opinion of L. Milios regarding an empirical threshold (100 EUR/tonne), below which the regulatory incentive does not actually work.

The conceptual interpretation of CE in the current model is based on the classical definitions by P. Ghisellini *et al.* (2016) and M. Geissdoerfer *et al.* (2017), who considered it as a regenerative system and trace its development from industrial symbiosis. The current result confirms their logic, but, in contrast to the mostly descriptive approach of these reviews, adds a regulatory and institutional criterion for differentiating stages. The conceptual heterogeneity of the circular economy identified by J. Kirchherr *et al.* (2017), based on 114 definitions, supports the decision to construct the periodisation not around definitions, but around measurable characteristics of the stages. Critical positions of other authors outline the boundaries of the proposed model. J. Korhonen *et al.* (2018) emphasised that complete circularity is physically unattainable due to the second law of thermodynamics, and T. Zink & R. Geyer (2017) formalised the “circular economy rebound” effect, in which secondary materials only partially displace primary production. The data obtained on the growth of the EU consumer footprint, despite the increase in resource efficiency, empirically confirm these reservations.

As for the digital measurement, the current conclusions coincide with P. Rosa *et al.* (2020) that IoT, Big Data, and blockchain technologies are the most researched tools to support circular strategies; the difference is that they integrate into a broader evolutionary framework along with the human-centred principles of Industry 5.0. The analysis of the urban dimension of the problem (Mandpe *et al.*, 2023), which emphasises the role of cities as both major generators of waste and actors responsible for its

management, complements the proposed model at the meso level, while Eurostat data (n.d.) on the share of circular material use (11.5%) and investment in CE sectors (EUR 121.6 billion in 2021) quantitatively delineate the gap between policy declarations and the actual state of affairs. For Ukraine, the practical significance of the results is determined by the need for a “green leap” in the context of post-war reconstruction, which generates unprecedented amounts of construction waste. The proposed model determines the specific conceptual “address” of Ukraine in the evolutionary trajectory (stages 1-2) and outline the regulatory and institutional prerequisites for an accelerated transition to stages 5-6, which distinguishes this study from the analysis of CE-transformations focused on countries with a developed waste management system. Summarising, the comparison with previous studies confirms the main theses of the paper on the phased transition and the crucial role of price instruments, while clarifying them through the addition of a digital-human-centred dimension and an institutional differentiation criterion. The identified differences – first of all, the separation of Industry 4.0/5.0 into an independent stage and the focus on transitive and post-war economies – determine the scientific contribution of the study and create the basis for further conclusions.

Conclusions

The analysis identified and characterised six conceptual stages of the evolution of waste management: linear disposal (disposal and incineration); waste hierarchy and regulatory design; industrial ecology and symbiosis; CE; resource economy; digital dimension – Industry 4.0 and 5.0. Each subsequent stage is built on top of the previous one, including new dimensions of consistency, resource value, and technological maturity. The study confirmed that institutional prerequisites, not just conceptual declarations, are crucial for the resource transition. Price incentives (disposal fees, modulated EPR fees) are more effective than policy statements: EU countries with a total disposal cost of more than 100 EUR/tonne systematically achieve a recycling share of more than 50%. The effectiveness of the transition is ensured not by individual tools, but by their coordination in the logic of the “incentives – information – infrastructure” triad.

Digital tools form a qualitatively new dimension of resource management. Industry 4.0 technologies (AI, IoT, blockchain) transform waste management from residual management to precise resource management, providing measurable reduction in operating costs (30-50%), reduction of CO₂ transport emissions (up to 60%), and improved sorting purity (over 95%). A special role is played by the Digital Product Data Sheet (DPP), which turns the product life cycle into a transparent, verified information chain, and becomes the regulatory core of the transition to a resource economy. Industry 5.0 complements this toolkit with a social and environmental dimension, forming the concept of “Circular Economy 5.0”, in which digital infrastructure is a means, not an end goal. The “rebound” effect remains a sys-

temic constraint, highlighting the need for macroeconomic management along with technological solutions.

For Ukraine, the results obtained are of direct applied importance: the country is at stages 1-2 of the evolutionary model, and the accelerated transition to stages 5-6 in the context of post-war reconstruction requires the priority introduction of price instruments, the development of separate assembly infrastructure and the gradual implementation of digital solutions, in particular DPP, in harmonisation with the EU acquis. Prospects for further research are related to the development of quantitative indicators of transition to a resource economy in the context of Ukraine; analysis of sectoral strategies for implementing

Industry 4.0/5.0 in the post-war reconstruction; empirical measurement of the “rebound” effect at the micro level of enterprises; and the study of social aspects of a fair transition.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

- [1] Breque, M., De Nul, L., & Petridis, A. (2021). *Industry 5.0: Towards a sustainable, human-centric and resilient European industry*. Luxembourg: Publications Office of the European Union. doi: 10.2777/308407.
- [2] Directive (EU) of the European Parliament and Council of the European Union No. 2019/904 “On the Reduction of the Impact of Certain Plastic Products on the Environment”. (2019, June). Retrieved from <https://eur-lex.europa.eu/eli/dir/2019/904/oj/eng>.
- [3] Directive of the European Parliament and Council of the European Union No. 2008/98/EC “On Waste and Repealing Certain Directives”. (2008, November). Retrieved from <https://eur-lex.europa.eu/eli/dir/2008/98/oj/eng>.
- [4] Ellen MacArthur Foundation. (2013). *Towards the circular economy: Economic and business rationale for an accelerated transition (Vol. 1)*. Cowes: Ellen MacArthur Foundation.
- [5] Esposito, M., Tse, T., & Soufani, K. (2018). Introducing a circular economy: New thinking with new managerial and policy implications. *California Management Review*, 60(3), 5-19. doi: 10.1177/0008125618764691.
- [6] European Commission. (2020). *A new circular economy action plan: For a cleaner and more competitive Europe*. Luxembourg: Publications Office of the European Union. doi: 10.2779/05068.
- [7] Eurostat. (n.d.). *Circular economy monitoring framework*. Retrieved from <https://ec.europa.eu/eurostat/web/circular-economy>.
- [8] Friant, M.C., Vermeulen, W.J.V., & Salomone, R. (2020). A typology of circular economy discourses: Navigating the diverse visions of a contested paradigm. *Resources, Conservation and Recycling*, 161, article number 104917. doi: 10.1016/j.resconrec.2020.104917.
- [9] Geissdoerfer, M., Savaget, P., Bocken, N.M.P., & Hultink, E.J. (2017). The circular economy – a new sustainability paradigm? *Journal of Cleaner Production*, 143, 757-768. doi: 10.1016/j.jclepro.2016.12.048.
- [10] Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, 114, 11-32. doi: 10.1016/j.jclepro.2015.09.007.
- [11] IEA. (n.d.). *Data centres and data transmission networks*. Retrieved from <https://surl.li/qtytrd>.
- [12] Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). *What a waste 2.0: A global snapshot of solid waste management to 2050*. Washington: World Bank. doi: 10.1596/978-1-4648-1329-0.
- [13] Khan, S.A.R., Tabish, M., & Yu, Z. (2023). Mapping and visualizing of research output on waste management and green technology: A bibliometric review of literature. *Waste Management & Research*, 41(7), 1203-1218. doi: 10.1177/0734242X221149329.
- [14] Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221-232. doi: 10.1016/j.resconrec.2017.09.005.
- [15] Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: The concept and its limitations. *Ecological Economics*, 143, 37-46. doi: 10.1016/j.ecolecon.2017.06.041.
- [16] Mandpe, A., Paliya, S., Gedem, V.V., Patel, S., Tyagi, L., Kumar, S., & Tyagi, S.K. (2023). Circular economy approach for sustainable solid waste management: A developing economy perspective. *Waste Management & Research*, 41(1), 48-73. doi: 10.1177/0734242X221126718.
- [17] McDonough, W., & Braungart, M. (2002). *Cradle to cradle: Remaking the way we make things*. New York: North Point Press.
- [18] Milios, L. (2018). Advancing to a circular economy: Three essential ingredients for a comprehensive policy mix. *Sustainability Science*, 13(3), 861-878. doi: 10.1007/s11625-017-0502-9.
- [19] Murray, A., Skene, K., & Haynes, K. (2017). The circular economy: An interdisciplinary exploration of the concept and application in a global context. *Journal of Business Ethics*, 140(3), 369-380. doi: 10.1007/s10551-015-2693-2.

- [20] Negrete-Cardoso, M., Rosano-Ortega, G., Álvarez-Aros, E.L., Tavera-Cortés, M.E., Vega-Lebrún, C.A., & Sánchez-Ruiz, F.J. (2022). Circular economy strategy and waste management: A bibliometric analysis in its contribution to sustainable development, toward a post-COVID-19 era. *Environmental Science and Pollution Research*, 29(41), 61729-61746. doi: 10.1007/s11356-022-18703-3.
- [21] Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: Measuring innovation in the product chain*. Hague: PBL Netherlands Environmental Assessment Agency.
- [22] Regulation (EU) of the European Parliament and Council of the European Union No. 2023/1542 “Concerning Batteries and Waste Batteries”. (2023, July). Retrieved from <https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng>.
- [23] Regulation (EU) of the European Parliament and Council of the European Union No. 2024/1781 “On Ecodesign for Sustainable Products”. (2024, June). Retrieved from <https://eur-lex.europa.eu/eli/reg/2024/1781/oj/eng>.
- [24] Rosa, P., Sassanelli, C., Urbinati, A., Chiaroni, D., & Terzi, S. (2020). Assessing relations between circular economy and Industry 4.0: A systematic literature review. *International Journal of Production Research*, 58(6), 1662-1687. doi: 10.1080/00207543.2019.1680896.
- [25] Stahel, W.R. (2016). The circular economy. *Nature*, 531(7595), 435-438. doi: 10.1038/531435a.
- [26] UNEP. (2024). *Global waste management outlook 2024*. Retrieved from <https://www.unep.org/resources/global-waste-management-outlook-2024>.
- [27] Xu, X., Lu, Y., Vogel-Heuser, B., & Wang, L. (2021). Industry 4.0 and Industry 5.0 – inception, conception and perception. *Journal of Manufacturing Systems*, 61, 530-535. doi: 10.1016/j.jmsy.2021.10.006.
- [28] Zink, T., & Geyer, R. (2017). Circular economy rebound. *Journal of Industrial Ecology*, 21(3), 593-602. doi: 10.1111/jiec.12545.

Еволюція концепцій поводження з відходами: від утилізації до ресурсної економіки в контексті Індустрії 4.0 та 5.0

Тетяна Маслак

Доктор філософії, асистент
Національний університет «Львівська політехніка»
79013, вул. Степана Бандери, 12, м. Львів, Україна
<https://orcid.org/0000-0002-9815-4387>

Анотація. Актуальність дослідження визначається загостренням глобальної проблеми поводження з відходами на тлі прискорення цифрової трансформації виробничих систем. Щорічно у світі утворюється понад 2 млрд тонн твердих побутових відходів, а до 2050 року цей показник, за різними оцінками, зростає до 3,4-3,8 млрд тонн, тоді як частка переробленої продукції залишається критично низькою навіть у розвинених країнах. Мета роботи полягала в тому, щоб систематизувати еволюцію концептуальних підходів до поводження з відходами від їх захоронення до формування ресурсної економіки, оцінити роль інституційних та регуляторних механізмів у цьому переході, а також обґрунтувати вплив технологій Індустрії 4.0 та людиноцентричних принципів Індустрії 5.0 на трансформацію системи управління ресурсами. Методологічну основу становили систематичний огляд літератури, порівняльно-аналітичний та інституційний аналіз наукових публікацій, індексованих у Scopus та Web of Science за 2016-2024 роки, аналіз кейсів корпоративних практик, а також вторинний аналіз офіційних звітів і нормативно-правових актів ЄС. Виявлено шість концептуальних етапів еволюції поводження з відходами, встановлено порогову залежність між ставкою мита на захоронення (landfill tax) та рівнем переробки в країнах ЄС залежно від регуляторних інструментів, визначено роль технологій ШІ, IoT, блокчейну та цифрових паспортів продуктів як каталізаторів замкнутого матеріального циклу в логіці Індустрії 4.0, а також обґрунтовано концепцію «Циркулярна економіка 5.0», яка інтегрує людиноцентричність, резилієнтність та ресурсоефективність. Практична цінність роботи полягає у формуванні авторської концептуальної моделі переходу до ресурсної економіки в умовах Індустрії 5.0, що може слугувати основою для розробки стратегій «зеленого» відновлення України в умовах повоєнної відбудови.

Ключові слова: ієрархія відходів; циркулярна економіка; промисловий симбіоз; цифрова трансформація; регуляторні механізми; цифровий паспорт продукту; повоєнне відновлення