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Sustainable development of smart cities through municipal waste incinerators: the examples of artificial intelligence in technological entrepreneurship

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ABSTRACT

The article aims to analyse AI's use for optimising management processes in urban waste incineration plants, making them consistent with the implementation of the sustainable development goals SDG #11 and SDG #12. The triangulation of research methods was chosen to achieve the most reliable research outcomes. The case study was the selected qualitative method. Among the available techniques, two were selected: Computer-Assisted Web Interviewing (CAWI) and in-depth interviews, both of which were employed to gather the necessary data. Scientific research analysed the AI-based technologies used by individual incinerators. The analysis encompassed trends in waste incineration plants utilising AI for sustainable development in smart cities, particularly for achieving SDG#11 and SDG#12, focusing on leveraging AI to enhance environmental outcomes. The effect of using AI in municipal waste incineration plants for SDG#11 and SDG#12 can be applied to other entities implementing the principles of sustainable development in smart cities. The identified trends underscore the importance of adopting and implementing integrated policies and plans that address inclusion, resource efficiency, climate change mitigation and adaptation.

KEY WORDS
technology entrepreneurship, sustainable development, artificial intelligence, AI, SDGs, smart city

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Introduction

The article presents selected aspects of implementing the principle of sustainable development of smart cities through AI in municipal waste incinerators. Moreover, it focuses on using artificial intelligence to mitigate urban problems, especially air pollution, waste management, and sewage treatment. The analysis focused on the activities of waste incineration plants in the context of achieving SDG#11 goals (Sustainable Cities and Communities) and SDG#12 (Responsible Consumption and Production).

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Compared to other research methods, the case study provides the richest array of techniques and tools for data collection. Among the available techniques, two were selected: Computer-Assisted Web Interviewing (CAWI) and in-depth interviews, which were employed to gather the necessary data. The research sample comprised all nine municipal waste incineration plants located in Poland at the time of conducting the survey. These initiatives focus on improving waste management processes, reducing emissions, and contributing to cleaner urban environments, which are in line with the broader objectives of sustainable development and smart city infrastructure optimisation.

The focus on Polish cities in achieving the SDGs reflects their critical role in the global sustainability agenda, emphasising the need for innovative approaches to urban planning and management that prioritise both environmental and social sustainability (Cubric, 2020; Šulyová & Kubina, 2022). Decision support tools for the sustainable development of smart cities are increasingly utilising AI to optimise these processes and ensure higher living standards for the inhabitants of Polish smart cities (Chui et al., 2018; Paiva et al., 2021; Szpilko et al., 2020).

1. Literature review

The discussion focuses on relationships between AI and rapid advancements in municipal waste incinerators and sustainable development (SD). The aim is to understand whether AI can influence the production of municipal waste incinerators to achieve sustainable resource management according to the Sustainable Development Goals (SDGs) outlined in the United Nations' 2030 Agenda. Table 1 illustrates the scope of AI definition in the chosen publications.

The first Analytical Engine was developed in the 1830s by Ada Lovelace and Charles Babbage. Lovelace created what is considered the first operational program for calculating Bernoulli numbers on Babbage's machine, thereby setting the standard for contemporary artificial intelligence and machine learning (AI) systems. Although Lovelace was enthusiastic about the Analytical Engine's potential to generate conclusions that the human mind could not achieve, she argued that the machine was incapable of producing original ideas. The Dartmouth Research Project defined AI as the problem of "making a machine behave in ways that would be considered intelligent if human behaviour were like this" (McCarthy et al., 1955). AI must be understood as the ability of a system to act intelligently and to do so in increasingly broader domains (Ertel et al., 2018; Chen et al., 2021; Gupta et al., 2023; Moravec et al., 2024), accurately interpreting external data and using these insights to achieve specific goals and tasks through flexible configurations (Jha et al., 2017; Kaplan et al., 2019; Lévesque et al., 2022). AI is a distinct concept from the Internet of Things (IoT) and Big Data, although interconnected. Artificial Intelligence (AI) transformed the mechanisms of generating and utilising information for decision-making processes (Mikalef et al., 2017; Subotic et al., 2021; Wu et al., 2021; Lazaroiu et al., 2022) and revolutionised business operations (Yigitcanlar et al., 2020; Wang et al., 2021), impacting trade practices and management across various sectors (Wirtz et al., 2019). These sectors are now offering increasingly competitive and sustainable products or services (Govindan et al., 2019; Garbuio et al., 2019; Wirtz et al., 2019). Currently, the synergy between artificial technologies and human intelligence is anchored in algorithms designed to assist managers in making informed decisions. This has initiated a cultural shift wherein a vast array of data, connections, and interactions become integral to the standard management protocols within organisations (Sievers et al., 2021). Such mathematical models facilitate managerial tasks by providing well-catalogued and organised information repositories. Previous research has even indicated that, in many instances, these algorithmic models outperform human decision-making capabilities. Sousa and Rocha (2019) proposed a developmental model for the requisite skills — innovation, leadership, and management — for disruptive business managers, given AI's application in business intelligence processes.

Current research on sustainable entrepreneurship based on artificial intelligence is also significant (Subotić et al., 2021). Many industries have been "touched" by the development of artificial intelligence (Bibri, 2020; Wang et al., 2020). Wynsberghe (2021) defined the term "sustainable artificial intelligence" as a way of using artificial intelligence to enable societies to achieve their sustainable development goals. Artificial intelligence is integrated with environmental and energy systems, as well as other innovative technologies, to facilitate sustainable development (Vinuesa et al., 2020).

This trend could assist enterprises in identifying the nexus between innovation and sustainability (Stone et al., 2016), aiming to incorporate AI into

Tab. 1. Scope of AI definition in the chosen publications

Authors and title of publications	Scope of AI definition
McCarthy et al. (1955)	as the problem of "making a machine behave in ways that would be considered intelligent if human behaviour was like this"
Nilsson (1983)	must be understood as the ability of a system to act intelligently and to do so in increasingly broader domains
Taddy (2018)	in many instances, these algorithmic models outperform human decision-making capabilities
Mikalef et al. (2017)	transformed the mechanisms of generating and utilising information for decision-making processes
Stone et al. (2016)	objective of incorporating AI into decision-making in municipal waste incinerators
Sousa et al. (2019)	developmental model for the requisite skills with AI's application in business intelligence processes
Schneider et al. (2019)	revolutionised business operations, impacting trade practices and management across various sectors
Subotić et al. (2021)	sustainable entrepreneurship based on artificial intelligence is also significant
Wynsberghe (2021)	defines the term "sustainable artificial intelligence" as a way of using artificial intelligence to enable societies to achieve their sustainable development goals
Vinuesa et al. (2020)	AI-like applications are integrated with environmental and energy systems and other innovative technologies to facilitate sustainable development

decision-making in municipal waste incinerators to fulfil the Sustainable Development Goals (SDGs). The business sector is pivotal in the strategy to achieve the United Nations' Sustainable Development Goals by 2030, as it is a primary driver of economic growth. In reality, municipal waste incinerators of any size production are capable of developing more responsible business models, thereby providing a critical impetus towards the implementation of Sustainable Development Goals (SDGs) through investments in technological innovations and the engagement of multiple stakeholders. Innovation serves as the lifeblood of business operations because, through cutting-edge technologies, it is feasible to implement sustainable models of production and consumption that align perfectly with the objectives of the UN 2030 Agenda, particularly with SDG#12 (responsible consumption and production — ensuring sustainable consumption and production patterns). The integration of new social and environmental demands with the company's standard, in alignment with neoclassical economic theory (Skowronek et al., 2015, Stawasz, 2016; Winkowska et al., 2019), necessitates the protection of ecosystems and individuals, as well as the assurance of social equity (Stubbs et al., 2008, Walicka et al., 2015, Czemiel-Grzybowska, 2022).

Subjects of smart cities that heavily rely on information and communication technologies have been realised in various countries (Alifi & Supangkat, 2016; Yamakami, 2017; Szpilko et al., 2023; Baali et al., 2022). AI continues to revolutionise management, energy generation, and consumption within smart cities, underscoring its far-reaching implications for entrepreneurship development (Muhammad et al., 2019; Pramod et al., 2023).

1.1. Research gaps

The systematic literature review identified research gaps regarding the nexus of sustainable technological entrepreneurship and AI for the years 2000–2023. The following thematic groups were addressed in publications and research gaps in the context of linking AI with sustainable development of technological entrepreneurship (Table 2).

Results presented in this article on Artificial Intelligence-based Decision Support Systems in urban resource management were selected for scientific research from the identified research gaps (Czemiel-Grzybowska, 2023). The topic was analysed in detail: the use of artificial intelligence to mitigate urban problems, especially air pollution, waste management, and sewage treatment. The analysis was conducted of the activities of waste incineration plants in the context of achieving SDG#11 goals (Sustainable Cities and Communities) and SDG#12 (Responsible Consumption and Production).

The aim was to address the literature gap by responding to the following research questions:

(1) What are the areas of AI application in municipal waste incinerators within the context of sustainable development of smart cities?

(2) What are the trends in activities of waste incineration plants using AI for sustainable development in smart cities, particularly in achieving SDGs, especially goals SDG#11 (Sustainable Cities and

Tab. 2. Research gaps in the field of AI and technological entrepreneurship

Common thematic areas of articles	Issues addressed within the areas	Identified research gaps in individual publication topics
1. Sustainable consumption	• sustainable construction, • water management systems with AI • agriculture 4.0, • sustainable energy sources, • the convergence of the Internet of Things and artificial intelligence in urban resource management, • evaluation of renewable energy technologies, • smart campuses, • energy optimisation	Ad.1. The use of artificial intelligence technology to make buildings more ecological and to increase the sense of responsibility among their inhabitants towards sustainable development
2. Artificial Intelligence-based Decision Support Systems in urban resource management		Ad.2. The use of artificial intelligence to mitigate urban problems, especially air pollution, waste management, and sewage treatment
3. Forecasting models		Ad.3.1. The use of artificial intelligence in transportation in the context of traffic forecasts or public transport planning
4. Economic and process issues		Ad.3.2. Analysis of the relationships between climate change and artificial intelligence in the aspect of the emergence of the field of "climate informatics"
5. Automated systems		Ad.3.3. The use of artificial intelligence in transportation in the context of traffic forecasting or public transport planning
6. Convergence with digital technology		Ad.4. The impact of artificial intelligence and other ecological technologies on the working conditions of farmers and farm operators
		Ad.5. Challenges faced by artificial intelligence algorithms and models in assessing renewable energy solutions
		Ad. 6. The potential of artificial intelligence for practical learning and training for various stakeholders, including farmers, residents, and employees

Source: elaborated by the author based on Czemiel-Grzybowska (2023, p. 126).

Communities) and SDG#12 (Responsible Consumption and Production), involve integrating AI to enhance efficiency and sustainability.

2. Research methods

In selecting the research methodology, the aim was not solely to adhere to scientific rigour but also to identify an optimal approach that ensures an objective, rational, organised, systematic, and structured scientific process (Campbell, 1966). Consequently, a triangulation of research methods was chosen to achieve the most reliable research outcomes. The case study was a selected qualitative method. Although this approach is characterised by strict requirements, it allows for considerable flexibility. Patton (1985) highlights that the strength of such a method lies in its ability to grasp the uniqueness of the situation, the nature of the specific phenomenon, its context, and its interactions with other elements rather than in attempting to predict future occurrences. Similarly, Yin (2009) advocates for the use of the case study method to gain a profound understanding of the phenomenon under investigation. Compared to other research methods, the case study provides the richest array of techniques and tools for data collection. Among the available techniques, two were selected: Computer-Assisted Web Interviewing (CAWI) and in-depth interviews, which were employed to gather the necessary data.

The research was conducted using the CAWI method. This quantitative research method allows for the administration of a prepared survey. The information from the survey was then supplemented with data from direct interviews. The sample was selected by including all municipal incinerators in operation as of January 15, 2024. In the first stage, surveys were sent out for completion. In the second stage, based on the survey results, in-depth interviews were conducted. The research model is presented in Fig. 1.

The research sample comprised all nine municipal waste incineration plants located in Poland at the time of conducting the survey. The survey included a metric identifying the municipal waste incineration plant in terms of location, processing capacity (size), thermal power, and electrical power (Table 3).

The survey questionnaire was sent to respondents via email. Based on the responses received from the survey, follow-up questions were prepared for the in-depth interview. The questionnaire consisted of an introduction outlining the purpose of the study, 20 survey questions, including some open-ended ques-

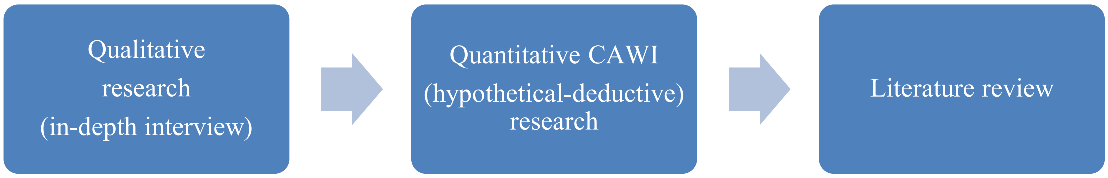

Fig. 1. Model research

Tab. 3. Research sample

Waste incineration plant and the year of commissioning	Estimated processing capacities (Mg/r.)	Percentage share in the total processing capacities	Thermal capacity (MWt)	Electric power (MWe)
Warsaw waste incineration plant (2001)	40 000	3.0	9.1	1.4
Konin waste incineration plant (2015)	94 000	7.0	15.5	4.4
Białystok waste incineration plant	120 000	9.0	17.5	6.1
Bydgoszcz waste incineration plant	180 000	14.0	14.0	14.0
Krakow waste incineration plant	220 000	16.0	27.7	9.2
Poznan waste incineration plant	210 000	15.0	34.0	15.0
Szczecin waste incineration plant	150 000	11.0	32.0	9.4
Rzeszow waste incineration plant	100 000	7.0	16.5	4.6
Zabrze waste incineration plant	250 000	18.0	bd	bd
ALL	1 364 000	100	x	x

tions, and a conclusion with a demographic section. The survey was directed at the management of the incineration plants. The goal of the survey technique was to gather comparative data on the performance of each incineration plant in terms of processing capacity, primary data for each plant, insights into absorption capacity for new technologies, operational challenges and limitations in the field, and competitive advantages. The purpose of the in-depth interview technique was to identify development conditions specific to each entity, determine the level of maturity, and assess growth prospects based on new technologies.

Approximately 450 waste incineration plants are operational across Europe. Poland currently has 157 facilities for the mechanical-biological treatment of municipal waste, including nine municipal waste incineration plants. In 2021, the utilised processing capacities for municipal waste in Poland remained at the same level as in 2020, which was 45 %. Municipal waste incineration plants, as in 2020, did not utilise their permitted capacities. The amount of municipal waste approved for thermal treatment in decisions accounted for about 19 % of the produced municipal waste. Municipal waste incineration plants in 2021 only converted a mere 8 % of the produced municipal waste. Countries advanced in ecology and health protection, such as Germany, the Netherlands, and the Scandinavian countries, have been utilising thermal waste disposal for years. Polish waste incineration plants dispose of municipal waste, i.e., household-originated waste. Currently, efforts are made to ensure that only non-recyclable and non-segregable waste is sent to incinerators. This approach prevents the destruction of recoverable materials, allowing their reuse. Additionally, incineration plants provide a safe method for disposing of solid waste from sewage treatment facilities. Table 3 presents the characteristics of the research sample, which includes all municipal incineration plants in Poland.

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3. Research results

The proliferation of sustainable development of smart cities involves the harmonisation of all three dimensions (economic, environmental, and social), which are "indissolubly connected and interdependent". Numerous scholars have demonstrated that the outcomes of SDGs are contingent upon the interactions among human, technical, and natural systems. It is crucial to ascertain whether and how the introduction of AI contributes to the SDGs.

All municipal incineration plants are making efforts to automate and forecast their flows and processes (Fig. 2). However, particularly sensitive processes are being forecasted using artificial intelligence. In the in-depth interviews, four out of nine respondents indicated that improvements to the system could be achieved by the AI application designed to identify proximity to the temperature of 1100°C, which is critical for waste containing over 1 % chlorinated organic compounds calculated as chlorine. One of the incineration plants stated, "this is a critical value for us". Subsequently, five out of nine respondents highlighted improvements through the AI application that identifies the approach to the temperature level of 850°C, which is crucial for wastes containing less than 1 % chlorinated organic compounds, calculated as chlorine (threshold level).

However, only two out of the nine respondents pointed to the use of AI application as a significant factor in improving processes that detects the dwell time of flue gases in the chamber — the minimum combustion time is two seconds at an oxygen content of at least 6 % (threshold level).

In the in-depth interviews, respondents highlighted both current and future possibilities for the application of AI in municipal incineration plants, aimed at optimising operations and achieving Sustainable Development Goals (SDGs). The proposals were systematically categorised into three heuristic categories. Respondent 1 stated, "The use of AI in data management: secure cloud storage with the capability of automatic sharing with stakeholders (regulatory bodies) — this facilitates bringing data control closer to the data entry point, as well as storage in a distributed ledger that enhances the activation of smart contracts (data control contracts)". Respondent 2 noted, "The use of AI in data tokenisation allows for the registration, storage, sharing, and transfer of digital assets using blockchain technology. Through tokenisation, it is possible to track the status of intangible objects and smart contracts, enabling the monitoring and comparison of data flows in real-time". Respondent 3 highlighted the future application of AI in "the reorganisation of inter-organisational work processes through smart contracts, aimed at reducing coordination efforts". This includes automating the elimination of unnecessary (unused) tasks by employing intelligent process variants, followed by optimising the sequence or parallel execution of tasks carried out by smart contracts. Respondent 4 emphasised the importance of AI in managing a portfolio of processes, stating that "strategic alignment is essential to connect data management processes with process management and the BPM platform". Respondent 5 indicated that "AI enables the future automation of monitoring activities on the BPM platform, starting from the control of quantity and quality parameters of individual incoming transports, through segregation, incineration, and the removal of sold recoverable materials (plastic, glass, metals), including energy. Respondent 6 pointed out that "AI will accelerate the elimination and remediation of inefficiencies and bottlenecks, and through innovative exploitation, it will identify areas for performance improvement as well as competency gaps". Respondent 7 observed that "the use of AI enables the identification of informational gaps in processes, supplementing previously 'fragmentary' data with comprehensive information by redesigning the flow of information". Respondent 8 highlighted "the demand for process risk analysis using AI, particularly in areas involving sensitive data subject to stakeholder scrutiny. The expectation in this domain is for automatic updates of risk factors". The final respondent, Respondent 9, indicated that "automated sorting — AI-driven robotics can

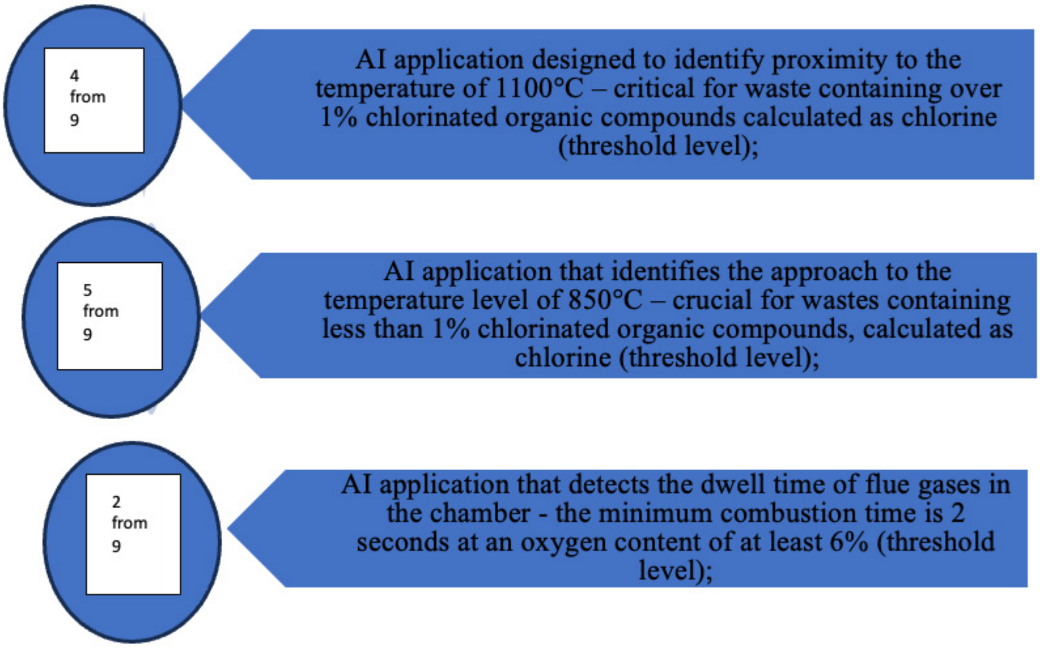

Fig. 2. AI applications in all municipal waste incineration plants

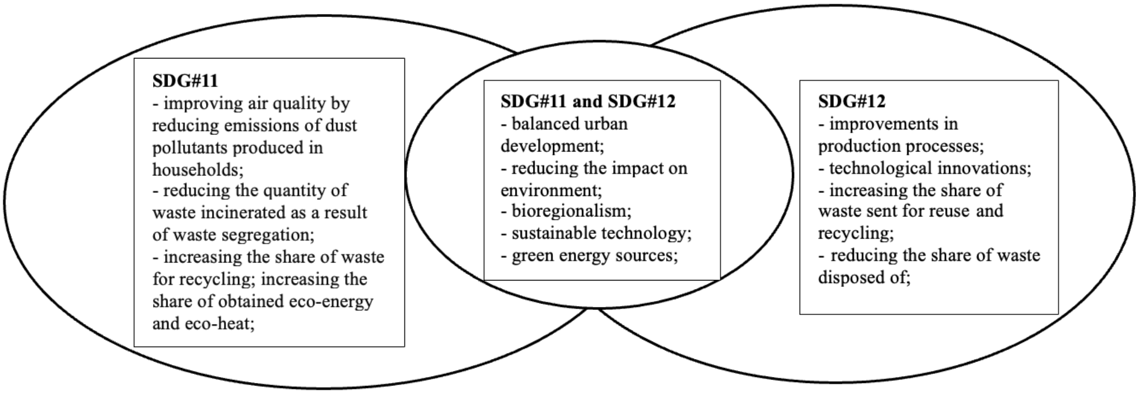

Fig. 3. What is the effect of using AI in municipal waste incineration plants for SDG#11 and SDG#12?

improve the efficiency of waste sorting before incineration, ensuring that recyclable materials are separated, thereby reducing the volume of waste that needs to be incinerated. Data Analytics with analysing waste composition data using AI can help in better understanding waste generation patterns, leading to more effective waste management strategies". Every respondent pointed out that incorporating AI in incineration plants offers a pathway to significantly improve operational efficiency, reduce environmental impact, and enhance the overall sustainability of waste management processes, thereby supporting multiple SDGs simultaneously.

Areas of AI application in municipal waste incinerators within the context of sustainable development of smart cities can include optimisation of combustion processes: AI can analyse data related to the composition of waste and combustion conditions to optimise combustion processes, reducing the emission of harmful substances and increasing energy efficiency (Fig. 3, based on the surveys and in-depth interviews). In the framework, waste management like AI systems can assist in sorting waste and deciding on the best methods for its processing, increasing the recovery of recyclable materials and minimising the amount of waste directed to incineration.

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Another area where AI is used can include maintenance and diagnostics. AI can support maintenance programs by predicting failures and assisting in diagnosing problems, increasing the reliability and operational efficiency of incinerators. One important aspect of AI use in waste incinerators is integration with urban systems. AI can aid in the integration of incinerators with other urban systems, such as energy management, waste transportation, and urban infrastructure, promoting a holistic approach to city management. The use of AI in these areas can contribute to more sustainable and efficient waste management in smart cities while minimising the environmental impact.

In municipal waste incineration plants, AI neutralises risks by optimising thermal processes to minimise the formation of dioxins and furans, employing predictive maintenance to prevent equipment failures, and refining emission control systems to enhance the capture and neutralisation of hazardous pollutants like mercury and nitrogen oxides, thereby ensuring compliance with stringent environmental regulations and contributing to public health and safety.

The trends in sustainable development activities of smart cities using AI involve various strategies and practices, especially in the context of achieving SDG#11 (Sustainable Cities and Communities) and SDG#12 (Responsible Consumption and Production). Key areas of focus include the development of frameworks for assessing city sustainability, which, although predating the SDGs, align with common sustainability principles. However, challenges remain in integrating and implementing coherent, city-specific values, principles, goals, and solutions that encompass not only infrastructure, housing, mobility, and technology but also social well-being in urban contexts. The interconnectedness of social and environmental sustainability is strongly emphasised, recognising that the majority of actions leading to global challenges, such as climate change and loss of biodiversity, originate in cities. Therefore, the achievement of the SDGs will largely be determined by actions taken within cities, necessitating locally relevant, applied, and quantitative methodologies to monitor progress toward sustainability both locally and globally. SDG#11 (Sustainable Cities and Communities) highlights the critical link between the quality of life in cities and the management of natural resources. The trend towards urbanisation brings increased pressure on the environment and a higher demand for basic services, making cities particularly vulnerable to the impacts of climate change and natural disasters. Building urban resilience and making cities resource-efficient is essential for mitigating these risks and ensuring sustainability. This includes providing access to safe and sustainable transport systems, enhancing inclusive and sustainable urbanisation, and reducing the adverse per capita environmental impact of cities.

AI can be utilised in municipal waste incineration plants in areas such as optimising furnace designs for better combustion efficiency, improving air-injection systems for complete combustion, and enhancing flue-gas recirculation to reduce emissions. AI can also support the control of auxiliary burners to maintain optimal furnace temperatures and assist in advanced air-pollution control techniques for removing particulates, acid gases, dioxins, and mercury.

Managers added that municipal waste incineration plants should employ AI applications in advanced predictive analytics for pre-emptive maintenance scheduling, thermodynamic modelling for optimising combustion efficiency, spectroscopic analysis for real-time emission monitoring, machine learning algorithms for adaptive control of incineration parameters, and robotic sorting systems integrated with computer vision for enhanced waste segregation, thereby improving operational efficiency, reducing environmental impact, and ensuring compliance with stringent environmental standards.

These initiatives focus on improving waste management processes, reducing emissions, and contributing to cleaner urban environments, which are in line with the broader objectives of sustainable development and smart city infrastructure optimisation. For more detailed insights, it would be beneficial to refer to specific studies or reports in this field.

4. Discussion of the results

The volume of municipal waste generated in Poland is increasing annually. The high-calorie fraction of the waste constitutes approximately 22 % of the total mass of municipal waste. This source of heat can locally lead to reduced heating prices or supply, for example, the tram network of a large metropolis. Incineration plants can locally reduce heating prices and be competitive with coal (Serban et al., 2020).

Waste incineration is inherently associated with the generation of by-products, namely slag and ashes, produced in the flue gas cleaning process. However, all Polish incineration plants are equipped with facilities to neutralise ashes and slag. This involves adding specific chemical compounds designed to neutralise the effects of incineration by-products.

In the course of these in-depth interviews, incineration plant managers highlighted various waste management approaches optimised through the application of AI technology (Ullach et al., 2020; Singh et al., 2020; Rani et al., 2021). These approaches include storage, use in construction, or filling in mining excavations. All managers reported that municipal waste incineration plants are fully ecological tools that complement recycling efforts (Park et al., 2020; Ragab et al., 2023). Unlike landfills, a municipal waste incineration plant neutralises waste without emitting toxic fumes, halting the release of foul odours and preventing groundwater contamination. In doing so, it aligns with the objectives outlined in SDG#11 (Sustainable Cities and Communities) and SDG#12 (Responsible Consumption and Production).

Polish municipal waste incineration plants are generating increasingly higher levels of electrical and thermal energy production year after year. The incineration process occurs at a temperature of 1100 degrees Celsius, releasing substantial amounts of heat that facilitate the production of electricity, heat, and steam. The energy derived from waste is primarily used for the plant's own needs, but an increasing proportion is sold to the public grid (Navarro-Espinoza et al., 2022; Lopez-Blanco et al., 2023). The revenue from energy significantly accelerates the payback of the incineration plant's initial costs and subsequently allows for the generation of increasing profits from operations (Muhammad et al., 2019; Ma et al., 2020). Managers emphasised that municipal waste incineration plants are a much better and more ecological alternative to landfills, which not only fail to resolve the waste problem but also pose serious threats to the environment and human health (Kamel et al., 2019; Golinska-Dawson et al., 2023).

The identified trends underscore the importance of adopting and implementing integrated policies and plans that address inclusion, resource efficiency, climate change mitigation and adaptation, and resilience to disasters (Ortega-Fernandez et al., 2020; O'Dwyer et al., 2019). The focus on Polish cities in achieving the SDGs reflects the critical role they play in the global sustainability agenda, emphasising the need for innovative approaches to urban planning and management that prioritise both environmental and social sustainability (Cubric, 2020). Decision support tools for the sustainable development of smart cities are increasingly utilising AI to optimise these processes and ensure higher living standards for the inhabitants of Polish smart cities (Chui et al., 2018; Paiva et al., 2021).

Conclusions

The article discussed the role of AI in enhancing the efficiency and sustainability of municipal waste incinerators within smart cities, contributing to the achievement of SDG#11 and SDG#12. The research emphasises the potential of AI in optimising waste management processes, thereby reducing emissions and improving energy recovery, which in turn supports more sustainable urban environments. The use of AI in municipal waste incineration plants contributes to SDG#11 (Sustainable Cities and Communities) by optimising waste management, thus improving urban environmental quality and public health. By enhancing combustion efficiency and emission controls, AI supports cleaner air and less environmental pollution. For SDG#12 (Responsible Consumption and Production), AI helps in achieving more efficient waste-to-energy conversion, reducing landfill usage, and promoting recycling and sustainable waste management practices, aligning with the goal of sustainable management and efficient use of natural resources.

For further research, it is recommended to explore more integrated AI applications across different waste management processes, assess the longterm impacts of AI-enhanced waste incineration on urban sustainability, and investigate the scalability of these technologies in diverse urban settings. Additionally, studies could focus on the socio-economic implications of adopting AI in waste management, including job creation, public acceptance, and policy frameworks to support technological integration.

Trends in waste incineration plants utilising AI for sustainable development in smart cities, particularly for achieving SDG#11 and SDG#12, focus on leveraging AI to enhance environmental outcomes.

Literature

Bibri, S. E. (2021). A novel model for data-driven smart sustainable cities of the future: The institutional transformations required for balancing and advancing the three goals of sustainability. *Energy Informatics, 4,* 5737. doi: 10.1186/s42162-021-00138-8

Campbell, D., & Stanley, J. (2000). Experimental and quasi-experimental designs for research. *Rand McNally, Chicago,* 196-217. doi: 10.1007/978-1-4615-1401-5_11

Chen, C., Hu, Y., Marimuthu, K., & Kumar, P. M. (2021). Artificial intelligence on economic evaluation of energy efficiency and renewable energy technologies. *Sustainable Energy Technologies and Assessments, 47*(3), 101358. doi: 10.1016/j.seta.2021.101358

Chui, K. T., Lytras, M. D., & Visvizi, A. (2018). Energy sustainability in smart cities: Artificial intelligence, smart monitoring, and optimization of energy consumption. *Energies, 11*(11), 2869. doi: 10.3390/en11112869

Cubric, M. (2020). Drivers, barriers, and social considerations for AI adoption in business and management: A tertiary study. *Technology in Society, 62.* doi: 10.1016/j.techsoc.2020.101257

Czemiel-Grzybowska, W. (2022). Conceptualization and mapping of predictors of technological entrepreneurship growth in a changing economic environment (COVID-19) from the Polish energy sector. *Energies, 15*(18), 6543. doi: 10.3390/en15186543

Czemiel-Grzybowska, W. (2023). Trendy rozwoju zrównoważonej przedsiębiorczości technologicznej opartej na sztucznej inteligencji. *Akademia Zarządzania, 7*(4), 126-137. doi: 10.24427/az-2023-0059

Ertel, W., & Black, N. T. (2018). Introduction to artificial intelligence. *Springer International Publishing,* 1-11. doi: 10.1007/978-3-319-58487-4

Garbuio, M., & Lin, N. (2019). Artificial intelligence as a growth engine for healthcare startups: Emerging business models. *California Business Review, 61*(2), 59-83. doi: 10.1177/0008125618811931

Golinska-Dawson, P., & Sethanan, K. (2023). Sustainable urban freight for energy-efficient smart cities—Systematic literature review. *Energies, 16*(6), 2617. doi: 10.3390/en16062617

Govindan, K., & Shaw, M. (2021). Social sustainability tensions in multi-tier supply chain: A systematic literature review towards conceptual framework development. *Journal of Cleaner Production, 279*(1-2), 123075. doi: 10.1016/j.jclepro.2020.123075

Gupta, B. B., Gaurav, A., Panigrahi, P. K., & Arya, V. (2023). Analysis of artificial intelligence-based technologies and approaches on sustainable entrepreneurship. *Technological Forecasting & Social Change, 186*(2), 122152. doi: 10.1016/j.techfore.2022.122152

Jha, S. K., Bilalovic, J., Jha, A., Patel, N., & Zhang, H. (2017). Renewable energy: Present research and future scope of artificial intelligence. *Renewable and Sustainable Energy Reviews, 77,* 297-317. doi: 10.1016/j.rser.2017.04.018

Kamel Boulos, M. N., Peng, G., & Vopham, T. (2019). An overview of GeoAI applications in health and healthcare. *International Journal of Health Geographics, 18*(7). doi: 10.1186/s12942-019-0171-2

Lazaroiu, G., Androniceanu, A., Grecu, I., Grecu, G., & Neguriță, O. (2022). Artificial intelligence-based decision-making algorithms, Internet of Things sensing networks, and sustainable cyber-physical management systems in big data-driven cognitive manufacturing. *Oeconomia Copernicana*, *13*(4), 1047-1080. doi: 10.24136/oc.2022.030

López-Blanco, R., Martín, J. H., Alonso, R. S., & Prieto, J. (2023). Time series forecasting for improving quality of life and ecosystem services in smart cities. *Lecture Notes in Networks and Systems, 603,* 74-85. doi: 10.1007/978-3-031-22356-3_8

Ma, Y., Ping, K., Wu, C., Chen, L., Shi, H., & Chong, D. (2020). Artificial intelligence-powered Internet of Things and smart public service. *Library Hi Tech, 38*(1), 165-179. doi: 10.1108/LHT-12-2017-0274

McCarthy, J., Minsky, M. L., Rochester, N., & Shannon, C. E. (2006). A proposal for the Dartmouth Summer Research Project on Artificial Intelligence. *AI Magazine, 27*(4). doi: 10.1609/aimag.v27i4.1904

Mikalef, P., & Pateli, A. (2017). Information technology-enabled dynamic capabilities and their indirect effect on competitive performance: Findings from PLS-SEM and fsQCA. *Journal of Business Research, 70,* 1-16. doi: 10.1016/j.jbusres.2016.09.004

Moravec, V., Hynek, N., Gavurova, B., & Kubak, M. (2024). Everyday artificial intelligence unveiled: Societal awareness of technological transformation. *Oeconomia Copernicana*, *15*(2), 367-406. doi: 10.24136/oc.2961

Muhammad, K., Lloret, J., & Baik, S. W. (2019). Intelligent and energy-efficient data prioritization in green smart cities: Current challenges and future directions. *IEEE Communications Magazine, 57*(2), 60-65. doi: 10.1109/MCOM.2018.1800371

Navarro-Espinoza, A., López-Bonilla, O. R., García-Guerrero, E. E., Tlelo-Cuautle, E., López-Mancilla, D., Hernández-Mejía, C., & Inzunza-González, E. (2022). Traffic flow prediction for smart traffic lights using machine learning algorithms. *Technologies, 10*(1). doi: 10.3390/technologies10010005

O'Dwyer, E., Pan, I., Acha, S., & Shah, N. (2019). Smart energy systems for sustainable smart cities: Current developments, trends, and future directions. *Applied Energy, 237,* 581-597. doi: 10.1016/j.apenergy.2019.01.024

Ortega-Fernández, A., Martín-Rojas, R., & García-Morales, V. J. (2020). Artificial intelligence in the urban environment: Smart cities as models for developing innovation and sustainability. *Sustainability, 12*(19), 7860. doi: 10.3390/su12197860

Pacelli, V. (2012). Forecasting exchange rates: A comparative analysis. *International Journal of Business and Social Science, 3*(10), 31-45. doi: 10.12846/j.em.2015.02.06

Paiva, S., Ahad, M. A., Tripathi, G., Feroz, N., & Casalino, G. (2021). Enabling technologies for urban smart mobility: Recent trends, opportunities, and challenges. *Sensors, 21*(6), 1-45. doi: 10.3390/s21062143

Park, S., Choi, M. I., Lee, S., Lee, T., Kim, S., Cho, K., & Park, S. (2020). Reinforcement learning-based BEMS architecture for energy usage optimization. *Sensors, 20*(17), 4918. doi: 10.3390/s20174918

Patton, M. (1985). Quality in qualitative research: Methodological principles and recent developments. *Journal of the American Educational Research Association, Chicago.*

Ragab, A., Osama, A., & Ramzy, A. (2023). Simulation of the environmental impact of industries in smart cities. *Ain Shams Engineering Journal, 14*(6), 102103. doi: 10.1016/j.asej.2022.102103

Rani, S., Mishra, R. K., Usman, M., Kataria, A., Kumar, P., Bhambri, P., & Mishra, A. K. (2021). Amalgamation of advanced technologies for sustainable development of smart city environment: A review. *IEEE Access, 9,* 150060-150087. doi: 10.1109/ACCESS.2021.3125527

Serban, A. C., & Lytras, M. D. (2020). Artificial intelligence for smart renewable energy sector in Europe—Smart energy infrastructures for next-generation smart cities. *IEEE Access, 8,* 77364-77377. doi: 10.1109/ACCESS.2020.2990123

Sievers, F., Reil, H., Rimbeck, M., Stumpf-Wollersheim, J., & Leyer, M. (2021). Empowering employees in industrial organizations with IoT in their daily operations. *Computers in Industry, 129,* 103445. doi: 10.1016/j.compind.2021.103445

Singh, S., Sharma, P. K., Yoon, B., Shojafar, M., Cho, G. H., & Ra, I.-H. (2020). Convergence of blockchain and artificial intelligence in IoT network for the sustainable smart city. *Sustainable Cities and Society, 63,* 102364. doi: 10.1016/j.scs.2020.102364

Skowronek-Mielczarek, A., & Czemiel-Grzybowska, W. (2015). Entrepreneurship research in Poland. *Technological and Economic Development of Economy, 23*(3), 504-519. doi: 10.3846/20294913.2015.1070770

Sousa, M. J., & Rocha, A. (2018). Digital learning: Developing skills for digital transformation of organizations. *Future Computer Systems, 91(February),* 327-334. doi: 10.1016/j.future.2018.08.048

Stawasz, D., & Sikora-Fernandez, D. (2016). Koncepcja smart city na tle procesów i uwarunkowań rozwoju współczesnych miast. *Łódź, Poland: Wydawnictwo Uniwersytetu Łódzkiego.*

Stone, P., Brooks, R., Brynjolfsson, E., Calo, R., Etzioni, O., & Hager, G. et al. (2016). Artificial intelligence and life in 2030. *One Hundred Year Study on Artificial Intelligence: Report of the 2015–2016 Study Panel.* Stanford University. Retrieved from http://ai100.stanford.edu/2016-report

Subotić, V., Eibl, M., & Hochenauer, C. (2021). Artificial intelligence for time-efficient prediction and optimization of solid oxide fuel cell performances. *Energy Conversion and Management, 230,* 113764. doi: 10.1016/j.enconman.2020.113764

Šulyová, D., & Kubina, M. (2022). Quality of life in the concept of strategic management for Smart Cities. *Forum Scientiae Oeconomia*, *10*(3), 9-24. doi: 10.23762/FSO_VOL10_NO3_1

Szpilko, D., Jiménez-Naharro, F., Lăzăroiu, G., Nica, E., & Torre Gallegos, A. d. l. (2023). Artificial intelligence in the smart city — a literature review. *Engineering Management in Production and Services*, *15*(4), 53-75. doi: 10.2478/emj-2023-0028

Szpilko, D., Szydło, J., & Winkowska, J. (2020). Social Participation of City Inhabitants Versus Their Future Orientation. Evidence From Poland. *WSEAS Transactions on Business and Economics*, *17*, 692-702. doi: 10.37394/23207.2020.17.67

Taddy, M. (2018). The technological elements of artificial intelligence. *The Economics of Artificial Intelligence: An Agenda, National Bureau of Economic Research,* 61-87. Retrieved from https://ideas.repec.org/h/nbr/nberch/14021.html

Ullah, Z., Al-Turjman, F., Mostarda, L., & Gagliardi, R. (2020). Applications of artificial intelligence and machine learning in smart cities. *Computer Communications, 154,* 313-323. doi: 10.1016/j.comcom.2020.02.069

United Nations' 2030 Agenda. Retrieved from https://sdgs.un.org/2030agenda

Vinuesa, R., Azizpour, H., Leite, I., Balaam, M., Dignum, V., Domisch, S., Fellader, A., Langhans, S. D., Tegmark, M., & Nerini, F. F. (2020). The role of artificial intelligence in achieving the Sustainable Development Goals. *Nature Communications, 11*(1), 233. doi: 10.1038/s41467-019-14108-y

Walicka, M., & Czemiel-Grzybowska, W. (2015). Technology entrepreneurship – State of the art and future challenges. *European Journal of Social Sciences, 3*(4), 10-21. doi: 10.15604/ejss.2015.03.04.002

Wang, K., Zhao, Y. F., Gangadhari, R. K., & Li, Z. X. (2021). Analyzing the adoption challenges of the Internet of Things (IoT) and artificial intelligence (AI) for smart cities in China. *Sustainability, 13*(19). doi: 10.3390/su131910983

Winkowska, J., Szpilko, D., & Pejić, S. (2019). Smart city concept in the light of the literature review. *Engineering Management in Production and Services, 11*(2), 70-86. doi: 10.2478/emj-2019-0012

Wirtz, B. W., Weyerer, J. C., & Geyer, C. (2019). Artificial intelligence and the public sector – Applications and challenges. *International Journal of Public Administration, 42*(7), 596-615. doi: 10.1080/01900692.2018.1498103

Wu, Z., & Chu, W. (2021). Sampling strategy analysis of machine learning models for energy consumption prediction. *2021 9th IEEE International Conference on Smart Energy Grid Engineering (SEGE 2021),* 77-81. doi: 10.1109/SEGE52446.2021.9534987

Wynsberghe, A. (2021). Sustainable AI: AI for sustainability and the sustainability of AI. *AI and Ethics, 1*(4). doi: 10.1007/s43681-021-00043-6

Yigitcanlar, T., Desouza, K. C., Butler, L., & Roozkhosh, F. (2020). Contributions and risks of artificial intelligence (AI) in building smarter cities: Insights from a systematic review of the literature. *Energies, 13*(6). doi: 10.3390/en13061473

Yin, R. (2009). *Case study research: Design and methods.* Thousand Oaks: Sage.