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The Convergence of Artificial Intelligence, Machine Learning, and New Technologies in Agricultural Waste Valorization Systems

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Abstract

Background and Objectives: The shift towards circular economic models renders new technologies for waste valorization highly competitive as waste streams are turned into resources. In this mini review, we discuss the recent advances in technologies such as artificial intelligence (AI)-based waste management, advanced thermochemical conversion processes, biotechnological approaches, and integrated waste-to-resource platforms.

Results and Conclusions: Recent results in the application of AI for sorting technologies report classification accuracies greater than 95% for different mixed waste streams; thermochemical processes such as pyrolysis and gasification report conversion efficiencies of 70-85% for plastic and organic waste streams; biotechnological approaches such as engineered microorganisms and enzyme systems show promising advancements for converting different complex waste streams into high-value chemicals and fuels. The combination of these technologies into circular economy models provides numerous opportunities for achieving the 2030 sustainable development goals by turning waste streams, which could be treated as disposal costs, into economic value.

What is already known about this topic:	• Low efficiency and high cost of conventional waste management systems; poor scalability of mechanical sorting (<70% accuracy) to handle tons of municipal solid waste in 2050 will be problematic. • Basic thermochemical processes (pyrolysis and gasification), conversion of waste; challenges in energy efficiency, product quality control, and handling of various waste streams for these processes exist. • Biotechnological processing can help for waste handling; however, limited accuracy and yield optimization hinder the commercialization of these approaches
What this article adds:	• Machine learning enabled waste sorting with >95% classification accuracy using convolutional neural networks, compared to 60-70% for mechanical sorting by humans. • Thermochemical conversion process conversion efficiencies for plastic and organic streams ranging from 70-85% using advanced pyrolysis and gasification processes. •

1. Introduction

Waste production has reached unprecedented levels worldwide. Annual generation is about 2.01 billion tons of municipal solid waste, but is expected to reach 3.4 billion by 2050 [1]. Such explosive growth, together with cons-umers' increasing environmental awareness and the decreasing availability of natural resources, has led to the development of new technologies to valorize waste material into products, energy, and resources [2]. The potential of waste streams for valorization has been particularly highlighted concerning the goals of the circular economy, that is, to decouple economic growth from the use of materials by maintaining them in use for longer periods [3]. Unlike traditional waste disposal technologies, valorization technologies use various conversion processes such as mechanical separation, thermochemical processing, and biochemical process-ing to derive the highest value possible from waste streams [4].

New technologies, over the last few years, have allowed a greater scale and more permanence in valorization. Recent innovations in artificial intelligence (AI) and machine learning have enabled the automatic sorting of waste with a high degree of accuracy. New thermochemical and biological technologies can transform many waste streams not commonly recycled mechanically into products of value [5]. This pandemic has also highlighted the importance of advanced waste management systems that handle diverse waste streams in a cost-effective and environmentally-friendly way [6].

2. AI in waste management and valorization

Artificial intelligence evolution is amazing; nowadays, we can see that the models of AI are creative, decision-making, and acting. This is a huge step forward from the simple brute force of symbol manipulation. AI systems developed in the mid-20th century were brute-force attempts to mimic human reasoning by simulating the human mind with the "if then" rules. Due to the lack of computational power, it was a too-simple and limited system [7]. Now there are AI systems with machine learning, deep learning, neural networks, and strong computing systems with agentic capabilities, 20-step tasks. Now the AI is interacting with us on a much deeper level because it can write complex computer programs, fake emotions, and even create art and perform multiple complex tasks. This has changed the paradigm of how we interact with the human computing system, and this has escalated new ethical, legal, and societal issues such as trust, privacy, and right to surveillance and command of the systems [8,9].

One of the most promising emerging AI applications is the use of AI for environmental sustainability. The use of old systems has a lot of problems; for instance, they are inefficient, costly, and non-scalable. Automation of the systems and data processing, all the way to the AI predictive algorithms, can take care of all the previous problems mentioned in this paper; they increase accuracy while decreasing the waste management environmental footprint [10]. Image recognition and robotics, on the contrary, are capable of sorting the waste with feature recognitional accuracies of 72.8-99.95% [11,13]. Manual sorting of waste has long been left behind by the automated sorting systems that not only increase the speed and accuracy of sorting waste but also largely increase the recycling quality by minimizing contaminants. Furthermore, AI systems are integrated with other systems to improve chemical analysis of waste pyrolysis, estimate carbon emissions, and energy recovery from waste streams [11,13]. The use of AI in environmental engineering not only helps optimize processes affecting the people and the environment but also provides information to make decisions affecting the urban waste systems in the fight against climate change across the globe.

2.1. AI-powered waste sorting and classification

AI technology has already transformed the waste sorting process (Figure 1) with computer vision and machine learning algorithms that automatically classify and separate different types of waste [14]. New AI-based sorting systems use convolutional neural networks and deep learning architectures to classify mixed waste streams with accuracies greater than 95% compared to traditional mechanical sorting systems of less than 60-70%. Sorting systems use various sensing modalities such as RGB (Red Green Blue) cameras, near-infrared spectroscopy, and hyperspectral imaging to distinguish different mat-erials based on their spectral properties and physical characteristics [15]. Hyperspectral imaging is espec-ially useful in differentiating similar-looking materials, such as different polymer types of plastics, for high-quality recycling streams. Recently, instance segmen-tation techniques have been applied to these sorting systems to detect and classify objects, even when materials are partially covered or partially occluded.

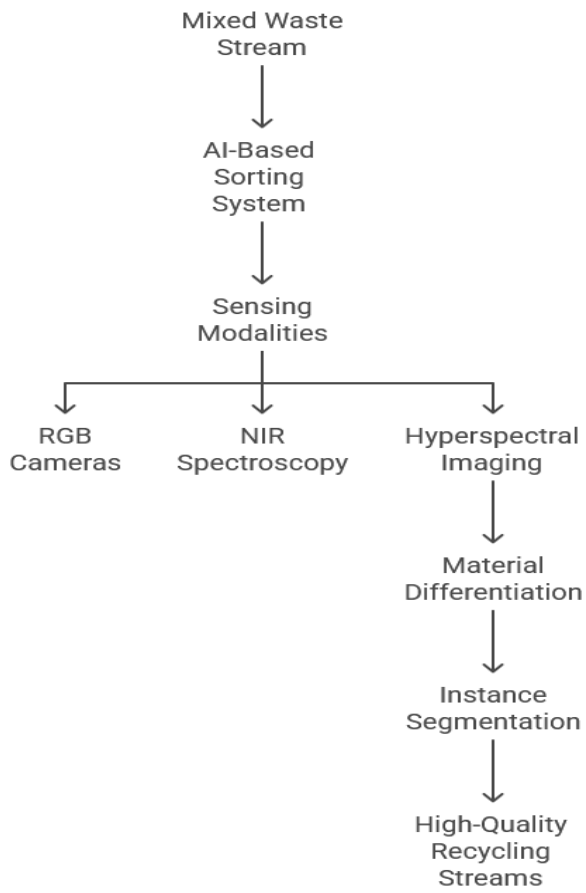


Figure1. AI-based waste sorting process

2.2. Smart waste monitoring and optimization

The Internet of Things (IoT) applications combining AI have allowed for smart waste management systems to optimize collection routes and predict waste generation for each collection point, as well as monitor environmental parameters [16]. These systems use a combination of ultrasonic sensors, load cells, and gas ensors installed in the waste containers to monitor fill levels, composition change events, and safety hazards. Machine Learning models trained on past waste generation data can predict future collection needs with an accuracy of 90% to optimize collection routes and collection points using smart waste management systems that can reduce costs by 15-25% for collection, while having a minimal environmental impact [17]. Predictive analytics models are continuously updated with new data from past and current collection events to take into account seasonality, local events, and demogra-phic changes.

3. Thermochemical conversion technologies

Thermochemical conversion technologies offer a variety of methods to transform waste materials into valuable energy and products. These methods include pyrolysis, torrefaction, gasification and plasma technologies, combustion, and hydrothermal carbonization, each with its advantages and applications.

3.1.Advanced pyrolysis systems and torrefaction

A thermochemical decomposition of organic matter in the absence of oxygen, producing a range of products including bio-oil, biochar, and syngas. Torrefaction is a mild pyrolysis process that produces a solid fuel with higher heating value and lower moisture content than the original biomass. The efficiency of the pyrolysis technology (Figure 2) concerning product yields and quality has been enhanced through advances in reactor designs and optimization strategies for the process [18]. Existing pyrolysis technologies can achieve 60-80% liquid product yields when processing different types of plastic waste, and the products, or "pyrolysis oils," have heating values on par with traditional fossil fuel materials and may be used as feedstocks for chemical treatments or refined for fuel use. The development of plastic waste to desired hydrocarbons via catalytic pyrolysis utilizing zeolite and metal oxide catalysts showed promise while minimizing tar and char by-products [19]. Another emerging technology that was more energy efficient and had better process control due to the ability to more selectively heat certain plastic waste components via microwaves was the selective conversion of mixed plastic waste streams into liquid hydrocarbon fuels via pyrolysis.

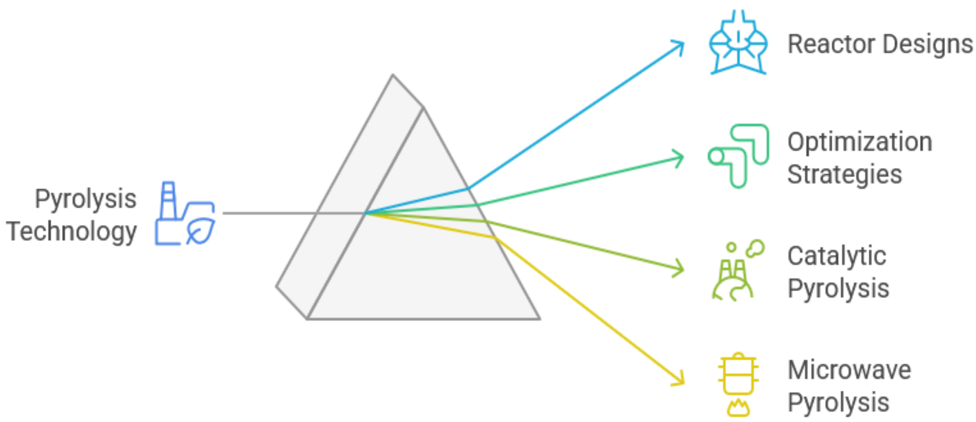


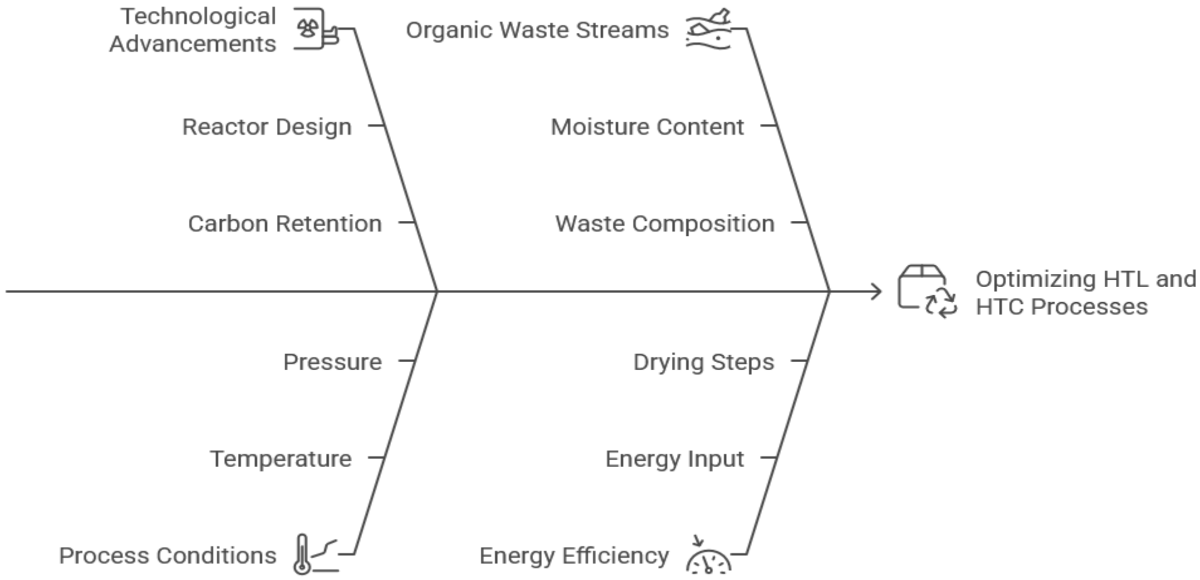
Figure 2. Unveiling pyrolysis technology advancements

3.2. Gasification and plasma technologies

Process-intensified advanced gasification and syngas cleaning technologies have been developed that can convert over 85% of certain waste feedstocks into syngas [20]. Because of operating temperatures over 1000°C, plasma gasification technology could accept virtually any organic waste feedstock and achieve reductions in volume of over 95% with very little tar production and high-quality synthesis gas outputs. An integrated gasification system produced energy and chemical feedstock as a waste biorefinery that could extract the most value from a heterogeneous waste stream [21]. Integrated gasifiers could transform municipal solid waste, agricultural waste, and industrial waste streams into electricity, heat, and chemical feedstocks.

3.3. Hydrothermal processing

The technological advantage of hydrothermal liquefaction (HTL) was the ability to upgrade high-moisture organic waste streams to biocrude oil products without necessitating energy-intensive drying steps [22]. HTL processes on organic waste streams have resulted in biocrude product yields above 50% at temperatures between 250-375°C and pressures between 5-25 MPa, and heating values that are comparable to fuels derived from petroleum. Organic waste streams were transformed into carbon-rich solids known as hydrochar through hydrothermal carbonization processes that show promise for use in energy storage, water treatment, and soil amendment [23]. Hydrothermal carbonization reactors ideal for the processing of different organic waste streams have been developed recently that improve on carbon retention and energy input.



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4. Biotechnological approaches to waste valorization

Biotechnological approaches to waste valorization involve using biological systems, like microorganisms and enzymes, to convert waste materials into valuable products. This process can transform waste into biofuels, biofertilizers, valuable chemicals, and other useful materials, promoting a circular economy and reducing environmental impact.

4.1.Engineered microorganisms and biorefinery concepts

Recent advances in synthetic biology have given rise to engineered microorganisms (Table 1) capable of converting complex waste streams to a variety of high-value biochemicals and fuels [24]. Metabolically engineered bacteria and yeast can produce platform chemicals such as organic acids, alcohols, and amino acids from cellulose and food waste, and even some plastics by converting with close to theoretical yields. This is done in the integrated biorefinery concept, where several biotechnological processes are combined to maximize the recovery of resources from an organic waste stream. These systems can have over 80% overall recovery percentages of resources, as anaerobic digestion facilities to produce biogas are integrated with aerobic fermentation facilities to produce high-value chemicals [25].

4.2. Enzyme waste processing

In a major enzymatic development for the circularity of actual plastics, new enzymes (Table 1) that are capable of degrading plastics have opened up numerous new possibilities for biological plastic waste valorization [26]. Engineered PETases and other polymer-degrading enzymes can hydrolyze polyethylene terephthalate (PET) plastics under mild conditions to monomers, which can then be used to produce higher-quality plastics. This allows the creation of true circular plastics, where waste plastics can be recycled forever without quality degradation. Over 90% sugars from lignocellulosic wastes can be achieved using enzyme cocktails obtained from agricultural residues and paper wastes that can be fermented into biofuels or biochemical [27]. These technologies have enabled the reusability of enzymes and the economics of the processes.

Table 1: Engineered microorganisms, biorefinery concepts, and enzyme waste processing

Topic	Key features	Example outputs	Advantages	Recovery/Yield rates
Engineered microorganisms and biorefinery concepts	-Use of metabolically engineered bacteria and yeast - Conversion of cellulose, food waste, and even some plastics -Integrated biorefinery: combines anaerobic digestion & aerobic fermentation -Production of platform chemicals from waste streams	Organic acids, alcohols, amino acids, biogas, high-value chemicals	-Maximized resource recovery -Efficient waste valorization -High integration and flexibility of processes	Over 80% total resource recovery
Enzyme waste processing	-Advanced enzymes (e.g., PETases) for degrading plastics -Enzyme cocktails for lignocellulosic waste -Mild operating conditions for plastic hydrolysis - Reusability of enzymes	Monomers for plastics, fermentable sugars, biofuels	- Enables circular plastic recycling - High sugar yields from agricultural/paper residues - Enhances sustainability and process economics	Over 90% sugar yields from lignocellulosic waste

5. Integrated systems and process optimization

Integrated systems involving enzymes and microbes offer significant potential for process optimization in various industrial applications. By combining the catalytic power of enzymes with the metabolic capabilities of microorganisms, these systems can achieve higher efficiency, improved product yields, and novel bioprocesses. Process optimization involves fine-tuning parameters like enzyme activity, microbial growth conditions, and substrate utilization to maximize desired outcomes.

5.1. Cascading valorization approaches

Recent waste valorization facilities are more in the fashion of cascading, where several value streams are extracted from one waste feedstock, maximizing economic profits and decreasing or eliminating residues [25]. These facilities use mechanical, chemical, and biological processes in combinations that maintain high-value streams while processing the residuals. With integrated food waste processing facilities, high-value compounds like enzymes and bioactive molecules are harvested first from the material stream; the remaining materials are processed in anaerobic digestion facilities to recover biogas, and the digestate is either composted or hydrothermally processed to become soil amendments [29].

5.2. Digitalization and process automation

Machine learning -based advanced process control systems improve conditions in real-time operation, resulting in improved product yield as well as lower energy use and emissions [30]. Digital Twin technology enables testing of changes to the process in the digital twin plant, leading to lower operational risk and faster technology development cycles. Some use models for predictive maintenance that rely on sensors and machine learning to predict equipment failure and optimal timing of maintenance, and thus reduce downtime [31]. As a result, this leads to a 20-30% increase in equipment lifecycle when compared to conventional maintenance.

6. Economic and environmental implications

The economic feasibility of waste valorization technologies is affected by many interdependent factors (Table 2) (such as feedstock availability and costs, values of products, processing efficiency, and regulations [32]. Life cycle assessments have shown that integrated waste valorization systems can result in overall environmental benefits and economic gains through a combination of products.

Table 2. Key economic and market factors affecting the feasibility of waste valorization technologies

Aspect	Key Points
Main economic factors	-Feedstock availability and costs -roduct values -Processing efficiency - Regulatory environment
Life cycle assessment results	- Integrated systems offer environmental and economic benefits via multiple product outputs
Techno-economic performance	- Achievable internal rate of return (IRR): **>15%** when treating mixed waste streams >100,000 tons/year
Market expansion areas	- Chemical sector: premium pricing for circular materials due to reputation concerns - Fuel sector: importance of environmental credentials
Drivers for economic feasibility	-Combination of multiple product streams - Broader environmental and market recognition
Regulatory impact	- Regulations influence operational costs and market access

Newer techno-economic analyses (TEA) have shown that a waste valorization facility can achieve an internal rate of return of more than 15% on investment when treating a mixed waste stream beyond 100,000 tons per year [33]. The market is expanding for products derived from waste, especially in the chemical sector, where reputation is a concern and a premium price for circular materials is developing, and in the fuel sector, where environmental credentials are becoming increasingly important.

7. Case studies

7.1. Case Study 1: AI-based waste sorting classification in circular waste management.

Several companies and waste sorting systems have been using AI and machine learning to address the challenges associated with traditional sorting and achieve higher levels of classification accuracy and operational efficiency. AI sorting systems with convolutional neural networks and deep learning algorithms have overcome the traditional 60-70% accuracy levels achieved with mechanical sorting, as AI systems have consistently surpassed the 95% benchmark [14,15]. Different types of plastics, metals, organics, and waste have been classified using RGB cameras, near-infrared spectroscopy, and hyper-spectral imaging, which has advanced the improvement in the quality of recycling streams and reduction of the contamination rates. In addition, the efficiency of municipal recycling facilities has improved significantly. Using robotics and real-time data analysis, the systems adapt to the changing compositions of the waste which improves the performance [11,13]. Currently, AI-powered systems are surpassing 95% accuracy in sorting which leads to improvement in recycling quality and efficiency.

7.2. Case Study 2: Hydrothermal liquefaction of agricultural organic waste conversion.

Thermochemical methods for the conversion of organic waste have faced challenges with wet organic waste due to the need for drying, which is an energy-consuming process. However, HTL can directly convert high-moisture-content agricultural waste into biocrude oil at moderate temperature and high pressure. HTL process occurs at a temperature range of 250-375 °C and a pressure range of 5-25 MPa, and can directly convert wet biomass into bio-oil without drying processes [22]. Various high-moisture agri-cultural wastes can be used as feedstock, such as food waste, manure, and lignocellulosic biomass. Biocrude yields from the HTL process have been reported above 50% and have a high calorific value similar to fossil fuels, which makes this process a suitable route towards sustainable biofuel production. Moreover, the greenhouse gas emission from the HTL process is reduced compared to incineration or landfilling, and is suitable for the circular economy [23]. Over 50% biocrude oil obtained from high-moisture content agricultural waste using the HTL process, a suitable method towards sustainable biofuel production [22,23].

8. Challenges and future perspectives.

Despite recent technological progress, there are still several challenges that hinder the commercial deployment of waste valorization technologies (Table 3). High capital costs, the need for robust regulations, and strict specifications of waste feedstock properties hinder the commercial deployment of waste valorization technologies [34]. The integration of multiple technologies requires advanced process control systems, which in turn complicate operations and demand specialized knowledge. Future research will focus on the development of more selective and efficient catalytic systems and the development of biotechnological solutions for waste streams [35]. The integration of renewable energy sources into the waste processing facility is another important area. The application of AI in the future is likely to extend to the full optimization of the supply chain and quality control of the integrated waste valorization network in real time.

Table 3 . Challenges and future direction for waste valorization technologies

Aspect	Current Challenges	Future Directions and Research Focus
Economic	- High capital costs	
regulatory/Feedstock	-Need for robust regulations - Strict waste feedstock specifications	
Technological integration	- Complex integration requires advanced process control and specialized knowledge	- Development of efficient catalytic systems - Biotechnological solutions
Operations	- Complicated operations due to process integration	
Energy		- Integration of renewable energy sources
Digitalization		- Application of AI for supply chain and quality control optimization

9. Conclusions

New technologies for waste valorization are essential to transform waste management and circular economy implementation from a paradigm of environmental and economic concern to one of opportunity. New applications for waste streams using innovative artificial intelligence, thermochemical, biotechnological, and hydrothermal technologies present the potential to convert problem waste streams into products of value, while simultaneously providing environmental and economic sustainability. Artificial intelligence is revolutionizing waste management with the ability to provide automated sorting and optimization technologies that provide orders of magnitude improvements in processing efficiency and product quality. Advances in process conversion efficiencies and product yields for thermochemical and biotechnological conversion technologies are bringing these conversion technologies closer to commercial reality, and recent developments have demonstrated the potential to achieve profitable operations at an industrial scale. The post-pandemic world will require resilient waste management to address varying waste streams and to create economic value. Ongoing research and development in waste valorization technologies will be crucial to achieving sustainability goals and realizing the true circular economic model of extracting a useful product from a waste stream while decoupling economic growth from resource consumption and environmental impact.

10. Declaration of competing interest

The authors report no conflict of interest.

11. Authors' Contributions

Writing-original draft, S.C.Z.D.; conceptualization, S.C.Z.D.; methodology, S.C.Z.D. and B.R.; visualization, S.C.Z.D.; data curation, B.R.; project administration, S.C.Z.D.; writing-review & editing, S.C.Z.D. and B.R; resources, S.C.Z.D. and B.R.

12. Using Artificial Intelligence Chatbots

No artificial intelligence chatbots have been used in any section of work.

References

1. Kaza S, Yao L, Bhada-Tata P, van Woerden F. What a waste 2.0: a global snapshot of solid waste management to 2050: World Bank Publications; 2018.
2. Negrete-Cardoso M, Rosano-Ortega G, Álvarez-Aros EL, Tavera-Cortés ME, Vega-Lebrún CA, Sánchez-Ruíz FJ. Circular economy strategy and waste management: a bibliometric analysis in its

contribution to sustainable development, toward a post-COVID-19 era. Environ Sci Pollut Res Int. 2022;29(41):61729–46. doi:10.1007/s11356-022-18703-3 Cited in: PubMed; PMID 35668274.

3. Moraga G, Huysveld S, Mathieux F, Blengini GA, Alaerts L, van Acker K, Meester S de, Dewulf J. Circular economy indicators: What do they measure? Resour Conserv Recycl. 2019;146452–61. doi:10.1016/j.resconrec.2019.03.045 Cited in: PubMed; PMID 31274959.

4. Iacovidou E, Velis CA, Purnell P, Zwirner O, Brown A, Hahladakis J, Millward-Hopkins J, Williams PT. Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: A critical review. Journal of Cleaner Production. 2017;166910–38. doi:10.1016/j.jclepro.2017.07.100

5. Fang B, Yu J, Chen Z, Osman AI, Farghali M, Ihara I, Hamza EH, Rooney DW, Yap P-S. Artificial intelligence for waste management in smart cities: a review. Environ Chem Lett. 2023;1–31. doi:10.1007/s10311-023-01604-3 Cited in: PubMed; PMID 37362015.

6. Sharma HB, Vanapalli KR, Samal B, Cheela VRS, Dubey BK, Bhattacharya J. Circular economy approach in solid waste management system to achieve UN-SDGs: Solutions for post-COVID recovery. Sci Total Environ. 2021;800149605. doi:10.1016/j.scitotenv.2021.149605 Cited in: PubMed; PMID 34426367.

7. Russell SJ, Norvig P. Artificial Intelligence: A Modern Approach, Global Edition 4e: Pearson; 2021.

8. Binns R, editor. Fairness in machine learning: Lessons from political philosophy: PMLR; 2018. 149-159.

9. He H, Gray J, Cangelosi A, Meng Q, McGinnity TM, Mehnen J, editors. The challenges and opportunities of artificial intelligence for trustworthy robots and autonomous systems: IEEE; 2020. 68-74.

10. Bibri SE, Krogstie J, Kaboli A, Alahi A. Smarter eco-cities and their leading-edge artificial intelligence of things solutions for environmental sustainability: A comprehensive systematic review. Environ Sci Ecotechnol. 2024;19100330. doi:10.1016/j.ese.2023.100330 Cited in: PubMed; PMID 38021367.

11. Ahmed MIB, Alotaibi RB, Al-Qahtani RA, Al-Qahtani RS, Al-Hetela SS, Al-Matar KA, Al-Saqer NK, Rahman A, Saraireh L, Youldash M. Deep learning approach to recyclable products classification: Towards sustainable waste management. Sustainability. 2023;15(14):11138.

12. Shahab S, Anjum M, Umar MS. Deep learning applications in solid waste management: A deep literature review. International Journal of Advanced Computer Science and Applications. 2022;13(3).

13. Zhang M, Fan X, Jia H, Peng W, Ren G, Du D. Green and Sustainable Biochar for Coastal Wetlands Management: A Review to Achieve In Situ Remediation by Artificial Intelligence. Water. 2024;16(14):1966.

14. Wilts H, Garcia BR, Garlito RG, Gómez LS, Prieto EG. Artificial Intelligence in the Sorting of Municipal Waste as an Enabler of the Circular Economy. Resources. 2021;10(4):28. doi:10.3390/resources10040028

15. Kumar NM, Mohammed MA, Abdulkareem KH, Damasevicius R, Mostafa SA, Maashi MS, Chopra SS. Artificial intelligence-based solution for sorting COVID related medical waste streams and supporting data-driven decisions for smart circular economy practice. Process Safety and

Environmental Protection. 2021;152482–94. doi:10.1016/j.psep.2021.06.026

16. Andeobu L, Wibowo S, Grandhi S. Artificial intelligence applications for sustainable solid waste management practices in Australia: A systematic review. Sci Total Environ. 2022;834155389. doi:10.1016/j.scitotenv.2022.155389 Cited in: PubMed; PMID 35460765.

17. Abdallah M, Abu Talib M, Feroz S, Nasir Q, Abdalla H, Mahfood B. Artificial intelligence applications in solid waste management: A systematic research review. Waste Manag. 2020;109231–46. doi:10.1016/j.wasman.2020.04.057 Cited in: PubMed; PMID 32428727.

18. Lee SY, Sankaran R, Chew KW, Tan CH, Krishnamoorthy R, Chu D-T, Show P-L. Waste to bioenergy: a review on the recent conversion technologies. BMC Energy. 2019;1(1). doi:10.1186/ s42500-019-0004-7

19. Hinton ZR, Talley MR, Kots PA, Le AV, Zhang T, Mackay ME, Kunjapur AM, Bai P, Vlachos DG, Watson MP, Berg MC, Epps TH, Korley LT. Innovations Toward the Valorization of Plastics Waste. Annu. Rev. Mater. Res. 2022;52(1):249–80. doi:10.1146/annurev-matsci-081320-032344

20. Beyene HD, Werkneh AA, Ambaye TG. Current updates on waste to energy (WtE) technologies: a review. Renewable Energy Focus. 2018;241–11.

21. Tsui T-H, Wong JWC. A critical review: emerging bioeconomy and waste-to-energy technologies for sustainable municipal solid waste management. Waste Dispos. Sustain. Energy. 2019;1(3):151–67. doi:10.1007/s42768-019-00013-z

22. Dhalsamant K, Dalai AK. Optimization and characterization of biocrude produced from hydrothermal liquefaction of food waste. Sustainable Energy Fuels. 2025;9(8):2119–36. doi:10.1039/D5SE00136F

23. He M. Tailored waste-derived biochar for energy recovery and environmental applications. 2023.

24. Lyu X, Nuhu M, Candry P, Wolfanger J, Betenbaugh M, Saldivar A, Zuniga C, Wang Y, Shrestha S. Top-down and bottom-up microbiome engineering approaches to enable biomanufacturing from waste biomass. Journal of Industrial Microbiology and Biotechnology. 2024;51kuae025.

25. Castaldi M, van Deventer J, Lavoie JM, Legrand J, Nzihou A, Pontikes Y, Py X, Vandecasteele C, Vasudevan PT, Verstraete W. Progress and Prospects in the Field of Biomass and Waste to Energy and Added-Value Materials. Waste Biomass Valor. 2017;8(6):1875–84. doi:10.1007/s12649-017-0049-0

26. Qin Z-H, Mou J-H, Chao CYH, Chopra SS, Daoud W, Leu S-Y, Ning Z, Tso CY, Chan CK, Tang S, Hathi ZJ, Haque MA, Wang X, Lin CSK. Biotechnology of Plastic Waste Degradation, Recycling, and Valorization: Current Advances and Future Perspectives. Chem Sus Chem. 2021;14(19):4103–14. doi:10.1002/cssc.202100752 Cited in: PubMed; PMID 34137191.

27. Patel AK, Singhania RR, Albarico FPJB, Pandey A, Chen C-W, Dong C-D. Organic wastes bioremediation and its changing prospects. Sci Total Environ. 2022; 824153889. doi:10.1016/j.scitotenv.2022.153889 Cited in: PubMed; PMID 35181362.

28. Peng X, Jiang Y, Chen Z, Osman AI, Farghali M, Rooney DW, Yap P-S. Recycling municipal, agricultural and industrial waste into energy, fertilizers, food and construction materials, and economic feasibility: a review. Environ Chem Lett. 2023;21(2):765–801. doi:10.1007/s10311-022-01551-5

29. Brancoli P, Bolton K, Eriksson M. Environmental impacts of waste management and valorisation pathways for surplus bread in Sweden. Waste Manag. 2020;117136–45. doi:10.1016/j.wasman.2020.07.043 Cited in: PubMed; PMID 32823078.

30. Tawo OE, Mbamalu MI. Advancing waste valorization techniques for sustainable industrial operations and improved environmental safety. Int. J. Sci. Res. Arch. 2025;14(02):127–49. doi:10.30574/ijsra.2025.14.2.0334

31. Goutam Mukherjee A, Ramesh Wanjari U, Chakraborty R, Renu K, Vellingiri B, George A, C R SR, Valsala Gopalakrishnan A. A review on modern and smart technologies for efficient waste disposal and management. J Environ Manage. 2021;297113347. doi:10.1016/j.jenvman.2021.113347 Cited in: PubMed; PMID 34314963.

32. Ganguly RK, Chakraborty SK. Plastic waste management during and post Covid19 pandemic: Challenges and strategies towards circular economy. Heliyon. 2024;10(4). doi:10.1016/j.heliyon.2024.e25613

33. Serpe A, Purchase D, Bisschop L, Chatterjee D, Gioannis G de, Garelick H, Kumar A, Peijnenburg W, Piro VM, Cera M. 2002–2022: 20 years of e-waste regulation in the European Union and the worldwide trends in legislation and innovation technologies for a circular economy. RSC Sustainability. 2025;3(3):1039–83. doi:10.1039/d4su00548a

34. Wikurendra EA, Csonka A, Nagy I, Nurika G. Urbanization and Benefit of Integration Circular Economy into Waste Management in Indonesia: A Review. Circ.Econ.Sust. 2024;4(2):1219–48. doi:10.1007/s43615-024-00346-w

35. Yang J, Jiang P, Nassar R-U-D, Suhail SA, Sufian M, Deifalla AF. Experimental investigation and AI prediction modelling of ceramic waste powder concrete – An approach towards sustainable construction. Journal of Materials Research and Technology. 2023;233676–96. doi:10.1016/j.jmrt.2023.02.024