International Journal of Sustainable Energy and Environmental Research
2024 Vol. 13, No. 2, pp. 105-113
ISSN(e): 2306-6253
ISSN(p): 2312-5764
DOI: 10.18488/13.v13i2.3868

Opportunities of artificial intelligence in valorisation of biodiversity, biomass and bioresidues – towards advanced bio-economy, circular engineering, and sustainability

Lourdes Orejuela-Escobar[1,2,3,4+]
Diego Venegas-Vásconez[5]
Miguel Angel Méndez[1,6]

[1]*Applied Circular Engineering Group, Department of Chemical Engineering, College of Science and Engineering, Universidad San Francisco de Quito, Quito, Ecuador.*
[2]*Institute of Biological and Environmental Research, Universidad San Francisco de Quito, Quito 170157, Ecuador.*
[3]*Biomedicine Research Institute, Universidad San Francisco de Quito, Quito 170157, Ecuador.*
[4]*Institute for Energy and Materials, Universidad San Francisco de Quito, Quito 170157, Ecuador.*
[1,2,3,4]*Email: lorejuela@usfq.edu.ec*
[5]*Wood Engineering Department, Universidad del Bio-Bio, 4081112 Concepción, Chile.*
[5]*Email: dvenegas@ubiobio.cl*
[6]*Computational and Theoretical Chemistry Group, Chemical Engineering Department, Universidad San Francisco de Quito, Quito 170157, Ecuador.*
[1,6]*Email: miguelangelms@gmail.com*

(+ Corresponding author)

Article History
Received: 20 June 2024
Revised: 23 July 2024
Accepted: 8 August 2024
Published: 16 August 2024

Keywords
Advanced bioeconomy
Artificial intelligence
Biodiversity valorization
Biomass-processing
Circularity
Sustainability.

ABSTRACT

Artificial intelligence (AI) has rapidly gained notoriety due to fast advances in generative AI. However, this field encompasses a broader set of already mature tools and methods. Here, we explore its broad impact on the valorization of assets directly derived from living organisms, biomass, produced in high quantities and used in non-traditional applications at an industrial scale. For this review, we have explored the trends in scientific publications as well as in patents to measure the current state of the art and the potential for commercial applications. The number of publications and patents is rapidly increasing, showing the penetration of these technologies into chemical and biochemical engineering processes. The ethical considerations of such rapid advances need to be addressed to maximize the benefits and minimize the unintentional collateral negative social impact. Considering AI's current limitations, biases, and economic impacts will facilitate a better transition to the broad implementation of these new technologies. The valorization of biomass and bioresidues, along with the sustainable use of biodiversity, faces important challenges and obstacles that AI tools are helping to overcome, accelerating basic research and optimizing industrial processes in the development of sustainable energy, and high value-added bioproducts and biomaterials. The application of AI in these fields promises industrial innovation, enhanced efficiency, cost reduction and increased product yields for a global growing market; and thereby promotes Circular Engineering and Advanced Bioeconomy to achieve United Nations Sustainable Development goals in the near future.

Contribution/Originality: This review paper seeks to fill a critical gap in the existing literature by exploring specifically the disruptive opportunities of Artificial Intelligence (AI) in engineering applications to transform biomass and bioresidues into valuable commercial products. In addition, it discusses the ethical considerations of the application of such technologies.

1. INTRODUCTION

The scientific community has a growing interest in addressing environmental challenges due to climate change. One of the major current concerns is contamination caused by the use of non-renewable fossil energy and fuels (Ramzan, Raza, Usman, Sharma, & Iqbal, 2022) thus it is imperative to find renewable energy sources and feedstock for valuable products and advanced materials (Deng et al., 2023). In this regard, biomass and residual biomass can play a significant role since their efficient use allows a sustainable circular economy (CE) and circular bioeconomy (CBE). These models seeks to decreasing residues and bioresidues in the environment, minimizing their negative impact and enabling energy and materials conservation, and thereby promoting Circular Engineering (CEng) and a sustainable Advanced Bioeconomy (ABE) (Marqués, 2023; Usmani et al., 2021). The processes of the conversion of biodiversity, biomass and bioresidues for their valorization into high value-added bioproducts and bionanomaterials have gained significant attention in the academy, industry, government institutions and international technical assistance organizations (Orejuela-Escobar, Landázuri, & Goodell, 2021). The demand for products and materials with enhanced properties for high tech applications is increasing rapidly, and therefore our modern society is moving forward to an Advanced Bioeconomy model. In this regard, AI emerges as a powerful tool with the capability to revolutionize the value creation/addition process of biodiversity, biomass and bioresidues (Dodo et al., 2024). By integrating AI approaches, the valorization of biodiversity, biomass, and bioresidues can be optimized, leading to more efficient and sustainable BE and CEng practices that enable the generation of sustainable bioenergy and biofuels and high value-added bioproducts and biomaterials through innovations by adapting novel eco-friendly technologies to promote Advanced Bioeconomy (ABE), contributing to the achievement of sustainable development goals (SDGs) (United Nations, 2015). Therefore, Goal 7 (Affordable and Clean Energy), Goal 8 (Decent Work and Economic Growth), Goal 9 (Industry innovation and infrastructure), Goal 11 (Sustainable cities and Communities), Goal 12 (Responsible Consumption and Production), Goal 13 (Climate Action), and Goal 17 (Partnerships' for the goals); all these goals aim to achieving a sustainable development and cooperation within the UN System.

A search of the number of publications on ScienceDirect was performed on May 15, 2024, using biomass and artificial intelligence as keywords (Figure 1a). The network map exhibited in Figure 1b was constructed from the search on Scopus using the same keywords: biomass and artificial intelligence. These figures show that the research regarding the use of AI in the field of biomass processing is increasing, indicating a new trend in the application of this area of knowledge in the valorization of biomass and residual biomass processing worldwide.

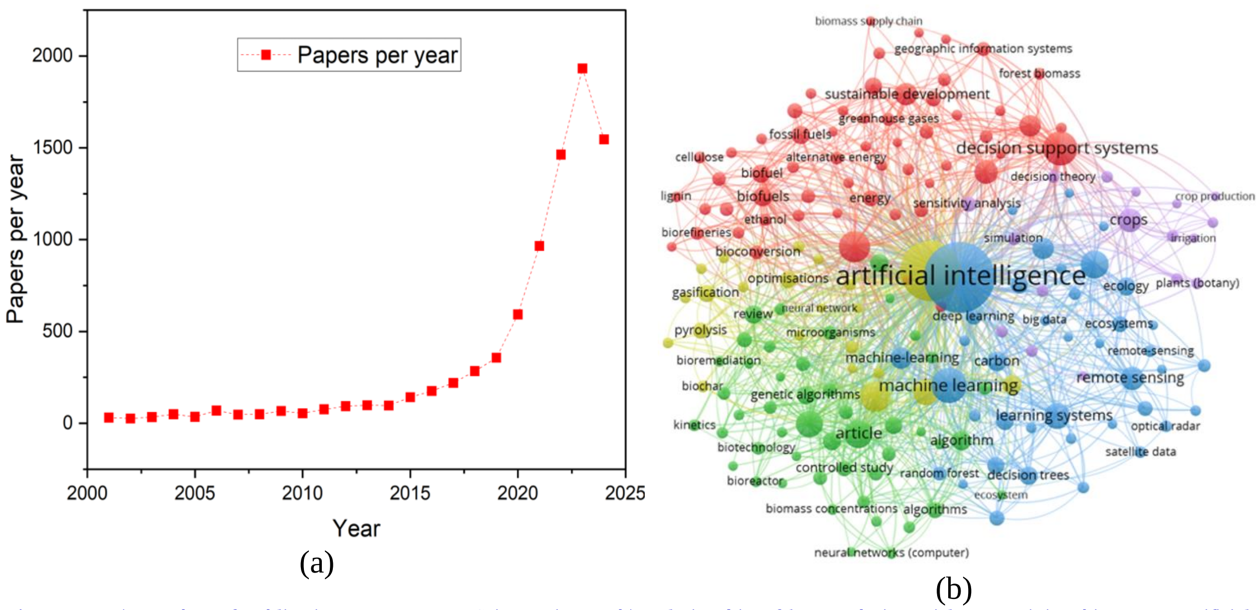
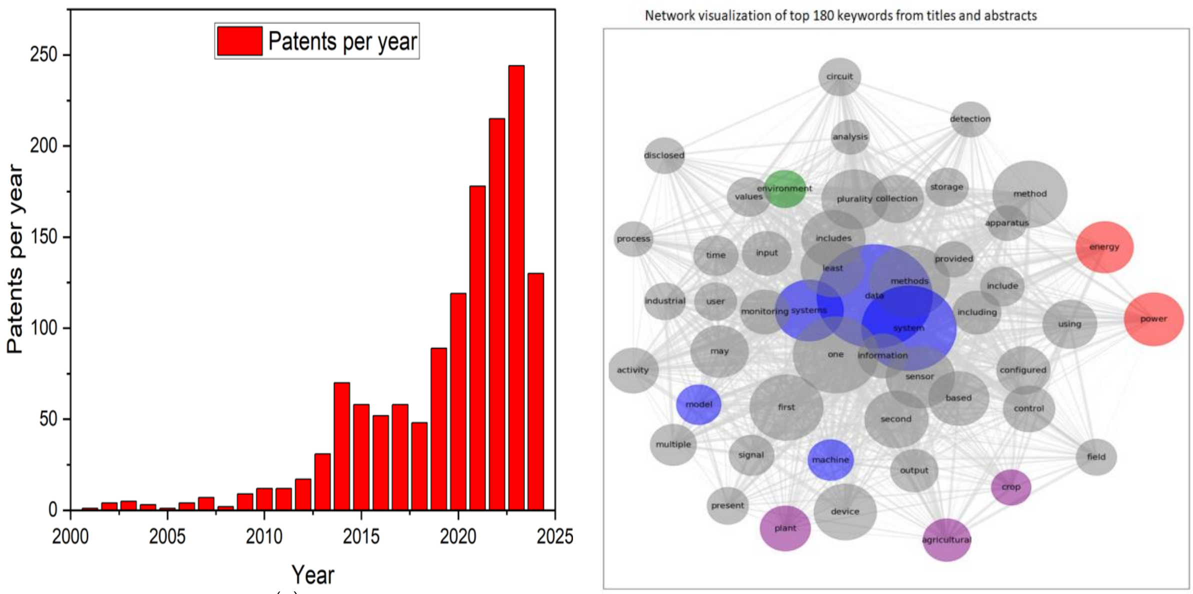


Figure 1. 1a) Number of publications per year on ScienceDirect. 1b) Relationship of keywords in articles containing biomass - artificial intelligence.

1.1. Understanding Biodiversity, Biomass and Bioresidues Valorization to Promote Advanced Bioeconomy, Circular Engineering and Integration of Industry 4.0

Biomass processing into bioenergy, enhanced biofuels, and high value-added bio-based products and bio-based nanomaterials requires the participation of all branches of science and technology from biology, genetics, chemistry, biochemistry, physics and mathematics, through all the biotechnologies developed so far; as well as engineering such as genetic engineering, chemical engineering, computational engineering, mechanical engineering, and informatics. Therefore, it is crucial that all sciences, technologies, and engineering disciplines adopt green, circular, and sustainable practices that lead us to achieve a sustainable bioeconomy (BE), efficient industry in a society with a clean environment. However, chemical engineering plays a pivotal role because its domain includes the transformation/conversion of energy and matter and their related changes, therefore the application of circularity and sustainability in the world of chemical engineering leads to Circular Engineering (CEng) (Londoño & Cabezas, 2021). Moreover, the integration of Industry 4.0 technologies such as AI, big data analysis, and the Internet of the Things (IoT), can transform the way biorefinery processes are designed, optimized, and evaluated (Mohan & Katakojwala, 2021).

One indicator of the advance in science, technology and engineering towards a sustainable innovation is the number of granted patents per year in the field of the use of AI in biomass conversion and processing. Therefore, we used the patent search platform Lenses (June 06, 2024), examining granted patents per year using the key words 'artificial intelligence' OR 'machine learning' AND 'biomass' or 'bioresidue'. An increasing trend in patents related to biomass and artificial intelligence is observed (Figure 2a). We also present the relationship and frequency of keywords in the titles and abstracts of the granted patents (Figure 2b).



(a) (b)

Figure 2. 2a) Lens's results for granted patents per year using the keywords 'artificial intelligence' OR 'machine learning' AND 'biomass' or 'bioresidue'. 2b) Relationships and frequency of keywords in the titles and abstracts of the patents.

Biomass valorization involves various techniques aimed at converting biomass, such as agricultural, and forestry residues, and organic by-products, into biofuels, biochemicals, and other high-value products (Afraz et al., 2023). Traditional biomass conversion techniques include thermochemical processes such as pyrolysis, gasification, and hydrothermal liquefaction, as well as biochemical processes like fermentation and enzymatic conversion (Xiu & Shahbazi, 2012). Conventional biomass valorization processes face several challenges that hinder their widespread adoption and commercial viability. These challenges include (Kumar et al., 2019; Venegas-Vásconez et al., 2023):

- Low Conversion Efficiency, leading to sub utilization of biomass feedstocks and reduced yields of valuable products.
- Limited Product Selectivity, resulting in complex product mixtures, making it challenging to isolate desired compounds and achieve high-purity products.
- High Energy Consumption, contributing to energy-intensive operations and inefficient heat transfer mechanisms that lead to high operational costs.
- Catalyst Deactivation, suffering deactivation due to fouling, sintering, or poisoning, therefore leading to reduced activity and selectivity over time of catalyst in biomass conversion processes.

1.2. Opportunities of Artificial Intelligence in the Field of Biomass Valorization

Traditional biomass valorization processes have limitations that AI can overcome. For instance, machine-learning algorithms are able to analyze immense quantities of data, recognize patterns, and perform process optimization to improve bioprocessing efficiency and biomass conversion yield (Huang & Koroteev, 2021; Jauhar, Sethi, Kamble, Mathew, & Belhadi, 2024; Jung et al., 2021; Liao, Ma, & Tang, 2022; Naveenkumar et al., 2023; Rejeb, Rejeb, Zailani, Keogh, & Appolloni, 2022; Shi, Ferrari, Ai, Marinello, & Pezzuolo, 2023). Some of the opportunities that AI provide to improve biomass conversion processes include:

- Process Optimization: Predictive modelling and AI algorithms can optimized parameters of biomass processing such as temperature, pressure, catalyst composition and reaction time; therefore, their application can enhance selectivity resulting less secondary reactions and by-products and hence, will increase efficiencies in biomass value addition processes.
- Catalyst design: Biomass conversion reactions need catalysts to shorten their kinetics and improve product yields. AI-supported approaches such as computational modelling enable design, performance, and stability of new catalysts for processing in biomass value addition.
- Resource Management: Computational intelligence can optimize biomass utilization by incorporating real-time data monitoring, quality control process, and predictive maintenance programs. AI can reduce energy consumption, minimize waste generation, and maximize the utilization of biomass feedstocks.

AI has a significant role in valorization of biodiversity, biomass and bioresidues through techniques such as neural networks, Bayesian networks, decision trees, and multivariate regression. AI would assist in predicting and optimizing bioenergy production processes, in modelling and simulating biorefinery operations, in identifying suitable biomass feedstocks and conversion routes, in supporting decision- making for sustainable biomass valorization strategies, and in analyzing/interpreting complex data related to biomass composition and conversion processes (Aniza et al., 2023).

2. INTEGRATION OF AI IN BIODIVERSITY, BIOMASS, AND BIORESIDUES VALORIZATION

The integration of artificial intelligence in biomass valorization holds immense promise for advancing sustainable energy and chemical production. Research directions may focus on:

2.1. Multi-Scale Modeling

Developing integrated models that take the complex interactions between biomass feedstocks, reaction kinetics, and catalyst behavior at various scales, from molecular simulations to reactor-scale modelling (Guo, Zhang, & Liu, 2024).

2.2. Autonomous Systems

Designing autonomous biomass conversion systems that leverage AI for adaptive control, self-optimization, and decision-making without human intervention, enabling continuous operation and real-time adaptation to changing feedstock compositions and process conditions (Guo et al., 2024).

2.3. Bioinformatics and Genomics

Bioinformatics and genomics are advancing with AI methods. These procedures employ bioinformatics and genomic engineering techniques to develop biomass feedstocks with enhanced properties tailored to specific conditions, facilitating improvements in bio productive processes (Cheng, Ren, Warkentin, & Ai, 2024). For instance, AI methods have successfully reproduced three-dimensional protein structures directly from sequences with atomic precision and at scale.

2.4. Predictive Modelling and Process Optimization

AI techniques, such as machine learning (ML) and deep learning are effective in creating models that predict and optimize biomass transformation processes. These models analyze large and complex datasets to identify crucial parameters, forecast process impacts, and recommend optimal operating conditions to maximize efficiency while minimizing pollution (Shi et al., 2023).

2.5. Biomass Supply Chain Management

AI and ML enable the management of biomass supply chains, from the sourcing location to the distribution of bioproducts. Optimization algorithms can identify nearby locations using Geographic Information Systems (GIS) tools. By combining these tools, it becomes easier to select the best site and optimally plan the distribution of goods, considering sustainable effects while minimizing transportation costs (Wang & Yao, 2023).

2.6. Sustainability Assessment (SA) and Life Cycle Analysis (LCA)

AI plays a crucial role in developing Sustainability Assessment (SA) and Life Cycle Assessment (LCA) for transformation processes that generate bio-based products (Gupta et al., 2024; Wang & Yao, 2023).

2.7. Intelligent Control Systems

AI/supports control systems can monitor and regulate biomass-processing facilities in real time. These systems can structure sensor data, predictive models, and optimization algorithms to maintain optimal operating conditions, reduce waste, and enable efficient resource usage (Gupta et al., 2024).

2.8. Data-Driven Material Design

AI techniques such as reinforcement learning and generative adversial networks (GANs) can be explored for data-driven design of bio-based materials with tailored properties. This will accelerate the development of advanced bio-based materials for different applications, including catalysis, energy storage and environmental remediation (Gupta et al., 2024).

Overall, AI is a promising technology that can address challenges such as data availability and scalability for the adoption of a sustainable utilization of biodiversity, biomass or bioresidues as well as in their processing.

3. ENVIRONMENTAL AND ECONOMIC IMPACTS OF AI-DRIVEN BIOMASS VALORIZATION

The widespread adoption of AI-supported biomass valorization technologies has the potential to significantly reduce greenhouse gas emissions (GHE) in biomass processing such as gasification, pyrolysis and fermentation while minimizing waste, maximizing product yields and leading to higher process efficiency and sustainability (Hussain et al., 2023). By improving the efficiency of biomass-to-energy processes, AI can help replace fossil fuels like liquefied petroleum gas (LPG) with cleaner fuels such as synthesis gas (syngas) derived from biomass; this reduces GHE and dependence on non-renewable resources (Chaverra, 2022). Syngas process produces biochar as a by-product, therefore applying AI for optimization, biochar yield can be maximized, and then can be used as a soil amendment to improve fertility and sequester carbon, mitigating climate change impacts. Sustainable feedstock management can also be impacted by AI and machine learning application to remote sensing data and GIS to accurately detect, map, and estimate biomass resources over large geographical areas; enabling optimal site selection and sustainable management of biomass feedstocks avoiding unsustainable harvesting practices (Gemno, 2022). By integrating AI across the entire bio-based materials lifecycle, from feedstock cultivation to production and end-used applications, it is possible to perform comprehensive sustainability assessments and optimize processes for minimal environmental impact. Additionally, AI techniques can help identify valuable components in waste biomass streams and optimize processes for their recovery and conversion into useful commercial products, promoting a CBE and ABE (Shi et al., 2023).

Applying AI techniques in biomass processing can provide significant economic benefits. AI can generate data that are difficult to measure directly, improving models for biomass conversion processes and biofuel properties; leading to more efficient and optimized processes, reducing costs (Liao & Yao, 2021). ML can predict accurately biomass and biofuels properties, and processes performance, eliminating the need of costly experimental trials. The integration of sensor systems with AI allows real-time monitoring and adjustment of biomass processing equipment and machines, improving process reliability, maximizing productivity and economic yield (Hatch, 2020).

By improving process efficiencies, reducing waste generation, and minimizing resource consumption, AI-supported biomass valorization contributes to bioresource conservation, sustainable environment and economic growth.

4. ETHICAL CONSIDERATIONS AND SOCIAL IMPLICATIONS

As AI technologies continue to advance, it is essential to consider the ethical implications and social consequences of their deployment in biomass valorization. Key considerations include data privacy, data ownership, algorithmic bias, transparency (about data collection, use and shared), and robustness of AI systems to minimize the risk of errors or failures and their subsequent negative consequences (Dara, Hazrati Fard, & Kaur, 2022).

Social implication involves workforce displacement and impact on rural communities by changing land use, transportation ways, and employment; therefore, it is important to assure that these changes benefit local communities. AI approaches need to consider social factors such as the effect of feedstock selection for biorefining on food prices and land rights, as well as energy access of local communities (Liao & Yao, 2021).

Rural and urban communities should have equitable access to AI-driven technologies, ensuring that the benefits of AI are shared equitably and ethically across society (Nieuwenhuis, 1997).

5. CONCLUDING REMARKS AND FUTURE PERSPECTIVES

Artificial intelligence holds immense potential to revolutionize biodiversity, biomass and bioresidues valorization by enabling the following:

- Optimization of processes, designing efficient catalysts, and enabling real-time control and monitoring.
- Integration of optical sensors with AI for generating data for accurate measurements of critical parameters of biomass-processing industrial plants that current methods fail to reliably determine.
- Generation of data that are difficult to measure directly. AI creates improved models of biomass conversion and enhanced biofuel for optimizing bioenergy, bioproducts and biomaterials supply chain.

- Modelling for simulation of thermochemical biomass conversion processes to assure efficiency and sustainability.

By harnessing the power of transformative AI-supported technologies, we can unlock the full potential of biomass as a sustainable and renewable resource, paving the way for a greener and more prosperous future. Continued research and collaboration are essential to recognize the promise of AI in an efficient biomass utilization and accelerate the transition towards a more sustainable resilient and advanced bio-based economy.

Funding: This research is supported by Universidad San Francisco de Quito, Research Poligrant 2022-2023 - Hubi (Grant number: 15783).
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: Conceptualization, methodology, supervision, funding acquisition, writing – original draft, L.M.O.E.; investigation, data acquisition, visualization, writing – review & editing, M.A.M.; investigation, data acquisition, visualization, writing – review & editing, D.V.V. All authors have read and agreed to the published version of the manuscript.

REFERENCES

Afraz, M., Muhammad, F., Nisar, J., Shah, A., Munir, S., Ali, G., & Ahmad, A. (2023). Production of value added products from biomass waste by pyrolysis: An updated review. *Waste Management Bulletin, 1*, 30–40. https://doi.org/10.1016/j.wmb.2023.08.004

Aniza, R., Chen, W.-H., Pétrissans, A., Hoang, A. T., Ashokkumar, V., & Pétrissans, M. (2023). A review of biowaste remediation and valorization for environmental sustainability: Artificial intelligence approach. *Environmental Pollution, 324*, 121363. https://doi.org/10.1016/j.envpol.2023.121363

Chaverra, D. (2022). *Project in biomass gasification plant integrated with artificial intelligence. Latinoamérica, Acr. The Latam HV AC/r Review*. Retrieved from https://www.acrlatinoamerica.com/en/2022062718200/news/enterprises/project-in-biomass-gasification-plant-integrated-with-artificial-intelligence.html

Cheng, F., Ren, Y., Warkentin, T. D., & Ai, Y. (2024). Heat-moisture treatment to modify structure and functionality and reduce digestibility of wrinkled and round pea starches. *Carbohydrate Polymers, 324*, 121506. https://doi.org/10.1016/j.carbpol.2023.121506

Dara, R., Hazrati Fard, S. M., & Kaur, J. (2022). Recommendations for ethical and responsible use of artificial intelligence in digital agriculture. *Frontiers in Artificial Intelligence, 5*, 884192. https://doi.org/10.3389/frai.2022.884192

Deng, W., Feng, Y., Fu, J., Guo, H., Guo, Y., Han, B., . . . Liu, H. (2023). Catalytic conversion of lignocellulosic biomass into chemicals and fuels. *Green Energy & Environment, 8*(1), 10-114.

Dodo, U. A., Dodo, M. A., Husein, M. A., Ashigwuike, E. C., Mohammed, A. S., & Abba, S. I. (2024). Comparative study of different training algorithms in backpropagation neural networks for generalized biomass higher heating value prediction. *Green Energy and Resources, 2*(1), 100060. https://doi.org/10.1016/j.gerr.2024.100060

Gemno, A. (2022). *Revolutionising biomass power plant efficiency with AI*. Retrieved from https://gemmo.ai/ai-for-biomass-power-plant/

Guo, S., Zhang, Y., & Liu, L. (2024). Sorption enhanced steam reforming of biomass-based feedstocks: Towards sustainable hydrogen evolution. *Chemical Engineering Journal*, 149760. https://doi.org/10.1016/j.cej.2024.149760

Gupta, R., Ouderji, Z. H., Uzma, Yu, Z., Sloan, W. T., & You, S. (2024). Machine learning for sustainable organic waste treatment: A critical review. *npj Materials Sustainability, 2*(1), 5. https://doi.org/10.1038/s44296-024-00009-9

Hatch, C. (2020). *Artificial intelligence helps turn biomass into energy. INL Idaho National Laboratory*. Retrieved from https://inl.gov/integrated-energy/systems-engineering/

Huang, J., & Koroteev, D. D. (2021). Artificial intelligence for planning of energy and waste management. *Sustainable Energy Technologies and Assessments, 47*, 101426. https://doi.org/10.1016/j.seta.2021.101426

Hussain, Z., Babe, M., Saravanan, S., Srimathy, G., Roopa, H., & Boopathi, S. (2023). Optimizing biomass-to-biofuel conversion: IoT and ai integration for enhanced efficiency and sustainability. In S. B. Zakir Hussain, M. Babe, S. Saravanan, G. Srimathy, H. Roopa (Ed.), Circular Economy Implementation for Sustainability in the Built Environment. In (pp. 191-214): IGI Global. https://doi.org/10.4018/978-1-6684-8238-4.ch009.

Jauhar, S. K., Sethi, S., Kamble, S. S., Mathew, S., & Belhadi, A. (2024). Artificial intelligence and machine learning-based decision support system for forecasting electric vehicles' power requirement. *Technological Forecasting and Social Change*, *204*, 123396. https://doi.org/10.1016/j.techfore.2024.123396

Jung, J., Maeda, M., Chang, A., Bhandari, M., Ashapure, A., & Landivar-Bowles, J. (2021). The potential of remote sensing and artificial intelligence as tools to improve the resilience of agriculture production systems. *Current Opinion in Biotechnology*, *70*, 15-22. https://doi.org/10.1016/j.copbio.2020.09.003

Kumar, R., Strezov, V., Lovell, E., Kan, T., Weldekidan, H., He, J., . . . Scott, J. (2019). Enhanced bio-oil deoxygenation activity by Cu/zeolite and Ni/zeolite catalysts in combined in-situ and ex-situ biomass pyrolysis. *Journal of Analytical and Applied Pyrolysis*, *140*, 148-160. https://doi.org/10.1016/j.jaap.2019.03.008

Liao, M., & Yao, Y. (2021). Applications of artificial intelligence-based modeling for bioenergy systems: A review. *GCB Bioenergy*, *13*(5), 774-802. https://doi.org/10.1111/gcbb.12816

Liao, X., Ma, H., & Tang, Y. J. (2022). Artificial intelligence: A solution to involution of design–build–test–learn cycle. *Current Opinion in Biotechnology*, *75*, 102712. https://doi.org/10.1016/j.copbio.2022.102712

Londoño, N. A. C., & Cabezas, H. (2021). Perspectives on circular economy in the context of chemical engineering and sustainable development. *Current Opinion in Chemical Engineering*, *34*, 100738. https://doi.org/10.1016/j.coche.2021.100738

Marqués, F. R. (2023). Circular bioeconomy applications in chemical engineering. Doctoral Dissertation, TU Wien.

Mohan, S. V., & Katakojwala, R. (2021). The circular chemistry conceptual framework: A way forward to sustainability in industry 4.0. *Current Opinion in Green and Sustainable Chemistry*, *28*, 100434. https://doi.org/10.1016/j.cogsc.2020.100434

Naveenkumar, R., Iyyappan, J., Pravin, R., Kadry, S., Han, J., Sindhu, R., . . . Baskar, G. (2023). A strategic review on sustainable approaches in municipal solid waste management and energy recovery: Role of artificial intelligence, economic stability and life cycle assessment. *Bioresource Technology*, *379*, 129044. https://doi.org/10.1016/j.biortech.2023.129044

Nieuwenhuis, F. (1997). Can research into the development of education in post-colonial Africa shape education policies in South Africa? *International Journal of Educational Development*, *17*(2), 129-143. https://doi.org/10.1016/s0738-0593(96)00035-1

Orejuela-Escobar, L. M., Landázuri, A. C., & Goodell, B. (2021). Second generation biorefining in Ecuador: Circular bioeconomy, zero waste technology, environment and sustainable development: The nexus. *Journal of Bioresources and Bioproducts*, *6*(2), 83-107. https://doi.org/10.1016/j.jobab.2021.01.004

Ramzan, M., Raza, S. A., Usman, M., Sharma, G. D., & Iqbal, H. A. (2022). Environmental cost of non-renewable energy and economic progress: Do ICT and financial development mitigate some burden? *Journal of Cleaner Production*, *333*, 130066. https://doi.org/10.1016/j.jclepro.2021.130066

Rejeb, A., Rejeb, K., Zailani, S., Keogh, J. G., & Appolloni, A. (2022). Examining the interplay between artificial intelligence and the agri-food industry. *Artificial Intelligence in Agriculture*, *6*, 111-128. https://doi.org/10.1016/j.aiia.2022.08.002

Shi, Z., Ferrari, G., Ai, P., Marinello, F., & Pezzuolo, A. (2023). Artificial intelligence for biomass detection, production and energy usage in rural areas: A review of technologies and applications. *Sustainable Energy Technologies and Assessments*, *60*, 103548. https://doi.org/10.1016/j.seta.2023.103548

United Nations. (2015). *United Nations: The 17 goals. The 2030 agenda for sustainable development. Department of Economic and Social Affairs*. Retrieved from https://sdgs.un.org/goals

Usmani, Z., Sharma, M., Awasthi, A. K., Sivakumar, N., Lukk, T., Pecoraro, L., . . . Gupta, V. K. (2021). Bioprocessing of waste biomass for sustainable product development and minimizing environmental impact. *Bioresource Technology, 322*, 124548. https://doi.org/10.1016/j.biortech.2020.124548

Venegas-Vásconez, D., Arteaga-Pérez, L. E., Aguayo, M. G., Romero-Carrillo, R., Guerrero, V. H., Tipanluisa-Sarchi, L., & Alejandro-Martín, S. (2023). Analytical pyrolysis of pinus radiata and eucalyptus globulus: Effects of microwave pretreatment on pyrolytic vapours composition. *Polymers, 15*(18), 3790. https://doi.org/10.3390/polym15183790

Wang, H. S.-H., & Yao, Y. (2023). Machine learning for sustainable development and applications of biomass and biomass-derived carbonaceous materials in water and agricultural systems: A review. *Resources, Conservation and Recycling, 190*, 106847. https://doi.org/10.1016/j.resconrec.2022.106847

Xiu, S., & Shahbazi, A. (2012). Bio-oil production and upgrading research: A review. *Renewable and Sustainable Energy Reviews, 16*(7), 4406-4414. https://doi.org/10.1016/j.rser.2012.04.028