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The new gold rush: unlocking the potential of waste through chemical science, society and policy

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The world faces a growing waste crisis due to industrialization, urbanization, and population growth. Waste production is expected to increase significantly, with a 28.9% rise by 2030 and 69.2% by 2050, leading to pollution, health hazards, and environmental destruction.[1] The animated film WALL-E in 2008 offered a haunting glimpse into a future Earth buried under waste, abandoned by humans due to excessive waste and reckless consumption. It is a wake-up call, urging us to rethink how we handle waste before it is too late. It starts with the way we see waste. Soon, waste may not be considered a problem. Instead, it could be a valuable resource for the future. Chemical sciences offer solutions by turning waste into valuable products. This reduces environmental harm while creating new economic opportunities for a sustainable future. Waste comes in different forms: solid, liquid, and gas, each requiring diverse waste management options, as shown in Fig. 1.

Solid wastes, such as plastics, agro-food waste, and electronic waste, are major contributors but are among the least efficiently managed. Plastic produces 400 million tons of waste annually, but only 9% is recycled.[2] Mechanical recycling often faces challenges due to contamination (varied composition and additives) and degradation of plastics over time. In contrast, chemical science offers better solutions like pyrolysis and gasification to overcome these issues. They are thermochemical processes that convert plastics into biochar, bio-oil, and syngas for energy generation or feedstock in chemical production.[3] Syngas, a mixture of hydrogen and carbon monoxide, is also used as a feedstock for the Fischer–Tropsch process to produce synthetic fuels and chemicals. Agro-food waste, such as food scraps and crop residues, can be processed through anaerobic digestion or fermentation to generate biogas or biofuels like bioethanol. E-waste rich in valuable metals like silver and copper can be recycled using hydrometallurgy to recover these precious resources. Regarding liquid waste, industrial wastewater can be treated to generate biogas for power generation, whilst the sludge can be repurposed as organic fertilizer. Even industrial waste gas like carbon dioxide (CO_2), which was once seen as a burden, has now become a potential resource. Notably, Integrated

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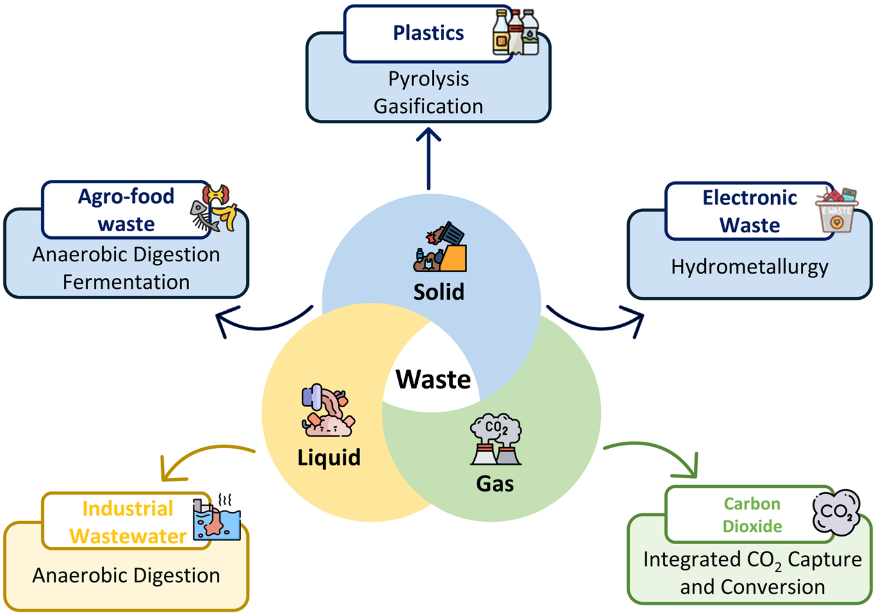

Fig. 1 Summary of different types of waste management through chemical science.

CO_2 Capture and Conversion (ICCC) technology revolutionizes the process by directly extracting CO_2 from flue gas and converting it into valuable products like syngas or methane in a single step,[4] which differs from the traditional methods that require performing carbon capture, transportation, and storage separately. This allows decision-makers to lower energy costs while turning waste into wealth, paving the way for a greener and more sustainable future.

Having chemical processes is just the beginning. Chemical science goes further by inventing catalysts to improve efficiency. Catalysts are essential to speed up chemical reactions, reduce energy use, and improve conversion rates, making waste-to-wealth solutions more practical. For example, metal-modified zeolite catalysts[3] aid in the pyrolysis and gasification of plastics, while Fenton-like catalyst nanocomposites[5] facilitate the production of reactive oxygen species to remove organic pollutants from wastewater. Recent advances in gaseous waste management introduced dual-functional materials (DFMs) and created new possibilities for efficient conversion. DFMs combine an adsorbent and a catalyst together. The adsorbent traps CO_2 from flue gas, while the catalyst, often composed of metals like Ru or Ni, converts the adsorbed gas into valuable products like methane through methanation.[4] ICCC processes with DFMs demonstrate the benefits of catalysts in reducing operating costs by 28.3% compared to traditional methods. These waste-to-wealth initiatives also reduce reliance on fossil fuels by converting waste into biofuels and energy. They support SDG 13 (Climate Action) by repurposing materials, diverting waste from landfills, and maximizing resource efficiency. Furthermore, they reduce pollution, leading to cleaner air and water, enhancing public health, and fostering economic growth through sustainable industries and job creation.

While chemistry provides the foundation for transforming waste into valuable products, its integration with mathematics offers opportunities to optimize efficiency, economic viability, and resource conservation. Mathematics does not replace chemical science; rather, it complements the latter further by providing data-driven insights and guiding process improvements, as illustrated in Fig. 2. One key application of mathematics in waste-to-wealth management is modeling and simulation. These models optimize the chemical reactions and overall process design to ensure each step is efficient before implementation. For instance, reaction kinetics modeling is vital in biofuel production. Chemical science converts waste oils into biodiesel through transesterification. Meanwhile, mathematical tools like kinetic modeling help determine the optimal operating conditions and catalyst concentration, ultimately maximizing biofuel yield.[6] Together, chemistry and mathematics drive innovation in sustainable resource management.

In terms of the process design level, chemical science identifies various waste-to-wealth conversion routes, but not all pathways yield products that meet quality standards. '*How to determine the most efficient route that consistently produces high-quality products?*' becomes the next question that needs an answer. This is where mathematics plays a pivotal role as the selection is not straightforward. For example, the quality and yield of biogas derived can vary depending on the type of waste. A mathematical model can be developed to determine the optimal waste type for biogas production. This model allows industries to select the most appropriate waste-to-wealth conversion pathway based on economic, social, and environmental factors.[7] If anaerobic digestion is deemed the best option for a particular waste, the model will suggest its application. If not, the model can suggest alternative pathways to ensure optimal resource use. In this way, chemical science with mathematics can unlock the full potential of waste. Nevertheless, achieving success in waste valorization goes beyond chemical science and mathematics. It requires societal involvement, economic incentives, and supportive policies to make a real impact.

Technological advancements have enabled the transformation of waste into valuable resources, but their success ultimately depends on consumers and industries adopting and committing to sustainable practices. The success of waste-to-wealth initiatives hinges on effective waste separation. Inaccurate sorting can lead to inefficiencies, costing medium-sized Swedish cities over 1.3 million USD annually.[8] To address this, consumers must adopt better waste segregation habits. Educational campaigns play a crucial role in improving sorting practices because many struggle due to a lack of

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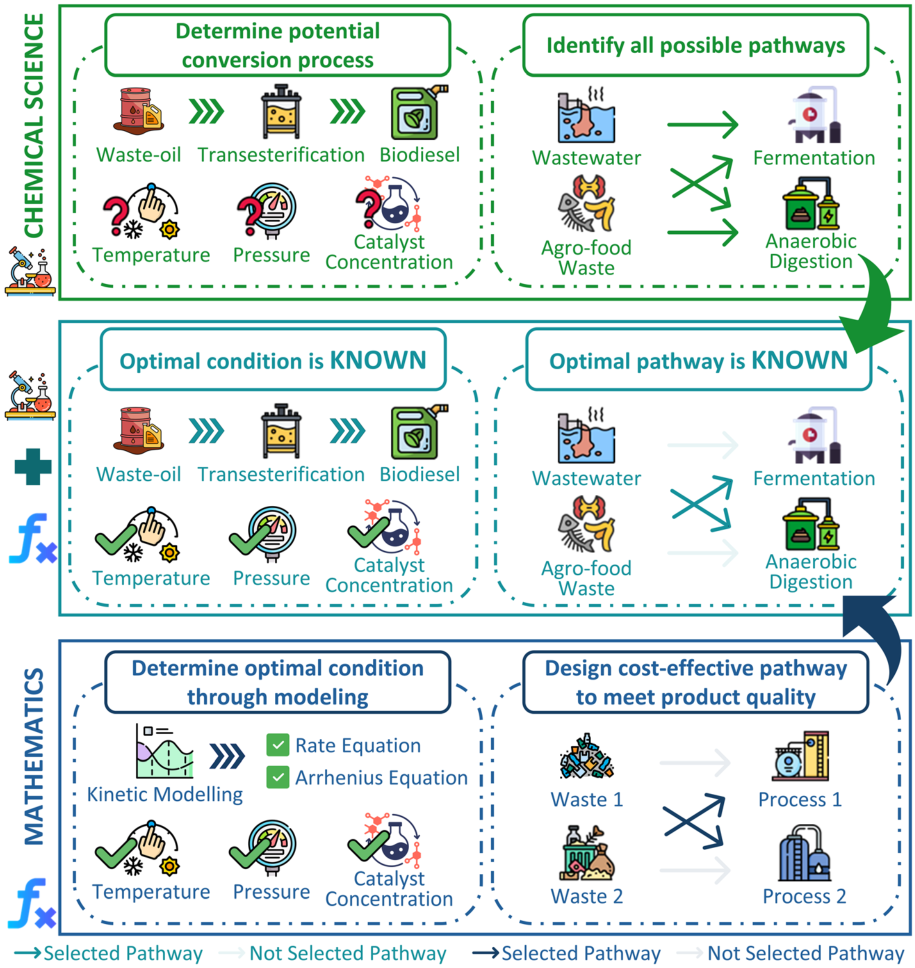

Fig. 2 Bridging chemical science and mathematics for waste-to-wealth initiatives.

knowledge.[9] Proper sorting reduces technical barriers for industries, lowering both capital and operating costs for re-sorting materials. It also enhances the availability of high-quality waste, facilitating the production of more valuable products. This, in turn, can drive down the cost of these products, making waste-to-wealth initiatives more viable.

While society participates in waste-to-wealth initiatives, government support is important to scale their impact. This requires investment in waste management technologies, which are associated with high investment costs. Governments can introduce carbon pricing, making pollution more expensive and incentivizing industries to reduce emissions. Another plausible solution is the Emissions Trading System, which allows nations to trade carbon credit. Nations that reduce emissions beyond their targets can sell surplus carbon credits to those struggling to meet their goals. Revenue generated from credit trading can then be used to subsidize sustainable waste management, driving the shift to a circular economy. Policies can be another key to success in waste-to-wealth initiatives. Governments must establish a strong framework to support the circular economy, aligning with SDG 12 (Responsible Consumption and Production). This framework should tackle economic, cultural, and technical barriers that hinder the shift from a wasteful linear model to a sustainable circular system. Countries like Malaysia,[10] the European Union,[11] Canada,[12] and Australia[13] have introduced policies to drive waste-to-wealth. One effective approach is the extended producer responsibility (ERP) policy that promotes sustainable practice by requiring manufacturers to be accountable for the entire life-cycle of their products. They can also adopt a Pay-As-You-Throw system to encourage waste reduction and recycling, as waste disposal fees are charged to residents based on the amount generated. Such policies have proven successful. For example, in Europe, the circularity rate has increased from 10.7% to 11.8% while landfill rates decreased from 23.3% to 16.1% between 2010 and 2023.[14]

Waste-to-wealth policies typically provide a top-down framework that guides the shift toward a sustainable future. This is where mathematics becomes indispensable by offering a bottom-up perspective, helping policymakers to see a bigger picture in allocating resources efficiently. These models enable scenario analysis to provide insights into the potential impact of

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various comprehensive waste management plans. For example, the models can determine optimal locations for sorting facilities and processing plants to maximize efficiency and minimize costs.[15] When these insights are integrated into policy execution, governments can refine strategies, ensuring resources are allocated where they can create the greatest impact, accelerating the transition toward a sustainable circular economy.

In conclusion, chemical science plays a crucial role in waste-to-wealth initiatives, while mathematics enhances these processes further by determining their optimal operating condition. Nevertheless, success requires collective action. Society and governments must collaborate to establish effective policies to drive global progress toward sustainability through innovation and responsible practices. The question now is: *how ready are we to take action and commit to these initiatives?*

Conflicts of interest

There are no conflicts to declare.

Data availability

There is no additional data associated with this article.

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