Innovative Pathways for Converting Biomass and Sewage Sludge into Valuable Resources – Integrated Multidisciplinary Research Excellence

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Green Solvent-Assisted Valorisation of Biomass for a Sustainable Bioeconomy

As the world moves toward cleaner and more dependable alternatives to fossil fuels, biomass has emerged as a central focus of sustainable research. This renewable feedstock, derived from agricultural residues, forestry byproducts, and other non-food plant materials, offers a practical pathway to reduce human reliance on limited petroleum resources. Transforming such biomass into fuels, chemicals, and materials not only supports a greener industrial landscape but also strengthens the foundations of a circular bioeconomy, where waste is reintegrated as a usable resource rather than discarded. The overall process of biomass valorisation and its contribution to a sustainable bioeconomy is illustrated in Figure 1.

A major step toward this transition lies in developing gentler, more efficient pretreatment methods that break down the complex structure of biomass. Conventional approaches often rely on strong acids or alkalis, which demand high energy input, are not environmentally friendly, and create waste streams. In contrast, green solvents such as ionic liquids (ILs) and deep eutectic solvents (DESs) provide a cleaner and more adaptable route. Well-studied ILs, including 1-ethyl-3-methylimidazolium acetate and 1-butyl-3-methylimidazolium chloride, have demonstrated the ability to disrupt lignin–carbohydrate linkages and enhance the conversion of cellulose to fermentable sugars. Similarly, DESs formed from combinations like choline chloride with glycerol or urea offer low toxicity, biodegradability, and straightforward preparation, making them suitable for sustainable processing.

In parallel, the study also investigates advanced DES systems, including the di-ionic ammonium-based DBTMEDABr/TFA and TMDPEDABr/LA, which provide an environmentally friendly and cost-efficient alternative for biomass pretreatment. These tunable DESs interact strongly with the carbohydrate matrix in biomass, supporting selective removal of lignin and enhancing the accessibility of cellulose for subsequent hydrolysis. Their application to diverse feedstocks, such as sugarcane bagasse, rice straw, and Napier grass, demonstrates the versatility of green solvent systems across varied biomass sources.

Beyond pretreatment, these solvents assist in generating valuable platform chemicals like 5-hydroxymethylfurfural (5-HMF) and furfural, compounds central to the development of bio-based polymers, fuels, and specialty chemicals. By enabling such transformations under moderate conditions, IL- and DES-based systems reduce energy consumption and minimise the formation of unwanted byproducts that commonly hinder downstream processing.

The broader impact of our research lies in its contribution to establishing sustainable biorefineries that align with principles of green chemistry. Through selective fractionation of lignin, cellulose, and hemicellulose, these solvent systems create opportunities for producing a wide spectrum of renewable products, from fermentable sugars and biofuels to high-value chemicals and advanced materials. The continued refinement of solvent design, process optimisation, and feedstock selection is essential to scaling these technologies and embedding them within a functional circular bioeconomy.

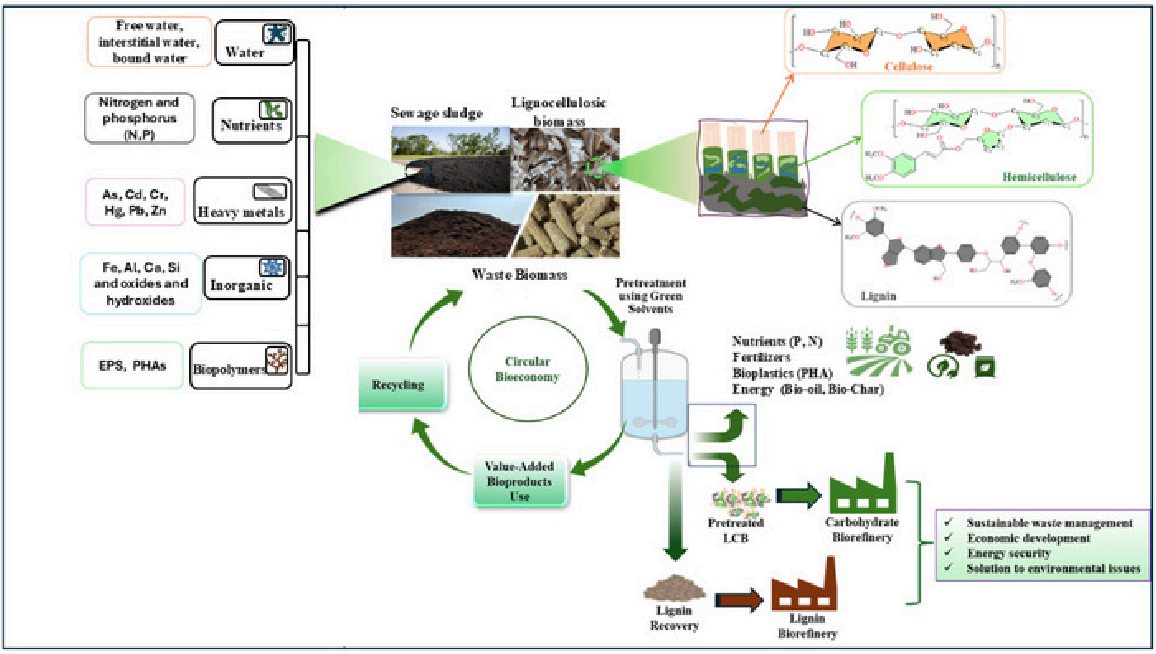

Figure 1. Waste biomass valorisation via a sustainable approach.

Advancing the valorisation of lignocellulosic biomass is inherently interdisciplinary, bringing together expertise in chemistry, biotechnology, materials science, and engineering. This work reinforces the value of such collaboration by demonstrating how innovative solvent development can unlock new efficiencies, lower environmental impact, and accelerate the shift toward resource-responsible industrial practices. With greener pretreatment pathways and more accessible conversion routes, the vision of transforming agricultural and industrial residues into valuable products becomes increasingly achievable, contributing to a sustainable and economically resilient future.

Sustainable Valorisation of Sewage Sludge: A Complementary Pathway

While biomass valorisation progresses toward greener methodologies, sustainable management of sewage sludge (SS) represents another critical challenge in waste-to-resource research. SS, generated as an unavoidable byproduct of wastewater treatment, is often produced in huge quantities and poses environmental, economic, and regulatory concerns. Turning this semi-solid waste into valuable products is therefore essential for closing resource loops and advancing sustainable waste-management practices.

At IITH, ongoing research work at the sewage treatment plant spans multiple research areas, including wastewater treatment, water reuse, and the valorisation of generated residues. One of the main areas of focus is the transformation of sewage sludge, an unavoidable byproduct of wastewater treatment, into value-added materials. Such efforts contribute to closing the loop within a circular economy and reflect the broader goals of sustainable resource recovery and management. SS contains organic matter, nutrients, and mineral components that can be harnessed to produce low-cost adsorbents, bioplastics, nutrient fertilisers (N and P), proteins, nanocomposite materials, and biofuels. For instance, adsorbents derived from SS can be further modified with metal oxides to enhance their capacity for removing contaminants, particularly micropollutants in water.

Despite the long-standing use of conventional SS management methods, such as land application, composting, incineration, and anaerobic digestion (AD), these approaches have limitations. Land application risks heavy-metal build-up and nutrient leaching; incineration leads to energy loss, air pollutants such as nitrogen and sulfur oxides (NO_x and SO_x), and the permanent loss of recoverable phosphorus; and while AD is cost-effective, its efficiency is limited by the slow biodegradability of certain sludge components. Additionally, sludge disposal represents more than half of the total operating cost of many wastewater treatment plants and contributes significantly to greenhouse gas emissions.

These limitations have intensified interest in non-conventional, sustainable conversion techniques. Thermochemical processes, hydrothermal carbonisation, hydrothermal liquefaction, pyrolysis, and gasification, offer multiple pathways to convert SS into solid, liquid, and gaseous fuels, carbon-rich materials, and precursor chemicals. Similarly, biochemical routes enable nutrient recovery and biopolymer extraction under environmentally benign conditions. Integrating these processes allows sequential recovery of diverse products, maximising resource utilisation while minimising waste. Figure 1 illustrates the sustainable valorisation pathways of sewage sludge and the range of recovered products.

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Our research focuses on the large-scale utilisation of SS as a raw material for value-added transformations. By adopting low-toxicity solvents, energy-efficient processing routes, and modular conversion strategies, the work aligns closely with the principles of sustainable biomass and waste management. We also explored amino-acid-based DESs as green solvents for the hydrothermal carbonisation of SS to generate a carbon-rich hydrochar. Ultimately, these efforts aim to develop economically feasible and environmentally responsible technologies that can reduce sludge burdens while generating useful products for industrial and agricultural applications.

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