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Editorial

Emerging Technologies for Waste Treatment, Reuse and Energy Production

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1. Introduction

The energy and environmental crisis, growing energy demand, and the degradation of natural resources [1–3] emphasize the importance of developing and implementing innovative, sustainable technologies for the material processing and energy recovery of these materials. In this context, the transition toward a circular economy [4–6] is key for enhancing resource efficiency, reducing environmental impact, and promoting sustainable production and consumption. At the same time, the utilization of organic-biomass and waste-residues as secondary raw materials can contribute to energy and biofuel production [7–12] and material recovery [13–19].

These challenges are directly linked to the UN Sustainable Development Goals (SDGs) (Goal. 7: sustainable and low-cost energy, Goal. 8: sustainable economic development, Goal. 9: creative thinking and innovate technologies, Goal. 11: green cities and societies, Goal. 12: conscientious manufacturing and usage, Goal. 13: practices that strengthen commitment to climate action [20,21]). Achieving these goals requires the establishment of integrated management of waste, the optimization of existing processes, and the utilization of combined technological approaches that can enhance energy yield, reduce environmental impact, and promote resource recovery.

In this context, this Special Issue (SI) named "Emerging Technologies for Waste Treatment, Reuse and Energy Production" published in the Journal "Applied Sciences" launched to discuss recent technological developments in energy production, waste treatment and reuse, and material recovery. The contributions collectively comprise original research papers and review papers covering a wide range of scientific fields, including the biomass thermochemical and biochemical routes, the biofuels and biogas production, the extraction of valuable materials from aqueous solutions, the energy value of agricultural and industrial residues, the adsorbents regeneration, and the evaluations of environmental concerns related to waste management. Additionally, it investigates problems related to thermal storage, heat recovery, energy efficiency, and the development of sustainable procedures for the better use of secondary resources. The contributions to this SI highlight the importance of an interdisciplinary approach to addressing complex energy and environmental challenges. More specifically, the energy recovery potential of biomass residues is highlighted using a variety of biomasses (such as from the brewing industry, microalgae, aquatic plants, pet food waste, and sawdust). Furthermore, by highlighting both the possibility of material recovery and efficient environmental risk management, research on the regeneration of activate carbon, the recovery of strontium from seawater, and the evaluation of microplastics in sewage sludge expands the application of circular economy principles. In addition, the

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study of Organic Rankine Cycle systems, in combination with thermal storage, emphasizes how crucial it is to effectively use thermal flows that would otherwise go unexplored.

Collectively, this Special Issue contributes to highlighting scientific and technological advances that support the transition from linear economy models to integrated circular resource management systems. The synthesis of research findings and literature reviews provides valuable insights into optimizing waste treatment processes, improving energy and material recovery, and developing more efficient and environmentally responsible technologies. The contributions to this Special Issue emphasize scientific and technological innovation's role in advancing sustainable energy transition, enhancing environmental protection, and supporting global Sustainable Development Goals efforts.

2. Overview of Contributions

Seven original articles and four review papers on the following topics are included in this Special Issue: waste management and environmental risks; environmental technology and resource recovery; biomass and bioenergy production; and heat efficiency and heat recovery.

Gimžauskaitė and Eimontas (contribution 1) studied several thermochemical biomass routes for sustainable biofuel production, aiming to reduce reliance on fossil fuels and mitigate environmental risks. The review article presents major conversion routes, factors affecting their effectiveness, and the potential for utilizing various types of biomasses. It also examines the challenges and future prospects of these technologies within the context of the development of sustainable energy. Vasileiadou et al. (contribution 2) studied not only energy production and the enhancement of overall process efficiency from the utilization of Brewer's Spent Grain (BSG), but also materials for energy storage applications based on BSG. A major byproduct of the brewing organizations is BSG. Particular emphasis in this review paper is given to minimizing environmental impacts and implementing the principles of the circular economy by transforming industrial waste into important sources of energy. About 302 NL CH_4/kg COD is produced by AD of BSG, which produces about 0.39 kWh of electricity and 1.71 MJ of heat energy per kilogram of BSG. Ultrasonic pretreatment lowers CO_2 emissions by 0.083 t CO_{2eq}/t BSG and increases CH_4 production (107 L CH_4/kg TVS). When BSG and other brewery waste was anaerobically co-digested, the yield rose to 88 mL CH_4/g TVS, about 0.35 kWh/kg TVS power was produced, and emissions were decreased by 0.114 kg CO_{2eq}/kg TVS. Up to 71.8% of the bio-oil produced by BSG pyrolysis has an average energy content of 22 MJ/kg. The BSG combustion led to a calorific value more than 19 MJ/kg while torrefied BSG showed a value of 25 MJ/kg. While biohydrogen production reached 5154 mL H_2/g glucose, bioethanol yields might approach 72%. For lithium-sulfur batteries, activated biocarbon derived from BSG offers a significant surface area (1792 m^2/g). The study demonstrated that BSG's conversion to sustainable energy and storage for energy conforms with sustainability and waste mitigation objectives. Additional studies in integrated technologies, artificial intelligence technologies, and merged alternative wastes may produce the greatest outcomes and increase yield.

Nganko et al. (contribution 3) experimentally examined the valorization of sawdust from Framiré wood, combining the recovery of compounds of biological interest with the production of solid fuel. More specifically, they explore the potential for extracting secondary metabolites from woody biomass and subsequently converting the remaining residues into fuel briquettes. The gross calorific value found approx. 26.15 (fuels with secondary metabolites) and 26.20 MJ/kg (for fuels without metabolic products). The precise amount of fuel consumed varied significantly, falling from 1.400 kg/L for fuels without secondary metabolites to 0.86 kg/L for fuels with them. The extracts' yellowness index varied between 73.490 (maceration) and 81.720 (infusion). The findings present encouraging

opportunities, especially for the development of flame-retardant products for wood and its derivatives using Framiré extracts. In addition, it highlights the potential to integrate energy and chemical compound generation. Dębowski et al. (contribution 4) investigate experimentally the effect of pretreating microalgae and cyanobacteria with sCO_2 on anaerobic digestion (AD) effectiveness. AD is an important biological route for transforming organic material into biogas. AD kinetics, changes in organic matter solubility, and CH_4 generation yield were examined. The study explores how a pretreatment method boosts energy recovery from aquatic biomass. Appropriate biomass pretreatment can improve the availability of organic components to microbes and aid in the disintegration of cellular structures. The results showed that in optimal variation (1 sCO_2: 2.5 biomass), CH_4 yield rose to 354 mL CH_4/gVS for T. subcordiformis and 403 mL CH_4/gVS for L. platensis, respectively. The efficiency of anaerobic biomass biodegradation relies on chemical composition, cellular structure, and physicochemical interactions. Utilizing sCO_2 as a disintegrant may effectively enhance fermentation efficiency in biowaste management and energy saving.

Puratich-Fernández et al. (contribution 5) experimentally examine the potential for utilizing unsellable pet food waste as biomass fuel for energy production. This waste category can provide alternative energy, but needs assessment of combustion properties, emissions, and equipment corrosion risks. The study assessed chemical composition, energy impact, VOC emissions, and boiler metal corrosion, while evaluating energy efficiency and sustainability in the production process and waste combustion characteristics. Similar to radiata pine wood, the material had minimal levels of heavy metals, a high energy content of 0.0195 GJ/kg, and an ash concentration of less than 1%. It was possible to reduce CO_{2eq} by 0.015 Mg/Mg of pet food produced. Because of the molecular nature of the molecules, VOCs had very little effect on the environment. Furthermore, in the case of cat food, the corrosion rate generated by waste combustion was similar to that of home gas, whereas dog food produced similar value to other biomass types like wood chips and pellets. The results show that it is possible to generate thermal energy, lower greenhouse gas emissions, and achieve carbon neutrality targets by 2050 by using a biomass combination of wood chips and unsellable pet food waste for industrial boilers.

With a focus on the existence of microplastics, Worek et al. (contribution 6) examined the environmental risk of using stabilized sewage sludge as a fertilizer in agriculture. Microplastics are persistent environmental contaminants in agriculture that pose a threat to soil, groundwater, and the food chain. The study focuses on evaluating these dangers and highlights the need for appropriate quality control of the sludge prior to its application on agricultural land.

The recovery of high-purity strontium (Sr) from seawater and the brine produced by desalination technologies is discussed in the review study (contribution 7). Sr is an essential component for numerous industrial applications. An alternative to removing Sr from deposits on land is to recover it from aqueous solutions. The paper explores the opportunities, limitations, and technological challenges related to the effectiveness and purity of the recovery process, with an emphasis on adsorbent materials that allow the selective capture of this element.

Zhang et al. (contribution 8) present an integrated approach for using duckweed to remediate zinc and ammonium-contaminated water, followed by the energy-valuation of the resulting biomass. Different starting zinc and ammonium concentrations were used to cultivate duckweed. After contaminants are eliminated from the water using aquatic plants, the collected biomass is first processed to AD to create biogas. The liquid fraction generates more CH_4 than the solid fraction. However, methane generation from liquid hydrolysate dramatically decreased in conditions high in zinc and ammonium, with the lowest yields from duckweed grown solely in zinc due to high zinc inhibition. This method

improves the more effective management of water and biological resources by combining the treatment of liquid waste with energy recovery. It also emphasizes how crucial it is to determine whether the biomass generated is suitable for energy usage, particularly if it has grown in contaminated waters. The paper presents a specific experimental implementation of an integrated approach on water remediation and energy recovery.

Birriel et al. (contribution 9) assessed exergy and thermal performance of an Organic Rankine Cycle (ORC) combined with a thermal storage system using several thermal oils. While exergy assessment helps in identifying losses and optimization opportunities, thermal analysis focuses on the system's energy efficiency. The difference in temperature concerning the heat source and the boiler had a major impact on thermal efficiency for the direct-heated ORC, reaching a maximum value of almost 50%. The exergetic efficiency was greatly increased by integrating a thermal energy storage system with a tuned temperature profile. The results demonstrate that the ORC system's exergetic efficiency is significantly increased by the incorporation of thermal oils, highlighting their vital role in enhancing energy transformation from renewable sources of heat.

The goal of Ye et al.'s research (contribution 10) was to develop a pyrolysis-activation regeneration technique that could produce extremely porous carbon materials from waste granular activated carbon (GAC). Thermochemical analyses were carried out to examine the spent GAC's thermal degradation behavior. The N_2 pyrolysis and CO_2 activation experiments were then conducted under different process conditions using the thermal regeneration system. In addition, they used a surface area and porosimeter for pore property measurement, scanning electron microscopy for porous texture observation, and energy dispersive X-ray spectroscopy for surface elemental distribution analysis. The findings showed that the pore characteristics of thermally regenerated GAC were considerably better than those of spent GAC, demonstrating the efficient removal or breakdown of deposited materials and adsorbed organics under process conditions. Furthermore, compared to simple pyrolysis, thermal regeneration through physical activation with CO_2 produced improved pore characteristics.

Last but not least, Ferreira-Filipe et al. (contribution 11) examined plastics derived from electrical and electronic waste (e-waste plastics), emphasizing their characterization, environmental presence, and biological treatment potential. Financial obstacles, a lack of research, and environmental concerns are obstacles to the characterization of environmental contaminants and treatment techniques for hazardous e-waste plastics. Improving the sustainable treatment of e-waste plastics requires further investigation, interdisciplinary cooperation, and policy support.

In general, the articles address a broad range of subjects pertaining to waste treatment, energy recovery from biomass, sustainable resource management, heat recovery, and environmental pollution prevention.

3. Conclusions

A summary of the papers published in the Special Issue titled "Emerging Technologies for Waste Treatment, Reuse and Energy Production" published in the Journal "Applied Sciences" reveals how significant the role of modern technological advances for energy recovery, secondary materials and value-added products, and waste treatment are to the promoting of sustainable development and a circular economy. The investigation of ways to transform biomass residues and waste into valuable energy or material resources while simultaneously reducing the environmental impact of their processes and treatment is a common feature of these studies, despite the variety of processes and materials examined.

Studies concerning the energy valorization of biomass residues are of particular significance. Thermochemical and biochemical conversions and the utilization of various types of

biomass residues/wastes (e.g., sawdust, pet food waste, brewing waste, aquatic plants and microalgae) offer a wide range of applications for (solid or biogas) biofuel production. In addition, biomass pretreatment and the optimization of the conversion method are crucial for energy recovery.

Additionally, studies on material recovery (strontium from seawater and desalination brine) and adsorbent (spent activated carbon) regeneration emphasize how crucial it is to utilize secondary resources to reduce the consumption of primary raw materials.

Similarly, the combined use of aquatic plants to remove contaminants from water and the energetic utilization of the generated biomass highlights the potential of integrated systems that combine energy recovery with environmental remediation.

Simultaneously, the assessment of the Organic Rankine Cycle in conjunction with thermal storage emphasizes the significance of low temperature heat recovery and the enhancement of energy efficiency. Utilizing thermal flows that would otherwise be lost can contribute to decreasing energy waste and increase energy operating efficiency.

For the selection of an appropriate route to transform waste into clean energy and secondary materials, we must consider waste composition, energy yield, economic costs, industrial feasibility and environmental impact. A comprehensive evaluation of technical, environmental and economic factors is essential to determine if the suggested solutions can be implemented in a sustainable and efficient manner.

The research included in this Special Issue shows that efficient waste management requires an integrated strategy rather than relying solely on a single technology for effective solutions.

In summary, this Special Issue highlights the potential of emerging technologies to transform waste into value-added products, generate cleaner energy from biomass residues, and reduce the environmental effect, promoting the United Nations Sustainable Development Goals (SDG7, SDG8, SDG9, SDG11, and SDG 13).

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