energies

Editorial

Recovery of Solid Waste in Industrial and Environmental Processes

Antonio Trinca [1], Valentina Segneri [1], Thanasis Mpouras [2], Nelson Libardi [3] and Giorgio Vilardi [1,*]

[1] Department of Chemical Engineering Materials Environment, "Sapienza" University of Rome, Via Eudossiana 18, 00184 Rome, Italy
[2] Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, Iroon Polytechniou 9, Zografou, 15780 Athens, Greece
[3] Department of Sanitary and Environmental Engineering, Federal University of Santa Catarina, Florianópolis 88040-970, SC, Brazil
* Correspondence: giorgio.vilardi@uniroma1.it; Tel.: +39-0644585580; Fax: +39-0644585451

In recent years, an alarming increase in CO_2 emissions has been noticed. For this reason, the reduction of greenhouse gas emissions seems mandatory. With this target in mind, the United Nations Framework Convention on Climate Change (UNFCC) came to a new agreement in 2015 with the aim of limiting the increase of the average atmospheric temperature to 2 °C. To achieve this goal, the total amount of CO_2 emissions in the atmosphere must be limited to only 1000 Gt by 2100. Finally, with the last agreement of the UE Climate Action, called the 2050 Long-Term Strategy, all European countries must achieve "carbon neutrality" by 2050. This means that net greenhouse gas emissions must be zero by 2050. During the last few years, the Renewable Energy Directive (RED) has been implemented, with the aim of reducing carbon footprints so as to achieve the EU's objective of climate neutrality by 2050.

The increasing amounts of municipal solid waste (MSW) generated contributes to the landfilling problem. One of the solutions to this problem is the thermal conversion of waste in thermal plants. Thermal treatment of waste is one of the methods to reduce the volume (up to 90%) and mass (approximately by 70%) of waste generated while recovering the waste energy. In an era of climate change and political pressures, there is an urgent need for new, more environmentally friendly energy sources.

The development of sustainable industrial and environmental processes through the recycling of material is considered a fundamental task for various researchers and companies, since the re-utilization of solid wastes is one of the pillars of Circular Economy.

The current aim is to develop sustainable processes to allow the complete re-utilization of various industrial and agricultural wastes. Among these novel materials, agro-industrial wastes have been demonstrated to be suitable for energy and raw material recovery, by transforming them in gaseous/liquid fuels (gasification/pyrolysis) or by activating them to produce functionalized adsorbent materials.

In this editorial, the authors analyze original research papers on the topics related to raw material recovery from agro-industrial waste. The studies report the complete reuse of the waste, focusing on the overall costs and sustainability of the proposed processes.

The topics covered are various, but strongly interrelated among each other, as quite different problems converge in the area of advanced waste to chemicals plant challenge. Therefore, selecting the proper keywords that characterize the research allows us to build the correlation matrix reported in Table 1, which helps the reader to have a global view of the arguments of the considered advanced research papers. Moreover, a short summary of all the papers is reported. The order of the discussed papers has been accurately chosen as follows.

Citation: Trinca, A.; Segneri, V.; Mpouras, T.; Libardi, N.; Vilardi, G. Recovery of Solid Waste in Industrial and Environmental Processes. *Energies* **2022**, *15*, 7418. https://doi.org/10.3390/en15197418

Received: 16 August 2022
Accepted: 26 September 2022
Published: 10 October 2022

Table 1. Correlation matrix of the selected keywords.

	[1]	[2]	[3]	[4]
Circular Economy	X	X	X	
Agro-Industrial Waste Reuse		X	X	X
Plant Analysis and Simulation		X		
Energy Recovery	X	X		
Environmental Processes		X	X	X
Energy and Exergy Analysis		X		

The amount of urban domestic garbage waste grows rapidly with economic and social development in developing countries, and this includes China, where it reached 343 million tons in 2019. In particular, the food waste component is the source of many of the serious environmental problems created when the mixed waste goes into landfills and incineration, because it produces methane and leachates. If food waste is sorted and diverted into other processes, such as composting or anaerobic digestion (AD), then much lower carbon emissions will be produced. Furthermore, the diversion of food waste in China would create other benefits through more effective use and reuse of resources and land use.

In the first article, Li et al. [1] have been investigated the outstanding diversion results of Shanghai Municipality since the introduction of the July 2019 Municipal Regulations, of over 9600 tons per day of clean waste, still maintained two years later. The July 2019 policy brought in legal responsibilities to very clearly defined roles for each stakeholder—including for the residents to sort and for local governances to support them—and this pulled all the operational elements together. The immediate and sustained jumps in clean waste collection fed biogas production (0.1–1.0 GWh/day) and energy-from-waste (5.4–8.6 GWh/day).

Right up to the July 2019 law implementation, contamination levels were generally too high for food waste to be useful for anaerobic digestion to produce biogas. Previous unsuccessful attempts to utilize it for composting had resulted in the closure of some composting facilities. In short, between the announcement of the new policy in January 2019, and one year after its mandatory implementation (July 2020), the waste management system for residential waste changed very significantly in every dimension. To understand why the final outcome was suddenly achieved—namely large tonnages of cleanly diverted food waste that allowed a shift from landfill to AD—it is necessary to note that the biggest changes occurred right around July 2019. The passing of the policy into law, and its crystal-clear role allocations, including for residents, seems to have provided the final element to bring the rest into fruition. Although all stakeholders needed to perform their part, they also needed to perform it in cooperation with each other, and the July 2019 policy was the first document which clearly set out the relative roles.

Shanghai is one of the biggest cities in the world. The waste sorting performance after the implementation of the July 2019 law is a huge success compared with other metropolises. Nearly 9200 tons/day of food waste is now sorted, which means nearly 70% of residential food waste. It is interesting that no other cities in China have yet managed to achieve sustained or large-scale success with residential food waste sorting in terms of contamination levels or scale. Therefore, there is clearly a need for further studies of the Shanghai example to understand how it was made to work. The indications from our findings are that the habitual behavior changes of residents at a community level were the most critical final element. The underpinning reasons for that would be useful to determine through more research. However, it is clear that good sorting behavior alone could not achieve the energy increases, even if all the engineering and transportation infrastructures were already in place. However, bad sorting behavior could prevent infrastructure investments from showing energy results. Therefore, this study suggests that the status of behavioral factors may well be a highly significant blockage in the final achievement of energy production from residential waste. It implies that perhaps the behavioral dimension should be held more to account for the overall performance of energy production achieved from integrated waste management systems. A further study of the causal links in this case would be very useful. The full contribution of energy-extraction facilities and technologies, such as energy-from-waste incinerators and anaerobic digestion plants, might not be able to be judged otherwise.

The REDII (Renewable Energy Directive II) establishes a common framework to promote energy from renewable sources in electricity, heating and cooling, and in the transport sectors for the 2021–2030 period, but it also includes as part of the definition of "recycled carbon fuels" liquid and gaseous fuels produced either from liquid or solid waste streams of non-renewable origin or from waste processing gases and exhaust gases of non-renewable origin, in order to incorporate the following criteria: greenhouse gas (GHG) emission savings need to be at least 70% compared to fossil fuels; energy inputs need to be counted in a similar way to electricity; and fossil energy inputs are to be calculated for biofuels when determining their GHG performance.

Under this scenario, one possible way to achieve the above target, and to exploit REDII in a bioethanol production process, by municipal waste valorization, have been investigated by Rispoli et al. [2]. In this case, a liquid fuel, such as ethanol, is produced from a waste source and the electrification of the heat transfer units allows to decrease the overall GHG emissions. The conversion of heating consumption into electrical consumption would be an important step in the energy transition route, once coupled to an increasing share of renewables in the grid, with the aim of meeting the GHG target imposed by RED II. This strategy can be adopted by increasing the use of green energy sources to reduce CO_2 emissions and fossil fuel dependency.

In their work, they found bioethanol to be a promising substitute for fossil fuels in terms of energy transition, which would help to mitigate GHG emissions. In this work a bioethanol production plant from waste conversion was considered, focusing mainly on an electrical-driven solution for the azeotropic water–ethanol distillation tower. The strategy used is Mechanical Vapor Compression (MVC), which converts the steam consumption required to boil the bottom of the column into electrical consumption. According to the authors' knowledge, this is the first work where a complete evaluation of the MVC implementation in the ethanol–water distillation operation is reported, focusing on the possibility of carbon footprint reduction.

The simulation of the whole distillation unit was carried out with the software Aspen Plus®, using which the authors selected the best option in terms of a column to be coupled with MVC (Mechanical Vapor Compression). Therefore, two fundamental analyses, especially in an energy transition perspective, were carried out: an economic analysis and an environmental one. These two analyses a restrictively correlated, due to the carbon tax, which economically quantifies the price of CO_2 emissions. It has been reported that, despite an increase in capital cost due to the necessity of a compressor, there is a notable reduction (63%) of the operative costs and a remarkable reduction of carbon dioxide emissions (i.e., a 79% reduction of the overall carbon footprint related to the column operation). Finally, also, the exergetic analysis shows improved efficiency because of the waste exergy stream reduction. Exergetic analysis allowed the quantification of possible improvements related to waste minimization, overcoming the limits of first-principle analysis, which does not take into account the influence of waste streams in its efficiency estimation. The significant reduction of carbon dioxide emissions led to the conclusion that electrification is a potential way to decrease the carbon footprint associated with the production of ethanol. Moreover, given the large number of distillation towers in the chemical industry, the authors are confident that this solution can be applied in different processes, allowing for the fulfilment of the UE goal of carbon neutrality by 2050 and the target of RED II with respect to GHG to be reached.

Plastics are one of the basic construction materials with a wide range of various applications. Polymers and plastics are an essential material in many areas of the economy, ranging from packaging, textiles and electronics to machinery and equipment components as well as various structures. This is due to their numerous advantages, such as low density, ease of shaping, high corrosion resistance and good mechanical strength.

One of their disadvantages is the problem of managing the waste they generate. Chemical recycling offers the possibility of liquefying polymeric waste and using it as fuel components. The quality of the received fuel components is influenced not only by the polymer waste processing technology, but also by the feedstock composition. Existing technologies giving good quality products are expensive.

The awareness of the risks posed by the growing production of plastic products is accompanied by the need to produce them due to the lack of natural alternatives to this type of material. Considering the scale of the problem, the development and dissemination of the best technologies for recycling and utilization of plastic waste becomes a priority. The predominant form of recycling plastic waste is energy recovery through combustion.

The combustion of plastics results in the removal of this material from the economy and the irrevocable loss of material that could be used in other ways. Material recycling is the most environmentally favorable waste management method (the lowest amount of emitted CO_2); however, the material loses quality with each successive processing cycle and, in order to improve the product quality, a regranulate is mixed with a fresh batch of polymer. This results in products with poorer properties (compared to those obtained from the virgin polymer), which in the end lose their quality to such an extent that they cannot be recycled using this method.

It is estimated that the cost of producing heating oil (and, therefore, fuel of lower quality) from waste plastics in the pyrolysis process is approximately $1.13/kg, which is over 50% more than in the case of market fuels. Therefore, there is a need for efficient and cost-effective technologies to recycle these materials. Such possibilities are offered by HT technology.

The HT technology developed and described by Matuszewska et al. [3] is cheaper and enables a high-quality product to be obtained. The presented thermolysis technology not only enables more advanced recycling, but also gives the possibility of partial improvement of the product quality. A product with the best physicochemical properties was obtained from a blend of PE:PP:PS used in the ratio 60:30:10. It was proved that diesel and petrol blends composed of a 5% v/v share of petrol and diesel fractions, obtained from thermolysis of plastics, meet the normative requirements of fuel quality standards.

The developed HT technology offers the possibility to liquefy plastics without a catalyst and conduct the catalytic hydrogenation process under atmospheric pressure (in a synthesis gas atmosphere), thus lowering the process costs. It is suspected that the possibility of carrying out hydrogenation under atmospheric pressure may be due to the catalytic effect of carbon monoxide present in the synthesis gas. At the same time, a product with desirable functional properties is obtained from the waste with high efficiency. The technology described is fully compatible with a closed-circuit economy and shows no waste, only unused raw materials.

The fraction of waste that cannot be recycled or for which a suitable conversion process does not yet exist (mixed waste classified as waste unsuitable for recovery and recycling), is often sent to landfill or incineration. However, the waste from conventional incineration, which contains hazardous substances, must be disposed of in an appropriate manner.

Modern incineration plants, thanks to the application of the best available techniques (BAT) presented in the Best Available Techniques Reference Document (BREF), ensure that no significant pollution is caused. However, the incineration process produces large amounts of residues, which can account even for 38% of the input material. These residues include, among others, fly ash 1–3% (FA), incineration bottom ash 20–30% (IBA), and air pollution control residues 2–5% (APCr). A number of studies have investigated the loss of valuable metals when residues are landfilled. While the production of significant amounts of these residues is associated with the challenges of their management and processing, most o IBA after weathering and the recovery of metals can be recycled as a road sub-base and replace natural aggregates typically used in that process. Unfortunately, some of these residues, due to their heavy metal content and leaching potential, have environmental impacts on soils and water and can be classified as a hazardous waste that requires specialized processing methods. Heavy metals, such as Cr, Cu, Pb, Hg, and Ni, are commonly present in leachate. A number of studies investigated IBA and their leaching potential as a function of time and pH or their particle size. The degree of leaching of environmentally hazardous substances has also been the subject of geochemical modeling.

The study of Bielowicz et al. [4] reports advanced statistical tools, such as control charts, trend analysis, and time series analysis, based on the leachability of selected elements and chemical compounds in incineration bottom ashes (IBAs). This paper is the first to use advanced statistical tools to examine the stability and seasonality in chemical compounds in IBA.

Using advanced statistical tools, the stability of the IBA composition was examined in terms of the amount of leaching elements, such as arsenic, barium, cadmium, copper, chromium, mercury, molybdenum, nickel, lead, antimony, selenium, zinc, and the following compounds: chlorides, sulphates, and fluorides, as well as the content of dissolved organic carbon (DOC) and total dissolved solids (TDSs). The research methodology, which was presented on the example of the leachability of elements and compounds from IBA, can also be used for other waste analyses.

Author Contributions: Conceptualization, formal analysis, A.T., V.S. and G.V.; writing—original draft preparation, A.T. and V.S.; writing—review and editing, A.T., V.S., T.M., N.L. and G.V.; supervision, G.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Li, C.; Firoozmand, F.; Harder, M.K. The Impacts of Shanghai's July 2019 Municipal Domestic Waste Management Regulations on Energy Production. *Energies* **2021**, *14*, 7658. [CrossRef]
2. Rispoli, A.L.; Rispoli, G.; Verdone, N.; Salladini, A.; Agostini, E.; Boccacci, M.; Parisi, M.P.; Mazzarotta, B.; Vilardi, G. The Electrification of Conventional Industrial Processes: The Use of Mechanical Vapor Compression in an EtOH-Water Distillation Tower. *Energies* **2021**, *14*, 7267. [CrossRef]
3. Matuszewska, A.; Hańderek, A.; Paczuski, M.; Biernat, K. Hydrocarbon Fractions from Thermolysis of Waste Plastics as Components of Engine Fuels. *Energies* **2021**, *14*, 7245. [CrossRef]
4. Bielowicz, B.; Chuchro, M.; Jędrusiak, R.; Wątor, K. Changes in Leachability of Selected Elements and Chemical Compounds in Residues from Municipal Waste Incineration Plants. *Energies* **2021**, *14*, 771. [CrossRef]