recycling

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Editorial

Special Issue "Feature Papers in Recycling 2021"

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1. Introduction

Recycling is the collection and conversion process of waste materials into second raw materials. It is crucial in the waste management hierarchy and also in sustainability. In fact, recycling helps in conserving natural resources, creating value, reducing carbon footprint and environmental pollution, increasing health. The concrete implementation of recycling requires the chemical and physical characterization of different types of waste materials, the development of technological processes, the definition of the proper legislative and policy frame and the involvement and education of consumers.

The purpose of this Special Issue was the collection of high-quality papers (original research articles or comprehensive review papers), focusing on the above-mentioned fields, which are also the main fields covered by the journal, and in particular include resource recycling, waste processing technologies, circular economy, zero waste programs, environmental and social impact of recycling, product (eco) design and recycling. The Special Issue has collected 4 review papers and 13 research papers. The papers involved fifty-five authors from seven countries of Europe (Italy, Spain, Finland, UK, Portugal, Germany, Macedonia), Africa (Egypt, South Africa), Asia (Malaysia, India, Indonesia, Japan, UAE and Saudi Arabia), Russia and Australia. The most relevant contributions of each paper are briefly described in the following section.

2. Research Findings

In this section, the research findings collected in the Special Issue are summarized and discussed, focusing on the following three main aspects: characterization of recycled materials, methods and trends for recycling, environmental, social and legal aspects of recycling.

2.1. Characterization of Recycled Materials

The demand for raw materials is continuously increasing worldwide with high production rates, which could result in a shortage of materials in the future. The recycling of secondary raw materials from waste is a sustainable option from both an economical and environmental point of view. To increase the recycling of different types of waste, a characterization of materials is needed.

In [1], the physical properties of metal and plastic bottle caps were studied, via SEM and FTIR spectroscopy analyses. The results show that metal caps are mainly made of iron and aluminum, while plastic caps were made by polyethylene (high-density HDPE and low-density LDPE), with a few particles of polypropylene (PP). The plastic's densities ranged between 0.752 and 0.956 g/cm^3, while aluminum and iron materials had significantly higher densities of 1.66–1.97 g/cm^3 and 4.43 g/cm^3. Slight reductions in the density values of the metal particles can be attributed to the inside plastic coatings. Experimental tests were also devoted to determine the settling velocities for the aluminum (12 cm/s) and iron (18 cm/s) particles, which were significantly higher than the rising velocities of the

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plastic particles (2.1 to 6.1 cm/s). These values give indications on the behavior of such materials in water and are used by the authors for developing a flowsheet for the recovery of plastic and metal bottle caps from sand coasts for further processing of the following three valuable products: the concentrate (plastic particles), the middlings (iron particles), and the tailings (aluminum particles).

Plastic recycling has high potential; to fully develop it, it is necessary to compare the properties of the recycled materials to those of the virgin materials.

In [2], the properties of the recycled PP and the virgin PP were compared using data from recyclers, virgin plastic suppliers, and the literature, in the automotive sector. Plastics are indeed a critical component for automotive manufactures in reducing their footprint. The use of recycled plastic is crucial in this sense, but it is necessary to verify that the technical properties are maintained with respect to the virgin material. Even though the available market data do not allow us to draw a direct dependency between the properties of virgin and recycled PP, the results show that recycling causes changes in the mechanical properties. The properties of virgin PP reflect the many PP grades available on the market. Finally, the recycled material is more brittle with lower elongation at break.

Another issue in the recycling of PP is the degradation of components during their lifetime, due to outdoor exposure. Photo-oxidation leads to the formation of oxygenated polar groups, resulting in an incompatibility between the degraded recycled PP and the virgin PP. Therefore, the content of recycled PP is limited and the prediction of the properties of these recycled/virgin blends is challenging. In [3], the authors prepared and characterized monopolymer blends of virgin and photo-oxidized PP. The samples were characterized in terms of mechanical and rheological properties (elastic modulus, tensile strength, elongation at break, viscosity, degree of crystallinity). The viscosity decreased with the increasing content of the photo-oxidized polymer, as well as the values of the elastic modulus, tensile strength and elongation at break. The decrease in the modulus is quite surprising, since the crystallinity degree increased with the presence of the photo-oxidized components; this must be then attributed to some new morphological aspects. Finally, the results were used to modify a previous model by the authors, considering the presence of the polar groups' well-fitted elastic modulus, tensile strength and elongation at break of the blends.

Fiber-reinforced plastic (FRP) composites are another group of materials used in the transport sector, as well as in construction and sports goods industries. The use of FRP composite materials generate waste at different stages of their life cycle and the available recycling technologies are unable to obtain a material of equivalent quality to the original, due to their heterogeneous nature. The recycling technologies for FRP composite materials that are currently available are mainly based on mechanical, thermal, and chemical technologies. In [4], a technology roadmap, based on patent data, was proposed to understand the current technology maturity level and the growth potential of each process. The results show that thermal and chemical recycling are the most promising and challenging processes and mechanical recycling is already a mature technology. Patents filed within this recycling category are mainly developed by final industries. These findings are useful both for decision makers and researchers for future technological investments in the field of FRP composite material recycling.

In addition, the use of waste materials, originating from cleaning operations of the *C. striatus* in rural areas as raw materials in the production of biomass pellets, needs characterization with regard to the residual biomass to assess the physicochemical properties and to evaluate the potential of its use in the production of biomass pellets. In [5], samples of *C. striatus* were collected in the municipality of Sabugal (Guarda, Portugal) to produce biomass pellets for laboratory characterization and pelletization tests. Pellets were then compared with the quality criteria presented in the ENPlus® standard.

The results of the physical-chemical characterization and the industrial line production show that pure *C. striatus* biomass is not suitable for energy valorization but it can be added to other materials in mixtures, allowing the dilution of less positive characteristics, such as the nitrogen and ash content, to meet the requirements of the ENPlus® certificate. This

valorization creates a value chain and reduces the costs associated with the control and cleaning of species that produce large fuel loads, such as *C. striatus*.

As far as the engineering applications are concerned, the characterization of recycled concrete is also essential. For example, the natural frequency of concrete is an important parameter to avoid resonance when it is used in concrete foundations for absorbing machine vibrations during spinning. The mechanical properties were investigated in [6], focusing on two types of composite concrete mixtures, including concrete with wood chips mix and concrete with rubber mix. The concrete samples were tested to calculate the mechanical properties of stiffness and mass. A fuzzy logic system was developed to calculate the natural frequencies in pure concrete, concrete with wood, and concrete with rubber samples. The results show that pure concrete had a higher natural frequency than wood concrete and rubber concrete mixes. Another relevant finding is that fuzzy logic is a promising tool to investigate the mechanical properties of recycled concrete.

Finally, one research paper in the Special Issue was dedicated to the collection and analysis of r-Cs-contaminated incineration ash, (both fly and bottom ash) at five municipal solid waste incineration facilities in Fukushima, Japan [7]. The characterization is necessary after the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident, since this has resulted in r-Cs leaching and environmental contamination during recycling or landfill disposal. The results show that r-Cs is present especially in fly ash and gradually leaches out after moisture absorption and contact with rainwater. In addition, the strong alkalinity and high Cl concentration of the filtrate can cause corrosion and damage to concrete long-term fly ash containers. Therefore, the authors recommend the use of 5–20 wt% acid clay to r-Cs-contaminated fly ash to inhibit the r-Cs leaching and improve safety during long-term storage.

2.2. Methods and Trends for Recycling

Recycling is the key step of waste management. Nowadays, large volumes of waste materials require management with novel fully automated processes. In [8], the authors investigated different types of neural networks to classify the garbage waste images into the following four classes: glass, paper, metal, and plastic and proposed an automatic system based on convolutional neural networks that is capable of separating the waste materials based on their category, with higher accuracy in object detection. The performance of the algorithm was tested in the waste collection facility located in the city of Kozani, Greece, with an overall accuracy of 92.43%.

To be effective, waste management should start from the design phase, enabling waste reduction and recycling. A BIM-based method to estimate construction waste during building design was proposed in [9]. The construction waste quantification model was applied to the structural system of a Spanish residential building to be validated, using three different BIM platforms. The three software identified the same types and amount of waste; the soil was the main waste due to excavation, followed by remains and packaging waste. The method allows designers to adopt possible corrective measures in order to increase construction efficiency.

Construction efficiency can be reached also through automated manufacturing processes, such as geopolymer 3D printing. The research in [10] proposed an economic evaluation of each principal stage of geopolymer 3D printing, from the extraction of raw materials to printing. The required time, cost, and quality of a 50 m^2 geopolymer 3D-printed house in Finland was investigated. A geopolymer 3D-printed house has almost 32% less production cost than a house built through conventional manufacturing techniques, reducing construction time, waste materials and energy.

As well as the construction sector, the electrical and electronic equipment (EEE) sector generates enormous waste streams (e-waste), with very low recycling percentages. For instance, only 20–30% of toner waste, which is a significant part of the e-waste, is recycled, causing environmental and health hazard.

The review in [11] discusses the challenges of toner waste recycling from an environmental, health, and feasibility point of view. The main emerging trends in toner waste recycling are devoted to the production of value-added products, nanomaterials, composite electrodes for power generation/storage devices, construction materials, and microwave absorbing composites, but more technological innovation should be pursued for large-scale and sustainable toner waste recycling.

Another type of waste that presents several recycling options is the aseptic beverage carton, made of multilayer polymer-coated paperboards with an aluminum layer. Despite the multi-layer structure, the review in [12] shows that there are several recycling options. Hydrapulping is the most widespread process, used to recover the paper fibers that constitute 75% of the carton. The focus should be on processes that are able to recycle 100% of the multi-layer carton, for instance, processes that aim to produce construction materials, such as boards and tiles. Then, there are mechanical, chemical and thermal processes to separate the polyethylene and aluminum layers, after the recovery of the paper fibers, such as agglutination and extrusion to obtain pellets; solubilization of polyethylene and the removal of aluminum; novel microwave-induced pyrolysis.

2.3. Environmental, Social and Legal Aspects of Recycling

Waste management is a strategic topic within sustainability. The prevention and recovery of waste, as a second raw material or energy, avoids emissions in several other sectors of the economy, with consequent environmental, economic and social benefits. One key step is the recycling of components to prevent the wastage of virgin materials and GHG emissions.

The study in [13] analyzed life cycle options (reuse, recycling and disposal) for computers' components in Korea and Japanese cases, using 0–1 integer programming with the ε constraint and showed the differences between the two countries.

The results of life cycle option selection on a computer used for five years show that the GHG saving rate was up to 97.39% in Korea and 96.95% in Japan, while the Korean case showed a minimum total profit of JPY 579.99, while the Japanese case showed at least JPY 225.08. GHG recovery efficiency was higher in Japan (43 g/yen) than in Korea (28 g/yen). So, in order to attain more profits, it is better to reuse the components in Korea, while if the maximum GHG recovery efficiency is desired, the Japanese methods are a better option. In general, a short period of usage brings a higher amount of recycling profits, while the longer the period of usage, the smaller the profit.

More than computers, mobile phones are changed frequently by users to take advantage of new models and designs, thus resulting in a large amount of e-waste, which often remains at home or in the office. The authors in [14] provided a review on the evolution of the reverse supply chain in mobile waste issues and on the factors that influence users' behaviors in the participation in reverse logistics or recycling.

The analysis shows that recycling behavior among users can be fostered by government regulations that support financial incentives and promotions among supply chain partners with revenue-sharing contracts. It is then essential to build secure and accessible channels for consumers and businesses to undertake regular recycling of mobile devices.

Similar conclusions were obtained in [11] with respect to toner recycling; an integrated approach, including policies and legislations, education of consumers on environmental and economic benefits, infrastructure for collection and treatment, and financial planning, is needed as well as the technological innovation.

The topic related to users' knowledge and perception towards e-waste management was investigated also in [15], in the area of Limpopo Province, South Africa, through questionnaire administration. The results indicate that 76% of the users believed that e-waste negatively affects the environment, while 85% are willing to pay for the proper disposal of their e-waste. The data also show statistical significance between gender and knowledge on e-waste management but no statistically significant difference occurs between

gender and perception on e-waste management. The study, as well as the previous studies, recommends awareness and educational campaigns as a key step in e-waste recycling.

The waste recycling topic, as part of environmental education, can be integrated into formal education as practical work. The authors in [16] aimed to determine the impact of a recycling project, integrated as practical work, in an under-resourced rural school on learners' understanding of recycling and their attitude towards recycling. The findings showed that participating in this project may not enhance Grade 7 natural sciences learners' perceptions and understanding of recycling, in contradiction with other studies in the literature. An open question still remains on other factors that may affect the effectiveness of a recycling project. Further research is required in this sense.

As previously mentioned, proper policies and legislations are necessary to promote recycling in all industry sectors. Ship recycling is an alternative to the traditional ship-breaking practice. The authors in [17] carried out a comparative study on the requirements of the national and international regulations for both ship recycling and existing ship-breaking practices in Indonesia. The Hong Kong Convention and Basel Convention are the core of the international regulations that govern ship-recycling activities. The results show that no ship-recycling yard in Indonesia conformed to international or national regulations. So, this is a sector that requires effort both for the ratification of the standards at national levels and the development of the industry to be able to gradually meet the requirements set out by the regulations. This could be achieved by dissemination, training and incentives.

3. Final Remarks and Future Trends

The guest editors believe that the seventeen papers published in this Special Issue contribute significantly to the implementation of sustainability and the circular economy, with focuses on waste recycling processes and the environmental, social and legal issues of recycling. Other studies, in the area of waste reutilization and resource recycling, may also be published in the following Special Issue: "Feature Papers in Recycling 2022".

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