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The Circular Economy Challenge

Towards a Sustainable Development

Edited by

Alessia Amato

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The Circular Economy Challenge: Towards a Sustainable Development

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Editor

Alessia Amato

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About the Editor

Alessia Amato is a non-tenured Assistant Professor in Theory for the Development of Chemical Processes at the Department of Life and Environmental Sciences (DiSVA) of the Polytechnic University of Marche, Ancona, Italy (UNIVPM). She graduated in Environmental Sustainability and Civil Protection at the DiSVA in 2013 after attaining a bachelor's degree in Chemistry and Technologies for the Environment and Materials (Bologna University, 2011). Her scientific career proceeded with a PhD in Environmental Sciences at DiSVA, with a thesis concerning "Innovative and sustainable strategies of urban mining" (2017). She was a post-doc research fellow from 2017 to 2020.

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Her scientific output is documented by 1 patent and 40 indexed publications, with an H-index = 13, and total citations = 641 (source SCOPUS, February 2022).

She has taken part in several grants (national and international).

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Editorial

The Circular Economy Challenge: Towards a Sustainable Development

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As it is now known, we have only one earth available for our life and it is our duty to preserve it.

The more recent manifestations in the squares worldwide confirm the increase of people's awareness of this subject. Nevertheless, the forecast is not promising to describe a resource consumption equal to three planets by 2050 [1] and the effects are in front of our eyes, just think of the biodiversity loss, the water stress and the climate change. Furthermore, the effect on the environment is often translated into economic impacts, the increase of the social gap and the poverty growth [2,3].

In this context the conversion of our economic system, from linear to circular, represents a challenge to overcome, no longer postpone.

Although the circular economy term is often reduced to the simple recycling concept, it represents a complex strategy which aims at the achievement of many ambitious targets. Among these: the increase of product life cycles, the implementation of the industrial symbiosis, the conversion of products into services, the reduction of waste production, the creation of secondary raw materials market [4]. The four main actors of the circular change are the institutions, the industry, the consumers, and the scientific research. Their actions must be closely linked to push the global markets toward the sustainability. Policies can dynamizing the low impact production and drive the consumers towards sustainable choice. On the other hand, the research could supply innovative solutions to the industries, increasingly interested in low impact technological innovation.

In this regard, the COVID-19 pandemic has given us an important lesson proving the resilience of our global market and its conversion rate to respond to the sudden change of consumer demand. The pandemic has proved the capability of consumers, companies and researchers to act on the product design for example for the production of disinfectants from residual products and face masks from textile leftovers for hospitals [5]. COVID-19 has tested the ability of countries to provide solutions (in a very short time) able to combine all the circular characteristics: repairability, reusability, and potential for remanufacturing, proving the relevance of secondary raw materials stocks and the competitiveness of countries [5].

Considering the results achieved in the most critical period of COVID-19 crisis, we should be able to transform the crisis into a chance. The current step of world recovery from pandemic must be the opportunity for the removal of barriers (bureaucratic, technical and economical) that often slow down the conversion to an effective circular economy [6].

The possibilities offered by the post-pandemic period to match the targets of circular economy and the Grean Deal are discussed by Bucea-Manea-Toniş et al., in the first contribution of Special Issue. They have carried out an analysis of competitiveness and innovation focusing on Romania and Serbia, an emerging country from the EU and EU accession country, respectively. They have proved a correlation between the eco-innovation index and the research and development sector, using a dual comparative analysis. The authors have demonstrated the essential role of research and human resources that, stimulated through innovative teaching in the circular economy field, produce positive effects for both society and market levels. In this transition towards a sustainable system, policies can make the difference by economic support and the monitoring of the best available technique use (Contribution 1).

Zhang et al. have analyzed another geographical area, considering the manufacturing sector of Pakistan. They have deepened the concept of circular economy implemented in a developing country. They have studied the connection between the constructs of total quality management and organizational sustainability with the mediating effect of knowledge management by the implementation of a structural equation modeling. The authors have proved that the transition towards the circular economy is not a very quick process and that it does not include only an industrial restructuring. There is the necessity of a structural shift and a change in the mindset, behavior, and priorities stakeholders involved in the market. They have concluded the paper discussing the necessity of the transition from a linear to a circular economy as opportunity to increase the competitiveness of companies in Pakistan (Contribution 2).

The implementation of an effective circular economy could have positive effects on several goals identified by The United Nation within the 2030 Agenda for Sustainable Development. In addition to the most obvious Target 12, related to the responsible consumption and production. In this regard, Buch et al. have proposed the circular economy as solution to address the issue of waste pickers in developing countries. They have described a cooperative system able to maximize the collection and the waste sorting (mainly plastic fraction), with an environmental gain in emission terms and an increase of landfilling site lifespans. Furthermore, the designed solution could alleviate several issues including in the 2030 Agenda, such as poverty, hunger, gender equality, and social inequality (Contribution 3).

It is evident that circular economy means new opportunities and Ilić et al. have chosen to analyze the European indicator of competitiveness and innovation considering both investments and patents related to the circularity field. The regression model performed by authors has identified the investment as the most crucial factor that stimulates the new patents. However, they have concluded that other elements should be added to the model for a sustainable economy, such as creating new jobs in the green field, the policy support, green public procurement, education for understanding, and the implementation of digital and transferable knowledge and competencies. The paper represents the starting point for the development of successful strategies for the overcoming of the old linear model in Romania (Contribution 4).

The availability of sustainable processes which respect the principles of circular economy represents an urgent need. In this regard, Almeida et al. have compared different strategies for the exploitation of tailings from Panasqueira mine, located in Portugal and classified as the largest Sn-W deposit in Western Europe. As reported by authors, the extractive industry needs technological innovations to increase its sustainability level and decrease the resulting environmental burdens and waste to manage. The implementation of a life cycle approach has allowed to estimate the benefit of an innovative approach able to combine the recovery of raw material, with the removal of hazardous As and the H2 recovery which could drive the mine towards a clean energy transition (Contribution 5).

An interesting reflection is proposed in the Contribution 6, where authors have discussed about construction and building sector, one of the key value chains reported in the European circular economy action plan [4]. They have analyzed the vernacular architecture in Egypt, the oldest civilization in the world, identifying the compliance with the principles of circular economy (i) Refuse, Reduce, Reuse, Repurpose and Recycle, (ii) Reduce by design, (iii) Repair, Refurbish and Remanufacture. Starting from the case study analysis, Debaieh et al. have suggested to draw inspiration from vernacular architecture to considerably reduce the impact of modern buildings (Contribution 6).

A connection with key product value chains could be recognized also in Contributions 7 and 8 (in particular Batteries and vehicles and Electronics and ICT), which have addressed issues related to end-of-life batteries and printed circuit boards, respectively. As reported by Giosuè et al. the self-sufficiency in the battery sector is one of the most ambitious European targets. Indeed, the demand of raw materials for battery manufacturing is expected to increase due to the growing diffusion of electric vehicle, in response to the Green Deal objective of reduction of the transport emissions [7]. The relevance of this topic has pushed the authors to undertake the study of regulations on end-of-life batteries in different European countries. The paper has allowed the identification of strength and weaknesses of policies, highlighting the necessity of a creation of a homogeneous reference schema for waste collection, able to improve the further recycling. The results have identified the need of specific regulations dedicated to Li-ion batteries to avoid loss of valuable materials to send to exploitation (Contribution 7).

The development of urban mining strategies, where the waste becomes a resource of secondary raw materials in agreement with the circular economy pillars has been discussed in the Contribution 8. The choice of printed circuit boards as waste to treat has been due to a double reason: the availability of high quantities of this kind of equipment (for its use in many applications) and its metal concentrations, higher than that the ores. Therefore, the identification of sustainable processes is essential to reduce the waste flows to manage and to create relevant stocks of valuable elements. In this regard, Becci et al. have developed a biotechnological approach able to extract copper from printed circuit board with high efficiency, using the fungal strain Aspergillus niger, avoiding the use of both high temperatures and high impact chemicals which characterize the most common hydrometallurgical treatments. In the perspective to maximize the eco-design of the process authors have suggested the use of milk whey as substrate for the fungal growth (Contribution 8).

The results described in Contribution 9 seem almost a provocation, encouraging the readers to a critical analysis of the solutions proposed in the circular economy field. The other authors, and me, have carried out a critical review of the scientific literature about the exploitation of agriculture by-products for the manufacturing of secondary products. The impact due to each process has been estimated by a life cycle assessment approach and compared to that of the corresponding traditional product (from virgin material). The results have proved that recycling is not always the most sustainable choice and that the development of innovative solutions should be always combined with a sustainability assessment, able to evaluate the real convenience of applications. These observations do not want to discourage the research of innovative recycling but want to sensitize the stakeholders to a more critical view of the available circular options (Contribution 9).

The development of the circular economy strategy has the great responsibility to face the current crisis of earth. As reported in the European action plan, the new strategy must contribute to the climate neutrality by 2050 and decoupling economic growth from resource use [4]. Innovation means opportunities so the environmental gain should be translated into the competitiveness of the EU and developing countries, as discussed in several contributions of the present special issue.

Although the topic of circular economy is a very popular topic in the current scientific literature, this special issue offers the possibility to broach the subject from different point of views. Authors belong to very different Department allowing a holistic overview that should be the foundation of an effective circular economy. The papers combine economical, scientific, engineering, mathematical approaches to face the challenge of circular economy in different corners of globe each one with specific criticalities.

List of Contributions

1. Bucea-Manea-Toniş, R.; Ševic, A.; Ilic, M.P.; Bucea-Manea-Toniş, R.; Popovic Ševic, N.; Mihoreanu, L. Untapped Aspects of Innovation and Competition within a European Resilient Circular Economy. A Dual Comparative Study.
2. Zhang, B.; Comite, U.; Yucel, A.G.; Liu, H.; Khan, M.A.; Husain, S.; Sial, M.S., Popp, J.; Oláh, J. Unleashing the Importance of TQM and Knowledge Management for Organizational Sustainability in the Age of Circular Economy.

3. Buch, R.; Marseille, A.; Williams, M.; Aggarwal, R.; Sharma, A. From Waste Pickers to Producers: An Inclusive Circular Economy Solution through Development of Cooperatives in Waste Management.
4. Ilić, M.P.; Ranković, M.; Dobrilović, M.; Bucea-Manea-Toniş, R.; Mihoreanu, L.; Gheţa, M.I.; Simion, V.-E. Challenging Novelties within the Circular Economy Concept under the Digital Transformation of Society.
5. Almeida, J.; Magro, C.; Mateus, E.P.; Ribeiro, A.B. Life Cycle Assessment of Electrodialytic Technologies to Recover Raw Materials from Mine Tailings.
6. Dabaieh, M.; Maguid, D.; El-Mahdy, D. Circularity in the New Gravity—Re-Thinking Vernacular Architecture and Circularity.
7. Giosuè, C.; Marchese, D.; Cavalletti, M.; Isidori, R.; Conti, M.; Orcioni, S.; Ruello, M.L.; Stipa, P. An Exploratory Study of the Policies and Legislative Perspectives on the End-of-Life of Lithium-Ion Batteries from the Perspective of Producer Obligation.
8. Becci, A.; Karaj, D.; Merli, G.; Beolchini, F. Biotechnology for Metal Recovery from End-of-Life Printed Circuit Boards with Aspergillus niger.
9. Amato, A.; Mastrovito, M.; Becci, A.; Beolchini, F. Environmental Sustainability Analysis of Case Studies of Agriculture Residue Exploitation.

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Article

Untapped Aspects of Innovation and Competition within a European Resilient Circular Economy. A Dual Comparative Study

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Abstract: The paper aims to develop—based on a particular dual comparative analysis that follows the current European concerns—the concepts of competitiveness and innovation as pillars uprighting companies' resilience, creating ecoinnovative jobs and social inclusion. In their struggle to meet the Circular Economy principles and Green Deal objectives, the countries chosen for analyses—Romania and Serbia—have started implementing added-value blockchain concepts in their societies to thrive in the resilient European market and build empowered societies. According to the World Economic Forum Global Sources of Competitiveness, skills considered in our study refer to businesses' versatility and societies' innovation capability. Based on specific data provided by Eurostat, the results showed a correlation between the ecoinnovation index and R&D personnel by sector and helped design a regression model. Hence, we demonstrate that R&D creativity, once stimulated through innovative teaching, blooms, having positive effects at society and market levels as reflected in the ecoinnovation index. Furthermore, cluster analysis within E.U. innovation helped identify strengths and weaknesses, provided new grounds in applying innovation, and led to further recommendations.

Keywords: circular economy; innovation capability and resilience; business dynamics; ecoinnovation index; R&D personnel by sector

1. Introduction

The European Union has placed a clear emphasis on the recovery of E.U. members from the COVID-19 pandemic in the Annual Plan for Sustainable Growth in 2021. It is envisaged that within the national strategies, member states will take special measures to support the following postulates: productivity, environmental sustainability, equity, and macroeconomic stability. All the stated goals ensure the full implementation of the Green Agreement mentioned above and lay the basis for revitalizing the European economy and society after the appearance of the SARS-CoV-2 virus. In line with these goals, the E.U. budget for 2021 is planned to be 672.5 billion Euros, including nonrefundable aid to all member states to "green recover". In this way, the importance of economic growth and preservation of the environment is further emphasised through sustainable investments based on saving resources and maximising the use of available materials (Annual Sustainable Growth Strategy, 2021). In addition, there is a "need to encourage a larger contribution of scholars from the Business and Economics area to explore the viability and profitability of CE strategies and related managerial practices to overcome akin issues" [1].

The circular economy (CE) represents a compelling management topic of the last decades. Expected and designed as a regenerative system, it subsists of effective and efficient utilisation of all resources of the ecosystem to optimise performance [2]. However, the scientific literature developed outside of management is mainly focused on defining innovative models to be adopted and implemented by companies [3].

This paper successfully investigated how Romania and Serbia, emerging country from the E.U. and E.U. accession countriy, acknowledge and adopt CE principles and Green Deal objectives, focusing on the CE Fourth Indicator—Competitiveness and Innovation. A regression model and a K-means cluster analysis showed a correlation between the ecoinnovation index and R&D personnel by sector, under the assumption that innovative teaching can stimulate the R&D creativity, as reflected in the ecoinnovation index increase. The K-means cluster analysis based on the PPIE subcriterion emphasises the (non) E.U. countries, showing specific week points that are to be acknowledged and corrected.

Regarding the motivation of the research, the authors motivated for their home countries to follow other countries in their transition from linear to circular economies reached the agreement that their purpose and tasks have been demonstrated and achieved. Sustainability is not a race, but there should be a shared interest among scientists, experts, national authorities, and society regarding the considerable expense in assisting countries lagging due to insufficient investment, knowledge, or other constraints. The research aims to help Serbia and Romania to choose the right path.

This article intended to measure innovation and competitiveness within the circular economy model by focusing on Romania's and Serbia's national elements and comparing each country's leadership and position with those of other countries. In this way, progress on Romania's and Serbia's paths to a circular economy and resilient development would be quantified based on current positions, representing the innovative contributions of the research. The paper touched its purposesș the primary findings indicate a lack of investment in Serbia and Romania, the critical importance of additional research and development investments, the use of new technologies (such as blockchain), and the importance of benchmarking.

One of the significant challenges is the absence of comparable data specific to the E.U. member countries, since Serbia is not a E.U member yet and compatible data is not available. This, however, is offset by other types of data and qualitative research. Regarding the study structure, after the introduction, chapter two presents the theoretical background of the research, prepared with document analysis. Chapter three outlines the data, variables, and research process and provides the results of the regression analysis and cluster analysis. The fourth chapter discusses the study results and divides the narrative into two separate subchapters: Romania and Serbia. Finally, the fifth chapter, the conclusion, summarises the most important research results, while chapter six addresses the study's limitations, mainly the lack of comparative and empirical data. Results achieved, based on the initial purposes of the research show that assumptions have been overpassed and goals achieved.

2. Theoretical Background

Innovation and competition within the circular economy are of growing interest for countries, companies, stakeholders, and civil society. CE is a unique system of achievements of efficient economies by narrowing and slowing different energy flows [4]. We introduce here the two socioeconomic terms of resilience and sustainability to better define the need for robustness and to point the value of innovative structural transformation. Hence, while sustainability defines the methods or process of harvesting by using resources that do not use up or destroy natural resources or permanently damage the environment, resilience represents the ability to create, adopt, and absorb new assets as energy; to translate knowledge into new types of behaviour and versatile policies; and give to the society a more comfortable shape after structural changes.

Sustainability or circularity means continuous changes towards the way firms generate their business and values. Researchers are still analysing these fields as a synergy of economic performance and environmental resilience, bringing apparent benefits to future generations [4,5].

In 2015, the European Commission regulated the investment framework, affecting it with alterations favouring competitiveness and innovations and leading countries to foster their growth in the future. On 11 December 2019, the same organisation earmarked the so-called European Green Deal as an essential work priority in the next decade. This program is the basis for fulfilling the signed goals from the Paris Agreement, which means reducing CO_2 emissions to 50% by 2030. The idea is for the European continent to become the first carbon-neutral territory and a world leader in the circular economy. The described set of economic measures concentrates on reducing and eliminating waste, taking better care of it, but also on saving energy by 2030 [6]. By 2030, it is estimated that the possible potential economic gain emanating from the transition to a circular economy would amount to 1.8 billion Euros [7]. Within the circular economy, creativity and innovation are essential pillars that support intelligent, resilient companies in their struggle to lead the market by creating new ecoinnovative jobs and social inclusion. The organisation model needs to be transformed to production–consumption–reuse as all stakeholders must be represented within the model [8].

The paper emphasises also the fact that companies need to rethink circular economy principles and processes by using resilient solutions and, for example, blockchain technologies in solving environmental problems [9,10]. Once understood and accepted, CE will drive sustainable behaviour. Blockchain technology is a practical solution that all countries can use to reduce waste management costs, ecological footprint, and fraud in green procurement as well as to enhance the green economy [11,12]. Nevertheless, the most critical impact that blockchain has is a significant, resilient change in the life-chain of different industries, with a positive impact on changing human mindset and sustainability [13,14]. Analysing the January 2021 model of innovation in teal and pluralistic organisations within CE (Figure 1), we noticed that blockchain facilities for the entire value-added life-chain infrastructure would create new opportunities for sustainable ecoinnovation within companies. Furthermore, many studies emphasise that blockchain technologies provide the secure implementation of CE R-Strategies (reduce, reuse, recycle, recover, repair, remanufacture) which is also our fulfilled intention [15,16].

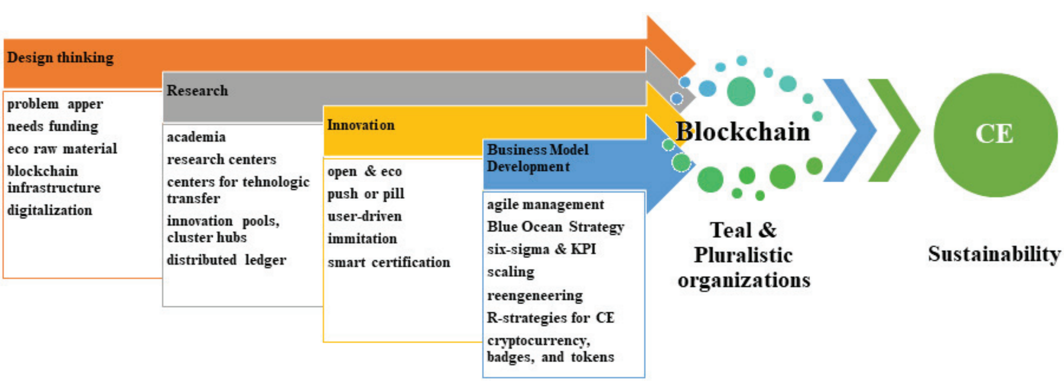

Figure 1. Innovation process in teal and pluralistic organisations in the context of circular economy.

Blockchain infrastructure will ensure material certification (expanding the use of non-polluting materials), smart contracts, and asset tracking (ensuring traceability, transparency, security of information for all the entire life cycle assessment (LCA)); nudge ecological behaviour and reward green employees through cryptocurrency, badges, and tokens; and stimulate corporate responsibility through credit rating trust mechanisms, and distributed ledger [17]. Furthermore, the decentralised ledger will facilitate information flux regarding the materials and their sources [15].

Thus, blockchain technology will also ensure security and privacy, effectiveness, cost reduction/profitability, decentralisation, new business models, and streamlining/automation [18]. For these reasons, blockchain may be a good solution in surpassing the challenges of CE [19]. Digitalisation (networks that provide real-time information about materials and ensure supply chain transparency and traceability) will be translated into resilient actions such as circular resource flows and waste management. Human resources have to develop new ideas for practical innovation [19]. Tracking all the activities in an LCA from a distance and blockchain safety proved to be an appropriate solution in the time of the COVID-19 pandemic.

The development of information technologies-conditioned changes in business models, especially the innovations brought by the digital revolution, concerning the fusion of technologies and their potentials in enabling changes in business and social spheres [20,21], have had a similar impact on new business models. Companies (especially) need to innovate within their business ecosystem networks. The authors of this paper present a model monitoring the entire life cycle of a product/service (awareness and training, analysis, product design, communication/certification) and the supply chain for the large companies and state institutions, based on blockchain technology, to invest in an open innovation platform and licenses. All companies with a new idea of a product/service can become members of the ecosystem (Figure 1) [22–24]. Similarly, Gassman et al. believe that the most significant innovation potential lies not in products or processes but innovative business models [25]. The Figure 1 shows innovation process developed by the authors of this paper as an adaptation after [26]).

Many researchers have already studied the impact of CE on the growth and development of environmental protection [27,28]. At the same time, others have focused on studying the impact of CE on progress in ecology and analysed the importance of its sustainability and the ramifications for the country's economic development as a whole [8,29]. The main pillars of sustainable implementation of CE principles are innovative and creative human resources, which can benefit from the hardware and software support of blockchain technology in developing green products using innovative green methods. These products can be easier to dismantle and convert into green raw materials, mitigating the energy expenditure and the ecological footprint. Waste management and averting pollution is also the responsibility of human resources departments in their struggle to implement CE strategies [30–32]. Referring to the CE sphere, there is a direct link to the workforce, investment, employment, and innovation [33]. Other studies have also argued that innovation in, for instance, the recycling sector is the basis for GDP growth [34]. Innovation is usually considered the most effective tool to achieve a certain standard of living and overcome environmental problems. However, production and service innovations in the field of CE are mainly observed from a long-term point of view. They are not always easy to generate, and therefore more researchers in this field deal with efficient business models that represent innovation through strategic business policies [35].

Schiederig et al. define ecoinnovation as "an object that is defined by its market orientation as well as its environmental benefit over its entire life cycle and that establishes a new innovation or green standard for the company, regardless of whether its primary objective is environmental or economic" [36]. Literature shows many types of ecoinnovation, such as [24,26,27,35,37–39].

1. Product innovation—involves significant improvements in the capabilities, characteristics, and utility of goods and services, or the design of completely new goods and services. Improvements are observed in the technical specifications, functional characteristics, components and materials from which products are made, product software, and utility and ergonomics in use. Examples include new car models and Tesla batteries [24].

2. Process innovation—involves important improvements in production or delivery methods. Innovation is based on significant changes in technologies, equipment

and/or software (AI, machine learning, chatbot, blockchain, IoT, 5G, XR, robots, etc.). Process innovation creates new jobs and eliminate some of those based on functionally outdated technologies.

3. Marketing Innovation—involves important improvements in marketing methods or even the discovery of new methods such as neuroscience or VR/AR (virtual reality/augmented reality) technologies used with great success in marketing. Innovations in marketing include 7P + 1G (price, product, promotion, placement, process, people, physical environment/location, green marketing). This innovation can be seen in: (a) product design and packaging (based on information provided by neuro-marketing/market surveys, focus groups have proved to be quite ineffective in market research; large companies choose the best advertising, packaging, presentation, etc. after analysing their impact on an experimental group by monitoring brain and emotional activity); (b) new promotion methods (e.g., with VR/AR you can place the customer in another time and space); placing products (e.g., moving a car showroom to the city centre, in very small spaces, where the customer experiences all the sensations of VR driving); (c) methods of pricing goods and services (e.g., online prices changing constantly depending on the number of product/service and web traffic requests and on the principle of auctions); (d) communicating with employees and customers on the basis of new discoveries in neuroscience; (e) the use of recyclable materials for production, in ecolabelling, etc. The goal of these innovations is to better meet the needs of customers and educate them by creating new needs and opening up new markets [2,7,35,37–39].

4. Organizational innovation—refers to the implementation of new organizational methods. In this context, leadership has a very strong impact on the modern management of the company. Large companies like Google invest in relaxation, leisure (meal breaks), kindergartens specially designed within the company, etc. to provide comfort to employees at work and stimulate innovation and productivity. Organizational innovation also includes the implementation of the concepts of corporate responsibility, a circular sustainable economy and one-health [24,26].

5. Management innovation—refers management principles and processes that ultimately change managerial practice. This is done through project management. Modern managers use new business resource management methods such as Six-Sigma and new management methods such as Agile. Outstanding results in human resources have been achieved in management. Neuroscience has shown that the most innovative and productive companies present are those that are directly concerned with the health and happiness of employees, materialised by methods of motivating mindfulness [26,33].

Summarising, the concept of ecoinnovation is important for both business and society. Correctly approached, it becomes a useful tool for policy makers to fully apply innovations for the benefit of the market and the environment. The value of ecoinnovation is higher if its analysis is holistic and serviceable, with environmental benefits. Defined by international bodies (e.g., OECD, European Commission) as a tool in measuring "the creation or implementation of the new", the qualities of ecoinnovation are in line with the most important book of innovation and quality—the Oslo Manual.

In connection to direct measurement—number of innovations, descriptions of individual innovations, data on sales of new products—inputs like R&D or patents help the indirect measurement of changes in resource efficiency and productivity using decomposition analysis. This approach, less explored, require a particular attention as it may enlarge and accelerate the knowledge base [40]. At the E.U. level, only two types of innovations are standardised with indicators: product and process innovation, which are measured through enterprises that introduce innovation (product and process innovative enterprises, PPIE). Thus, we choose to analyse PPIE in our paper and see which factors influence it.

Having these concerns in mind, we moved further and designed a research methodology to evaluate the relationship among ecoinnovation, R&D, and PPIE in E.U. countries. We analysed two primary skills: businesses' versatility and societies' innovation capability (World Economic Forum Global Sources of Competitiveness). Then we expanded/deepened our study on a detailed comparison of two partner countries, one from the E.U. (Romania) and one not (Serbia), dedicated to implementing CE principles. The purpose of this comparison was to see how the two countries (one with the support of the E.U. and the other without) perform in the context of the circular economy.

3. Experimental Data Complex Analysis and Significant Results

3.1. Data and Variables

The article used data published about Serbia and Romania by WEF and Innovation Balanced Scorecards. In addition, Eurostat databases were consulted to analyse the factors and degree of innovation in both countries, and three variables were included in statistical interpretations. The variables included in the initial conceptual framework were:

1. PPIE = product and process innovative enterprises that introduced innovation by type of innovation, innovation developer, NACE Rev.2 activity, and size class (Table 1) (INN_CIS10_PROD$DEFAULTVIEW) (last updated 03/07/2019) [41]
2. ECO-INNIV = ecoinnovation index (T2020_RT200) 2013–2019 (last updated 08/02/2021) [42]
3. R&D = R&D personnel by sector (SDG_09_30) 2013–2019 (last updated 10/03/2021)—percentage of active population—numerator in full-time equivalent (FTE) [43]

Table 1. Subcriterion of product and process innovative enterprises which introduced innovation PPIE (variable coding-own source).

E.I. (R&D)	Enterprise Itself (R&D Performers)
E.I. (non-R&D)	Enterprise itself (non-R&D performers)
E.T. (R&D)	Enterprise together with other enterprises or organisations (R&D performers)
E.T. (non-R&D)	Enterprise together with other enterprises or organisations (non-R&D performers)
E.A. (R&D)	Enterprise by adapting or modifying products and process originally developed by other enterprises or organisations (R&D performers)
E.A. (non-R&D)	Enterprise by adapting or modifying products and/or process originally developed by other enterprises or organisations (non-R&D performers)
O.E. (R&D)	Other enterprises or organisations (R&D performers)
O.E. (R&D)	Other enterprises or organisations (non-R&D performers)

We chose to analyse the ecoinnovation index because it brings a holistic perspective of economic, environmental, and social performance, in accordance with CE principles of sustainability. It is composed of 16 subindexes, grouped into five categories: (1) ecoinnovation inputs (related to socioeconomic objectives and HR in science/technology and investments); (2) ecoinnovation activities (related to certification in innovation); (3) ecoinnovation outputs (related to patents, academic publication, and media coverage); (4) resource efficiency outcomes (GDP, domestic material consumption, freshwater abstraction, primary energy consumption, and greenhouse gas emissions); and (5) socioeconomic outcomes (exports of products from ecoindustries and employment/revenue in ecoindustries and the circular economy) [42]. At a closer look, we may observe that all these subindexes are in strong correlation with or depend on HR. As the index emphasises that ecoinnovation depends on research and development, we decided to analyse R&D personnel by sector. The literature review shows that innovation can be associated with product, processes, marketing, management, and organization. From Eurostat we can extract information regarding only two types of innovation (process and product); thus, we decided to include this PPIE indicator in our research.

3.2. Research Process

Our previous research regarding innovation within a network business environment [44] urged us to check if there is a relation between ecoinnovation and R&D. Innovation can be the result of many factors, including product and process innovative enterprises. Also, the market experience and other international studies provided by OSCE, WEF, CGI led us to the same assumption. In this regard, we decided to collect data from Eurostat. Having in mind the opportunities brought by introducing blockchain technology into the L.C.A. to gain a sustainable economy we collected data from Eurostat to ground our study on very specific elements that can have an impact on innovation, such as PPIE and R&D. Literature review and our model (Figure 1) prove that a sustainable economy is facilitated by using blockchain technology for the entire L.C.A. Also, other studies show that there is a relation between ecoinnovation and smart working [21]. We applied, in this study, a more profound analysis to verify how ecoinnovation is influenced by R&D personnel by sector and PPIE (Product and process innovative enterprises which introduced innovation by type of innovation, and innovation developer), having the support and security offered by blockchain technology. Thus, our study evaluates if there is any relation between ecoinnovation, R&D, and PPIE. In addition, our study evaluates the impact of R&D, and PPIE (and their subindexes) on the ecoinnovation index. In order to deepen our analysis, we designed a cluster analysis to find out where innovation potential comes from.

Hypothesis 1 (H1). *R&D and PPIE have no influence on ECO_INNOV*.

Hypothesis 2 (H2). *R&D has a strong and positive correlation with ECO_INNOV, emphasising the importance of stimulating the creativity, motivation, cooperation, and communication of human resources, which in turn positively impact ecoinnovation resilient development*.

Hypothesis 3 (H3). *Product and process innovative enterprises (PPIE) have a significant impact on the ecoinnovation index*.

In the first stage, our research purpose was to choose what kind of data can be analysed to achieve our aim, based on our previous findings from the literature review: ecoinnovation, R&D, and PPIE. Different analytical tools were applied to Eurostat data for the 2013–2019 period [41–43]. A forecast for 2020–2021 was added. The data gathered was inserted in tables and graphs (Table 1, Figure 2). After correlating data, the variables were introduced into a regression model assuming that the ecoinnovation index depends on R&D personnel by sector and PPIE.

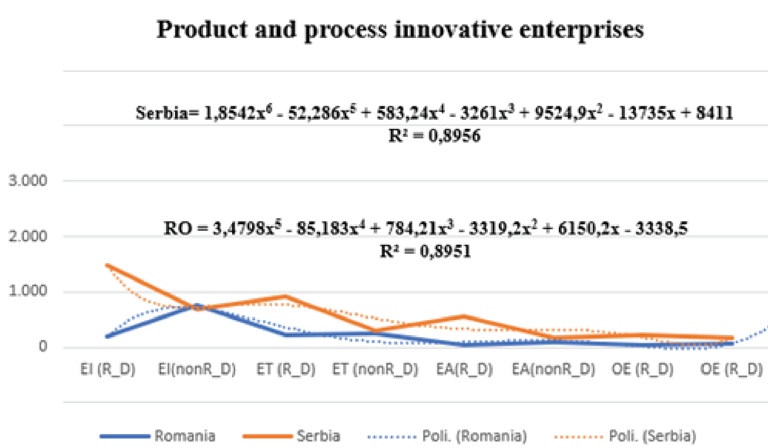

Figure 2. Product and process innovative enterprises that implemented innovation in Romania and Serbia, by type of innovation (polynomial regression).

In the second step of our analysis, a K-means cluster analysis was implemented to understand the data better and see where Romania and Serbia are situated vis-à-vis the

E.U. from the point of view of competitiveness and innovation. This analysis grouped the countries by product and process innovative enterprises. which introduced innovation PPIE subcriteria (Table 1). PPIE represents the criterion for introducing the data into groups and the countries into a certain particular cluster.

3.3. Results

The results of the study are divided into separate subchapters. The first subchapter discusses the results of conducted regression analysis, and the second discusses the results of the cluster analysis.

3.3.1. The First Stage—Regression Analysis Results

The ecoinnovation, R&D, and PPIE variables were introduced into a regression model. The Pearson correlation coefficient (0.847) shows a strong positive correlation between the percentage of the active population employed in R&D (R&D variable) and innovation by circular economy principles (ECO_INNOV variable), with minimal probability of mistake (Sig. = 0.000 < 0.01), as seen in Table 2. We may assume that the H1 (null hypothesis) was rejected and H2 (alternative hypothesis) was accepted. Product and process innovative enterprises, PPIE, had a moderate influence, but an ANOVA test excluded this factor from the model. Thus, the H3 hypothesis was partially confirmed. We may explain this partial influence with the fact that innovation in marketing, management, and organizations are not included in PPIE. For this reason, the PPIE was analysed separately and represented a criterion in our cluster analyses.

Table 2. Correlation, regression model, coefficients, and ANOVA.

		ECO_INNOV	**R&D**
Pearson Correlation	ECO_INNOV	1.000	0.847
	R&D	0.847	1.000
Sig. (1-tailed)	ECO_INNOV		0.000
	R&D	0.000	
N	ECO_INNOV	22	22
	R&D	22	22

R Square	**Adjusted R Square**	**Std. Err Estimate**	**Change Statistics**					**Durbin–Watson**
			R Square Change	F Change	df1	df2	Sig. F Ch.	
0.718	0.703	15.57	0.718	50.816	1	20	0.000	1.409

Coeff	**Unstandardized Coefficients**		**Standard. Coeff.**	**T**	**Sig.**	**95% Confidence Interval for B**		**Collinearity Statistics**	
	B	Std. Error	Beta			Lower	Upper	Tolerance	VIF
(Constant)	31.052	8.480		3.662	0.002	13.363	48.741		
R&D	48.614	6.820	0.847	7.129	0.000	34.389	62.839	1.000	1.000

ANOVA	**Sum of Squares**	**Df**	**Mean Square**	**F**	**Sig.**
Regression	12,312.769	1	12,312.769	50.816	0.000
Residual	4846.004	20	242.300		
Total	17,158.773	21			

Our regression model well estimated data series, having an R^2 = 0.718 with a Sig. = 0.000 < 0.01. The R^2 value empowers us to say that 71% of the variance of the dependent variable (ECO_INNOV) is explained by the variance of the independent variable (R&D), emphasising the importance of human resources in ecoinnovation. The companies have to support the creativity and motivation of human resources and stimulate cooperation and communication between clusters, to gain highly skilled employees. Durbin–Watson's statistic confirms this assumption by being very close to the interval 1.5–2.5, where there is no autocorrelation between variables. The value of Durbin–Watson's statistic =1.4 shows that the residuals might have a very small linear autocorrelation.

Since the adjusted R^2 value is close to the value of R^2, this allows the extension of the proposed regression model assumptions to the entire population. In this case, the variance of the dependent variable decreases with the difference between the two coefficients (0.718 − 0.703 = 0.015). This difference can be seen to be below 1%. The *t*-test for a constant and R&D variable validates the model and contributes to the predictive power of regression. The significance threshold (Sig.) of the variables is less than 0.01, meaning that the coefficients are very well estimated.

SPSS statistics offer us the regression equation coefficients with a very small probability of error. This fact was confirmed by ANOVA analysis. On the other hand, the F-statistic offers arguments in supporting or rejecting the null hypothesis (H1). As the F-statistic has a low value (0.00), the probability of making a mistake if H1 was rejected was very small; thus, H2 (that R&D personnel influence the ecoinnovation index) was accepted.

Regression equation: ECO_INNOV = 31.052 + 48.614 × R&D

3.3.2. The Second Stage—K-Means Cluster Analysis Results

In the second step of our research, the analysis focused on product and process innovative enterprises that implemented innovation PPIE subcriterion because statistics showed a moderate influence. We observed some differences between Serbia and Romania. When it comes to R&D performers in Serbia, more enterprises tend to innovate independently or in collaboration with other enterprises or organisations, or to adapt or modify products and/or processes developed initially by other enterprises or organisations, than in Romania. When talking about non-R&D performers, both countries have the same behaviours (Figure 2).

Designing clusters on these criteria, Italy formed cluster 1, and France cluster 3, by themselves, with the highest centre values (Appendix A). These countries appear to have many innovative enterprises, either independently or in collaboration with others, in both cases: performers and nonperformers of R&D. They make relatively few adaptations or modifications to products and processes developed by other businesses (Table 3—Final cluster centres). Italy is known for the high spirit of entrepreneurship. In Italy, there are regions, such as Bassano, where the number of SMEs is higher than that of families. Cluster 4 is formed by Belgium and the Netherlands, and Cluster 5 comprises Austria, Spain, Poland, Switzerland, the Czech Republic, and Portugal. Belgium and the Netherlands are very innovative countries [36], but they innovate within consolidated hubs and consortiums. This is the reason for the lack of many enterprises that innovate by themselves. In cluster 5, there are innovative countries, but in this cluster, the category "other enterprises or organisations" seems to have a higher weight than other cluster structures. Cluster 2, which contains Serbia and Romania, is the least innovative across all criteria. The software allocated countries to clusters. The main criteria were ANOVA and F-test, confirming that the cluster was chosen to maximise the differences among cases in different clusters.

Table 3. Cluster analysis.

Final Cluster Centres					
Innovation Subcriteria	**Cluster**				
	1	**2**	**3**	**4**	**5**
EIR&D	21,949	934	15,648	5334	3720
EInonR&D	17,674	705	15,092	1147	3148
ETR&D	12,688	666	10,157	3851	2367
ETnonR&D	8682	408	7954	1023	1470
EAR&D	5377	353	5424	1773	814
EAnonR&D	3782	255	4839	545	810
OER&D	2518	222	2650	1148	672
OEnonR&D	3026	260	3308	1029	1331

Table 3. *Cont.*

Final Cluster Centres					
COUNTRY	Cluster	Distance	COUNTRY	Cluster	Distance
Italy	1	0.000	Croatia	2	252.595
France	3	0.000	Hungary	2	448.024
Belgium	4	2270.924	Bulgaria	2	558.451
Netherlands	4	2270.924	**Serbia**	**2**	**656.321**
Austria	5	1119.004	Estonia	2	706.716
Spain	5	1387.060	Latvia	2	774.156
Poland	5	1575.197	Slovenia	2	779.269
Switzerland	5	1624.932	Slovakia	2	795.558
Czech R.	5	1821.724	Lithuania	2	935.163
Portugal	5	2268.435	**Romania**	**2**	**991.201**
			Luxembourg	2	998.966
			N Macedonia	2	1145.697
			Cyprus	2	1171.157
			Norway	2	1741.533
			Greece	2	1992.155
			Finland	2	2935.487

4. Discussions and Further Recommendations

Our study started from the innovation process model in teal and pluralistic organisations in the circular economy proposed by January 2021 [26] (Figure 1). To adapt it to the opportunities opened by the COVID-19 pandemic, we propose a model that includes the facilities brought by a blockchain infrastructure for the entire value-added life-chain infrastructure (raw material identification and management to reduce the ecological footprint; data transparency, traceability, and security; human resources training for stimulating innovation and creativity, rewarded by virtual currency, badges, and tokens; product (re)design, reengineering, and R-strategies; communication/certification through smart contracts; and new business models adapted to the digital circular economy.)

Numerous studies and case studies demonstrate that the life-cycle value added in the circular economy (CE) can be implemented using blockchain technology, thereby securing CE R-Strategies (reduce, reuse, recycle, recover, repair, remanufacturing) in a variety of activity fields, including information technology/electronics/industries, construction, agriculture and food, manufacturing, and plastics [15,16]. The ingenuity and creativity of human resources, as well as the hardware and software support for blockchain, are the primary foundations of blockchain deployment in the CE. Human creativity is critical in developing innovative methods for designing green products that are easier to disassemble, recycle, consume less energy, and have a smaller ecological footprint. The creativity of human resources is also important in the waste management process and in preventing environmental pollution. Human innovation is required in R strategies; in transforming waste into new raw materials, products, or energy; and in saving resources and energy [30–32].

This model is strengthened by the regression model, which shows a positive relation between ecoinnovation and R&D, meaning that investments in R&D and new innovative methods of stimulating creativity ensure greater ecoinnovation, which can lead to a sustainable economy. In the second step, a deeper K-means analysis was done on the subcriteria of PPIE. The graphs (Figure 2) and analysis (Table 3) show that both Serbia and Romania were included in cluster 2, with the smallest values for all innovation subcriteria. Therefore, we continue with a detailed discussion on Romania and Serbia. The novelty and valuable contribution to the field of sustainable development might be observed after introducing blockchain facilities in LCA, implementing the innovation model developed by us and presented in Figure 1.

4.1. Discussion on Romania

According to recent data on European innovation calculated by European Innovation Scoreboard (https://ec.europa.euodest Innovators group—June 2020), based on 27 major indicators, the E.U. countries fall into four groups—Innovation Leaders, Strong Innovators, Moderate Innovators, and Modest Innovators. Romania ranks the last group together with Bulgaria, demonstrating long-term policy and national strategy misconduct. Romania has some achievements and good results in the field of "innovation-friendly environment" and "sales impacts", while the "innovators", "firm investments", and "human resources" are the weakest. "Broadband penetration" and "medium- and high-tech product exports" are the only two indicators showing close to EU average performance.

In Romania, technological innovation is based primarily on R&D and knowledge development from a highly skilled young working force driven by experienced specialists in different fields. These factors are associated with highly populated countries' economies [45,46]. Romania exports medium- and high-tech products with outstanding productivity and have "high performance on knowledge generation—both R&D-based and nontechnological—and are very successful in attracting money (R&D funding, FDI, ESIF funds, new enterprises), talents, and people into the region. They also have the most educated workforce and are experiencing positive population change". Private enterprises accessed most FP7 funds, demonstrating a direct correlation between innovation and the R&D system in Romanian enterprises [47]. Universities in Romania became a pillar in stimulating this cooperation, responsible for nudging creativity and "interests in knowledge, technology, and innovation transfer", contributing to a robust economy [48]. Furthermore, in Romania, heritage tourism brings important economic capitalization [48,49]. Green procurement sustained in Romania depends on market participants' level of knowledge and skills [50]. Companies that apply agile management and foster the working force's motivation through innovative organisational culture have high productivity rates with a low footprint on the environment [51,52].

Our regression model's close relation between ecoinnovation and R&D personnel includes Romania. Romania holds innovation capability, but the overall business dynamism is not very relevant because of the very long time needed to start a business and a very high insolvency rate. A smoother procedure to set up a business, more governmental support, consultancy, and knowledge technological transfer support are needed for sustainable innovation. Romania also has to improve its entrepreneurial culture.

4.2. Discussion on Serbia

The Serbian legal framework in the field of innovation started to develop after the adoption of the Law of innovation in 2010. This law enables the formation of establishments supports for innovative activities and technological transfers, the setup of intellectual property rights, and the Serbian Innovation Fund. If ten years ago there were no bodies effectively tracking the key metrics to evaluate the innovation capacity of companies in need to assess particular sectors of interest to foreign direct investors, today the situation is totally different and shows people and market versatility as well as the desire to provide a strategic and legislative framework for innovation. [53–61].

Infrastructure and support for high-tech research expand academic applicative programs, create venture/private equity investment, and channel R&D entrepreneurship to preserve the environment. Serbia has the ability to absorb new knowledge and adapt imported/purchased technologies—an essential capability to grow and innovate within an official service enabled to advertise competences and capacities to foreign investors, learn metrics and innovation auditing, and create a set of key metrics to track for each industry group [53–61].

Thanks to the analysed effects of competitiveness and innovation in the field of CE in Serbia, it is certain that the introduction of the circular economy would move the country from the manufacturing industry to an innovative industry that would automatically have a higher value of finished products—this would assume a much faster transition from manufacturing to services. Multiple connections would be established with foreign companies and potential investors, so Serbia would become more competitive in offering products and services in the circular economy. The latter would mean automatic access to several financial sources that would significantly support innovation processes and improve relations with those countries that support CE through cooperation programs. All of the above would inevitably lead to technological and educational independence and reduce the economic gap between Serbia and other highly developed countries in the region and beyond. It is important to emphasise that Serbia will not be admitted to the European Union unless it changes the way it uses existing resources; the implementation of CE is a unique opportunity for accelerated accession to this community [53–61].

5. Conclusions

We conducted an analysis of competitiveness and innovation in the E.U. based on Eurostat data: ecoinnovation index, R&D personnel, and PPIE (with its subcriteria). A regression model on innovation and a K-means analysis proved that investments in human resources and proper management of LCA, based on blockchain technology, will create new models of business and innovation that will ensure a sustainable economy. Our analysis revealed that R&D stimulates HR creativity, innovation, and collaboration, which in turn have a positive impact on ecoinnovation and sustainable development. Secondly, product and process innovative enterprises (PPIE) have a relatively moderate impact on ecoinnovation. Cluster analyses on this criterion grouped the E.U. countries from the point of view of ecoinnovation. This revealed that Serbia and Romania are weak innovators.

Innovations in a business organisation can be stimulated and initiated, so they can also be managed, keeping in mind that good ideas may also come from the environment and the company itself. Wisdom is to recognise which ideas are good, realistic, achievable, and profitable enough to turn into innovations. It is much easier to copy a product than an organisation with unique people, ideas, and values. A part of an organisation's "magic" reflects its ability to be new, different, and better than the competition, thanks to new ideas. Combined with other abilities, innovation gives companies a competitive advantage, depending on how revolutionary the innovation is and how long it takes the competition to copy it or develop an equally revolutionary idea. The market race never stops.

In implementing these activities, it is desirable to actively involve representatives of the employees who are part of the team changes that are necessary to implement to achieve betterment in society. The importance of involving all actors identified through a particular working group for CE should not be emphasised. Additionally, intensive capacity-building and training for the economy and public administration are needed in order to be ready to prepare project proposals for available transitional E.U. grants. It is necessary to actively monitor E.U. policy regarding the coherent framework of production policies for different sectors and the measurability of their contribution to CE, but also to monitor the use of best available techniques in the context of CE. It is also essential to actively raise the capacity of the economy for the transition to the CE model. It is imperative to harmonise the time frames for activities in the waste management sector following the new policies and the needs of CE implementation.

6. The Limitations of the Study and Future Research Agenda

The main limitation of this study is that we based our analysis mainly on Eurostat, WEF, OSCE, and CGI data in the absence of strong contact with the business field (we got information only from our universities and their partners, their entire value-added life cycle). Another problem lies in the fact that Serbia does not have a comparative CE methodology as a non-EU country. We have already developed a survey that contains questions regarding (1) entrepreneurial and hybrid university capabilities and characteristics, (2) blockchain platform implementation case studies and future recommendations, (3) green procurement, green methodologies, and policies within the economic–social environment, and (4) future sustainability pillars regarding ecoinnovation and R&D, especially in relation with human resources. This survey will be promoted through the U.S.H. Pro-Business Centre, the Wallachia Hub Consortium, CERMAND (Centre for Renewable Energy on the Black Sea and the Danube), the DANUBE Furniture Cluster, the DANUBE Engineering Hub Bio Concept Valea Prahovei Cluster, and the Smart eHub Consortium in Romania.

As part of the Annual Sustainable Growth Strategy for 2021, the E.U. has focused on the mechanism for recovery and resilience. With national plans, recovery measures are expected in the context of a Sustainable Growth Strategy that contains environmental sustainability, productivity, equity, and macroeconomic stability [61]. The concept of the circular economy and CE business models, which are increasingly discussed in Serbia, could create conditions for faster recovery of the national economy. Such a transition in the industry is possible with a clearly defined public policy of green recovery and financial support. This document presents the regulatory and economic directions designed to recover from the economic and social crisis caused by the COVID-19 pandemic through the transition to a business based on CE principles. The "green recovery" and sustainable ways of doing business constitute the path that the E.U. has traced and dedicated significant financial resources to, the latter of which have been made available to both the member states and the countries of the Western Balkans.

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Appendix A

Table A1. Cluster statistics.

Distances between Final Cluster Centres					
Cluster	**1**	**2**	**3**	**4**	**5**
1		31,514.587	7383.879	26,745.590	27,162.729
2	31,514.587		25,147.985	5798.475	4428.874
3	7383.879	25,147.985		20,685.780	20,808.642
4	26,745.590	5798.475	20,685.780		3212.406
5	27,162.729	4428.874	20,808.642	3212.406	

Table A1. *Cont.*

Distances between Final Cluster Centres						
ANOVA	**Cluster**		**Error**		**F**	**Sig.**
	Mean Square	df	Mean Square	df		
EIR&D	149,794,115.544	4	849,412.426	21	176.350	0.000
EInonR&D	111,631,962.669	4	591,626.973	21	188.686	0.000
ETR&D	54,111,814.566	4	476,959.599	21	113.452	0.000
ETnonR&D	27,956,253.821	4	135,775.135	21	205.901	0.000
EAR&D	11,694,031.173	4	173,269.441	21	67.490	0.000
EAnonR&D	7,476,563.816	4	61,461.766	21	121.646	0.000
OER&D	2,697,414.000	4	66,485.071	21	40.572	0.000
OEnonR&D	4,427,127.404	4	101,218.738	21	43.738	0.000

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sustainability

Article

Unleashing the Importance of TQM and Knowledge Management for Organizational Sustainability in the Age of Circular Economy

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Abstract: Despite the growing importance of the concept of circular economy, the case of developing countries remains under-explored. Against this backdrop, the present research aims to examine the association between the constructs of total quality management (TQM) and organizational sustainability (OS) with the mediating effect of knowledge management (KM) from the perspective of a circular economy. The data were collected from the manufacturing sector of a developing economy (n = 510) to serve the purpose of the current research through a self-administered questionnaire (paper-pencil technique). Structural equation modeling (SEM) was employed for hypothesis testing of the current survey. Six TQM dimensions were drawn from the Malcolm Baldridge National Quality Award (MBNQA) model. OS is composed of economic, social, and environmental sustainability, and KM is composed of four dimensions including acquisition, creation, sharing, and application of knowledge. The empirical examination suggests that TQM positively relates to OS, with KM playing a partial mediation role between this association. This study provides important insights for the management of the manufacturing industry of Pakistan on how to ensure organizational sustainability in the age of a circular economy by using the constructs of TQM and KM.

Keywords: organizational sustainability; knowledge management; total quality management; sustainable development; circular economy; linear economy

1. Introduction

Due to the technological, social, political, and environmental changes that emerged over the past few decades, sustaining a viable and competitive organization has become a real challenge [1]. These changes not only create more opportunities for consumers but also change their needs and wants patterns [2]. It also aims to reduce consumers' unnecessary usage of natural resources including, water, air, and soil [3], and encourage companies to improve their environmental footprint through the use of environment-friendly activities. Currently, companies like to follow several methods simultaneously and continue to support their strategic guidelines to achieve sustainable development objectives [4].

According to a report by the United Nations Brundtland Commission, if businesses sense the requirements of upcoming generations without compromising their ability to fulfill their specific business needs, such businesses are referred to as "businesses with sustainable development practices" [5]. This information applies to individuals who value and share concerns for future generations, especially for the non-renewable natural resources, so that the goal of sustainable development may be achieved. Organizational sustainability (OS) is three-dimensional. That is, it comprises social stability, which implies a stable economy that focuses on people, society, a stable environment, i.e., the natural resources, and is also focused on the economic growth of the enterprises [6]. Previous studies have also used the term triple bottom line (TBL) for these measurements [6–8].

With the rise of sustainability concerns and sustainable development, the notion of a circular economy has been receiving a lot of attention from scholars and policymakers in recent years [9]. When businesses embrace the essence of circular economy, it benefits not only the environment but the organization as a whole, as reducing the level of wastage is one of the primary objectives of such an approach [10]. Perhaps this is the reason that in the current age, many corporations are striving to incorporate sustainability and practices relevant to the notion of a circular economy. Undoubtedly, embracing the concept of a circular economy not only benefits organizations by mitigating the level of waste but also helps an economy to improve its environmental footprint [11].

The words "reduce, reuse, and recycle" are at the heart of the philosophy of circular economy and sustainability [12]. This implies that corporations need to incorporate such strategies through which they can reduce not only their wastage but also can incorporate such practices that can enable them to reuse and even recycle their wastage for further manufacturing processes. Central to the concept of circular economy is the concern for waste reduction [13]. To do this, businesses are required to conduct a waste audit to identify defects in business operations that are producing more waste than necessary. In this scenario, the importance and relevance of total quality management (TQM) are self-explanatory as one of the basic concerns of TQM is cost reduction through waste reduction. Therefore, one of the objectives of the current research is to investigate the relationship of TQM and organizational sustainability (OS) from the perspective of circular economy.

Given the large business competitive market landscape, regulated environment, customer care, quality products, and authorized incentive, companies believe in well-established modeling methods including TQM and knowledge management (KM). TQM recognizes the method of improving organizational and individual performance to enhance competitiveness [14]. This not only improves business economic health but also increases customer and employee satisfaction [15]. The goal of TQM is to focus on sustainable performance, using the least resources to maintain a well-functioning working environment [16]. In addition, the effective implementation of TQM, a key component of sustainability, will have a significant influence on OS [17]. As Abbas, [18] noted, activity-focused companies (one of the critical factors of TQM) can offer an eco-friendly product or service.

Specifically, the implementation of the concept of circular economy is not an easy task as this includes a shift from a linear economy (the traditional one) to an iterative economy (circular) [19]. This requires specific capabilities and KM abilities of an organization. More specifically, from the perspective of a circular economy, a close knowledge-related collaboration from all stakeholders and continuous improvement in the specific business processes are preconditions for OS and for a circular flow of manufacturing processes [20]. Moreover, the process of circular value creation is imperative for improving ecosystems [21], implying that KM has a significant place in all these processes. Therefore, another objective of the current research is to investigate the mediating effect of KM between the relationship of TQM and OS from the perspective of a circular economy.

The proposed relationships were tested in the manufacturing sector of Pakistan. This sector was taken into consideration purposefully. Firstly, the majority of the manufacturing sector of Pakistan follows the linear economy pattern which results in an inefficient resource management approach [22,23]. The approach of circular economy is more holistic to extract value from the waste to achieve sustainability objectives [24]. In the current context, along with other issues, inefficient management, poor knowledge, and quality standards are the critical factors that restrict this sector's adoption of a circular economy. Thus, the findings of the current study will be helpful for this sector towards a circular economy by considering KM and TQM practices. Secondly, Pakistan produces approximately 90,000 tons of solid waste daily. The contribution of the industrial sector to this huge solid waste is critical [25]. To address this discouraging situation, an approach of the circular economy characterized by proper knowledge-based and quality management approaches may improve the current situation. Hassan and Daud [26] argue that the OS can be achieved through efficient KM activities. Despite the importance of these ideas, researchers have paid limited attention to the relationships between the "key operating structures" of TQM KM and OS.

The current study offers some significant contributions to existing knowledge. To begin with, this is one of the pioneering studies from the perspective of developing economies that attempt to bring to focus the importance of circular economy. Specifically, the current study has a special focus on the manufacturing sector of Pakistan. Notably, the adoption of the concept of circular economy is still in its evolving stages in most manufacturing cases in the country [22]. To further aggravate the issue, the concept of a linear economy still prevails and the full potential of the concept of circular economy has yet to be analyzed [27–29]. Moreover, the bulk of literature on circular economy has largely focused on sectors from developed economies [9,11,30], whereas the case of developing countries is still underexplored, which clearly highlights the dire need to conduct more research in this area. Especially, in the case of Pakistan, almost every sector follows the concept of the linear economy (take → make → waste), rather than adapting to a circular economy. Given that there is no synergic approach between different industries for a cyclical sharing of resources. This has led Pakistan to a situation of scarce resources along with different environment-related issues. Poor waste management including unmanaged dumps has placed Pakistan on the list of the countries with high solid wastages. The country, on average, wastes more than 3 million rupees of plastic each year [31]. With the current approach of the linear economy, it will not be possible for Pakistan to achieve a sustainable future. Clearly, the circular economy model is at the heart of a sustainable approach. In this regard, the scientific knowledge-related capabilities and TQM practices may be helpful for enterprises of Pakistan to achieve sustainable manufacturing practices along with achieving the circular economy objectives.

Moreover, the current study also enriches the available literature by introducing KM as a mediator between the relationship of TQM and OS which has barely been discussed from the perspective of a circular economy in the context of developing countries, though there have been some studies highlighting the importance of KM from the perspective of a circular economy [32,33]. However, these studies did not consider developing economies. In this context, it is to be stated that, due to the environmental complexity which changes from sector to sector and region to region, it is not possible to generalize the findings of previous studies in the context of an emerging economy. In line with the above arguments, the current research study investigates the effect of TQM practices on OS with the intervening effect of KM practices in the manufacturing sector of Pakistan.

The remainder of the current work is divided into four major divisions. The coming section deals with the related theories, literature, and hypotheses followed by the methodology section in which we discuss the sample, data collection, and instrument-related discussion. The last two sections are relevant with the analysis of the data and discussion of the results along with the implications.

2. Literature and Hypotheses Development

The current research seeks support from the concepts of knowledge management, sustainability management, and the concept of TQM. The perspective of corporate sustainability management stresses how corporations and communities, together, can thrive environmentally and socioeconomically in the long run [34].

More specifically, this theory asserts that by embracing sustainability practices, corporations not only improve their environmental footprint but also can thrive with economic efficiency as at the heart of sustainability management is the use of the least resources to produce the greatest good. Meanwhile, in recent years, the importance of TQM has also been emphasized on all grounds. As a full-fledged organizational philosophy, TQM intends to grow across all departments of the organization [18]. This component is strongly associated with organizational stability [35]. The TQM spectrum can expand economies to a broad-based perspective ranging from a social to an environmental perspective. Likewise, to accomplish this objective, enterprises must accept the concept of quality management by selling valuables to consumers, even after the sale [36]. KM is generally regarded as a process of knowledge-creating, utilizing, sharing, storing, and managing by an organization in order to achieve its business objectives [37]. During the past couple of decades, different studies reported on the relevance of KM with sustainable development [38–40]. The general argument in this perspective is that contemporary organizations are likely to lose their competitive position if they do not incorporate sustainability into the core of their business operations. To this end, sustainability management requires an extensive and continuous learning orientation from organizations based on several trial and error interventions to prepare a solid organizational knowledge for decision making and problem-solving [41]. In a nutshell, all these perspectives seem helpful to develop the theoretical framework of the current research.

2.1. TQM and Organizational Sustainability (OS)

The European Foundation for Quality Management (EFQM), the Swedish Quality Award (SIQ), and the Malcolm Baldridge National Quality Award (MBNQA) describe the basic TQM based on its key themes. The American MBNQA model combines the strengths and weaknesses of TQM with a focus on regulatory governance in both public and private enterprises. The sample model includes six variables, i.e., strategic planning, leadership, process management, customer focus, information and analysis, and human resource focus [42]. Because of the integrity of this model, this study used it to examine the relationship between TQM, OS, and KM.

Manufacturing companies are quickly utilizing natural resources to increase their profits; they produce more products. Compared to the services sector, manufacturing organizations utilize more natural resources which cause environmental mutilation in the form of pollution, especially water and air contamination [43]. Such practices have now led to a constant increase in the temperature of the planet and a decrease in natural resources. In response to this problem, many environmentalists, including several international organizations and NGOs are attempting to raise awareness on environmental issues. Enterprises of the recent era focus on stability, diversity, and cost savings [44].

The natural resource-based view (NRBV) focuses on organizational resources and capabilities as a way of integrating its operations along with a sustainability perspective. Moreover, NRBV provides a basis for determining the relationship between TQM and organizational sustainability [35]. These characteristics are related to the conditions that allow companies to achieve sustainable development to attain a long-term sustainable competitive advantage, in line with NRBV. This method is similar in the manufacturing and service industries [45]. From the stand of green organizational practices, it is important to discuss the three dimensions of the survival of an organization [46]. Companies that invest in organizational sustainability perform better, sell more to their consumers, and are more competitive in their maneuvers [47]. The theme of a sustainable environment focuses on the steps taken by corporations to preserve nature for future generations. It also examines the environmental effect of business activities, the utilization of natural resources, and preservation [48].

Saving resources and energizing a sustainable environment is essential for the survival of future generations. Organizations cannot neglect their moral responsibilities for society and the environment in the current age. Thus, different stakeholders, particularly government, communities, and consumers expect enterprises to participate in society-environment-enhancing initiatives to balance the negative effect of their operations [49]. Companies that take steps to protect the environment have a constructive effect on their customers and a satisfied workforce as well. Unlike economic stability, which is more abstract and numeric, environmental and social stability are more theoretic and conceptual [50]. In the social landscape of sustainability, organizations have moral programs for social welfare that go beyond their financial and economic well-being [51], for example, organizations' contributions to community development programs, such as contributions to NGOs and participating in public awareness programs, including information on improving products and quality responsibilities [52].

This dimension of OS also takes into account the effect of the organization's social actions on social structures, health protection, work ethics, etc. [53]. In this context, TQM focuses on continuous improvement while striving for optimal performance; there is a long-standing association with longevity, which is important for OS. TQM and OS are one of the priorities of many organizations—their practice is crucial for the production and service businesses [54]. As a result, many companies claim their environment is kind and sustainable in their operations. Since TQM is a process, it can be lengthened to contain all aspects of the OS, as TQM aims not only to improve performance planning but also to make better use of resources. Poor products or services not only lower the economy but also deplete natural resources, resulting in an unsustainable environment. Therefore, we propose the following hypothesis.

Hypothesis 1 (H1). *TQM positively relates to organizational sustainability.*

2.2. Knowledge Management and Organizational Sustainability

Knowledge is an inimitable asset for enterprises to base their competitive position on a solid foundation. KM is the process of ensuring that a company's representatives have accurate information at the right time and place to make an efficient decision [18]. Companies based on KM foundations have a high level of quality and efficiency. Efficient management and understanding processes of new products rely heavily on the KM system [55]. As a result, KM has been considered as a solid foundation for companies to become more competitive in the various industries in the current age. Moreover, KM has every potential to improve the company's innovative potential which is a critical factor of competitive advantage for an organization. According to Zizakov et al. [56], for the ability of a company to develop new products, the process of workflow is highly dependent on efficient KM practices. Thus, KM creates a footing for enterprises to become more advanced and competitive in the market.

With the help of KM practices, organizations translate tacit knowledge into a clear idea so that it could move freely within the organization [57]. KM, through the knowledge workers, leads to knowledge-based economics and companies can receive knowledgeable insights to improve their process [58] and be able to produce new products and services. Commitment to leadership and organizational repute are key factors in shared knowledge. Enterprises can only use KM efficiently and effectively when they use knowledge from diverse foundations. The company should use the knowledge gained from customers, employees, and other shareholders to improve the overall operation of the company.

There are different research studies in which the relationship between TQM and KM has been established. For example, scholars like Stewart and Waddell [59] asserted that enriching the intervention of quality to a wide range of business process including product specifications, customer needs, and continuous improvement indicate a clear relationship between TQM and KM. Moreover, KM practices of organization support in establishing a quality culture which is essential for an organization's success in a competitive landscape [60]. Likewise, the work of Lin and Wu [61] also indicated that there exists a positive relationship between TQM and KM. The study of Colurcio [62] showed that the TQM orientation of an organization positively influences the KM capabilities of an organization, especially for successful knowledge creation and dissemination. To sum, companies that successfully implement TQM include KM in their operations earn a high-profit share. Therefore, the following hypothesis is proposed.

Hypothesis 2 (H2). *TQM positively relates to knowledge management*.

2.3. TQM, Knowledge Management, and Organizational Sustainability

Relating KM with OS has become a critical business imperative for present organizations to achieve business goals and objectives effectively. Knowledge is essential for the development of an individual, an organization, and a nation. Ashraf [63] and Abbas [18] argue that KM is an important factor in the development of a sustainable organization. Knowledge-based companies are more innovative as compared to other organizations, as they can see new signs of organizational stability [64]. Companies that incorporate knowledge management activities into their business operations are responsible for sharing information with the community [65]. KM helps organizations to develop sustainable use of information resources, social considerations, and environmental and economic issues [66]. Organizations involved in KM activities encourage the sharing of information within and outside the organization. Organizational strengths focus on the efficient organization of KM across all organizational strategies to achieve sustainability in all areas [67]. KM activities support an organization in achieving its sustainability objectives. Thus, the following set of hypotheses is framed. Figure 1 shows the conceptual framework of the current study.

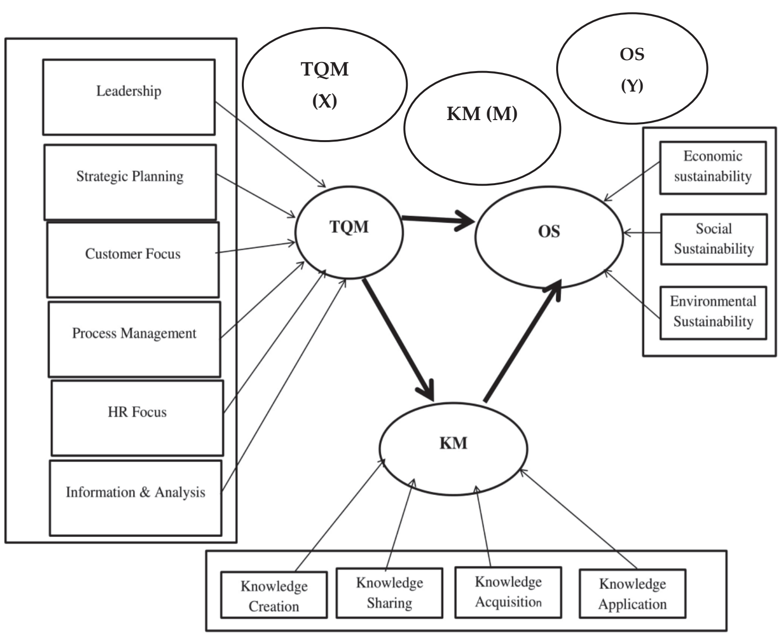

Figure 1. Research model of the current analysis: TQM (X) = the independent construct, OS (Y) = the outcome construct, KM (M) = the intervening construct.

Hypothesis 3 (H3). *KM positively relates to organizational sustainability.*

Hypothesis 4 (H4). *KM mediates the relationship between TQM and OS.*

3. Methodology

3.1. Data Collection

We collected the data from manufacturing organizations in Lahore city, Pakistan. It is to be mentioned here that Lahore city is the industrial hub of Pakistan which constitutes a population of several million. We intentionally selected this city to serve the purpose of the current survey. The specific reason for this intention lies in the fact that during recent years, the city has been declared more than one time as the most polluted city in the world [68]. In this regard, industrial malpractices have been regarded as one of the major reasons for this poor environmental situation [69,70]. Mainly, we visited the Quaid E Azam industrial estate and the Sunder industrial zone of Lahore to collect the data. We only contacted ISO-certified organizations because these ISO-certified organizations are ready to apply environmental certification and social responsibility (for example, ISO 14000 and 26000). In this regard, we formally contacted the selected organizations to support us in the data collection process in the larger interest of academia and the industry. After receiving their formal approval, we then planned a detailed schedule indicating the timing and frequency of our visits in different organizations.

We included low, middle, and senior executives in our dataset, as they responded positively to the survey. Not only did they understand their organizational policies, but they were able to understand different concepts like TQM, KM, and sustainability. Moreover, before starting the data collection phase, we ensured that the ethical guidelines given in the Helsinki Declaration [71] were met accordingly. For example, informed consent from each respondent was obtained to participate in the survey voluntarily. For this purpose, a separate sheet was attached with every questionnaire. Likewise, each respondent was given an equal opportunity to quit the survey at any stage if he/she felt uncomfortable disclosing the information during this process. The instrument for collecting the data was a questionnaire (self-administered) which was given to each participant. Initially, we distributed 800 questionnaires to different organizations. As happens in most data collections through surveys, we did not receive back in full what we distributed. Of those 800 (initial distribution), some questionnaires were incomplete, thus, we could not include them in the final dataset. In this regard, we received 510 valid responses that were processed to analyze the data. This method of data collected is also supported by different scholars [72,73]. The data were collected between December 2020 and March 2021.

3.2. Measures

The questionnaire consisted of three parts. The first part included 36 items based on six TQM dimensions adapted from the MBNQA model. Specifically, the items of TQM were taken from the studies of Saraph et al. [74], Samson and Terziovski [75], Kaynak [76], and Sila [77]. The second part included 14 OS-related items, taken from Turker [78] and Kaynak [76]. Finally, part 3 included 22 items of the KM construct which were taken from Darroch [79] and Lee and Wong [80]. All items were rated on a 5-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree. To confirm the reliability and validity of the questionnaire, we conducted a pilot study and collected 42 responses from companies located in Lahore. Preliminary analysis showed an internal consistency of 0.89 for TQM, 0.90 for OS, and 0.82 for KM, which met Hair et al. [81] guidelines of a 0.70 cut-off value.

4. Results

4.1. Common Method Bias

The general approach to detect a common method bias issue is suggested by Podsakoff et al. [82]. Thus, we followed several sequential steps. For instance, the respondent was told that the questions must be answered honestly and that there are no “good” or “bad” answers. This strategy attempts to reduce the fear in practice and prevents them from giving important social responses. (2) The structure of the instrument was designed very carefully to avoid any possible ambiguity. This is why the instrument had short, simple, and straightforward questions. (3) The importance of the study and the responses from the respondents' participation were explained to them in details. We also initiated a single-factor analysis as recommended by Harman [83]. All items of the instrument were loaded on a single factor using exploratory factor analysis. The results confirmed that there is no single dominant factor that explains more than 50% variance which means there is no issue of common method bias. The above information shows that the general bias of our research does not indicate a major problem [84,85].

4.2. Structural Equation Modeling (SEM)

SEM is an advanced-level data analysis technique that has some significant advantages over conventional multivariate techniques. For example, SEM provides an explicit assessment measurement error. It also enables a researcher to estimate a latent variable through observed variables [86]. In addition, SEM helps an analyst carry out a simultaneous evaluation of the complex models, especially models with mediators or moderators, which was not possible through the conventional data analysis techniques. On a final note, a fully developed model can be tested against the data using SEM as a conceptual or theoretical structure or model and can be evaluated for the fit of the sample data. This is why researchers in the current age prefer to analyze the data by employing SEM [87–89]. According to Chin, Peterson, and Brown [85], SEM is suitable for analyzing the cause and effect analysis of complex models, as is the case with the current study. Similarly, SEM is useful when used to evaluate the implementation of multiple modeling, multiple paths, and/or multi-segment models for each structure. For these reasons, we felt SEM was a useful technique for data analysis of the present study.

To test the hypothesized model, we used a two-step SEM analysis, for all parameter estimations, we used the maximum likelihood method using AMOS. Similarly, to measure the modeled constructs and evaluation, we used confirmatory factor analysis (CFA). With the help of CFA, we were able to examine convergent and discriminant validities along with a reliability analysis of the measurement model. The values of average variance extracted (AVE) were examined to assess convergent validity and composite reliability (CR) values were analyzed to evaluate the reliability of the instrument. Similarly, the discriminant validity was established by taking the square root of AVE. The results of AVE and CR are presented in Table 1, and the results of discriminant validity are shown in Table 2. According to these results all variables have acceptable CR values greater than 0.6. Similarly, the values of AVEs were also within the acceptable range as each construct showed a variance greater than 50%, which means that captured variance by the variable is greater as a result of measurement error [90]. All these results indicate that our proposed model has good internal validity and reliability. As a matter of fact, convergent validity is a measure of association between two observed factors measuring the same construct. Factor loadings more than 0.5 are considered significant loading in the context of convergent validity [90]. In this regard, all factor loadings in our final measurement model exceeded the cut-off level of 0.5. We had to delete some standardized factor loadings due to their weak loading on the respective latent construct. Finally, we examined the discriminant validity of our data by observing square root values of each construct and comparing them to correlation values among other constructs. The rule of thumb is that if the square root of AVE exceeds the correlational values, it means there is evidence of discriminant validity. These results are shown in Table 2.

Table 1. Convergent validity and reliability.

Variable	Items	FL [b] (Min–Max)	T-Value [b] (Min–Max)	α [b]	CR [b]	AVE [b]
TQM second order CFA	6	0.77–0.94	12.06–18.56	0.92	0.96	0.69
Customer focus	4	0.91–0.96	23.49–31.57	0.84	0.86	0.86
Strategic planning	3	0.74–0.82	13.76–17.91	0.88	0.90	0.61
Process management	6	0.75–0.94	11.24–19.78	0.82	0.85	0.69
HR focus (HR)	4	0.75–0.86	14.52–18.86	0.88	0.91	0.65
Information and analysis	4	0.73–0.90	17.94–23.55	0.87	0.89	0.67
Leadership	7	0.76–0.91	16.39–22.82	0.81	0.84	0.67
OS second order CFA	3	0.71–0.95	13.97–21.25	0.89	0.93	0.64
Economic sustainability	3	0.74–0.87	12.84–17.11	0.84	0.87	0.65
Social sustainability	4	0.71–0.95	13.91–19.54	0.92	0.95	0.70
Environmental sustainability	3	0.73–0.84	15.79–20.66	0.86	0.89	0.57
KM second order CFA	4	0.58–0.97	14.48–22.47	0.79	0.82	0.74
Knowledge application	4	0.78–0.96	15.34–21.77	0.91	0.93	0.76
Knowledge creation	4	0.76–0.90	15.92–20.09	0.87	0.90	0.73
Knowledge acquisition	5	0.78–0.94	10.54–16.98	0.80	0.83	0.71
Knowledge sharing	4	0.81–0.90	19.80–24.74	0.92	0.94	0.75

Note: [b] FL, factor- loading; α, Cronbach's α coefficient; CR, composite reliability; AVE, average variance extracted.

Table 2. Discriminant validities and correlations.

	CF	SP	PM	HR	IN	LD	KP	KS	KC	KA	ES	SS	EN
CF	0.93												
SP	0.49 **	0.88											
PM	0.53 **	0.66 **	0.87										
HR	0.41 **	0.48 **	0.56 **	0.81									
IN	0.33 **	0.39 **	0.53 **	0.59 **	0.81								
LD	0.48 **	0.33 **	0.47 **	0.62 **	0.54 **	0.84							
KP	0.50 **	0.47 **	0.51 **	0.46 **	0.60 **	0.64 **	0.92						
KS	0.49 **	0.45 **	0.59 **	0.47 **	0.52 **	0.53 **	0.58 **	0.88					
KC	0.54 **	0.48 **	0.54 **	0.53 **	0.56 **	0.51 **	0.49 **	0.41 **	0.84				
KA	0.49 **	0.39 **	0.51 **	0.59 **	0.59 **	0.53 **	0.43 **	0.48 **	0.65 **	0.87			
ES	0.57 **	0.52 **	0.58 **	0.42 **	0.58 **	0.45 **	0.31 **	0.34 **	0.61 **	0.47 **	0.81		
SS	0.56 **	0.44 **	0.50 **	0.54 **	0.35 **	0.54 **	0.52 **	0.36 **	0.57 **	0.61 **	0.54 **	0.80	
EN	0.42 **	0.48 **	0.53 **	0.58 **	0.59 **	0.47 **	0.32 **	0.48 **	0.64 **	0.48 **	0.49 **	0.56 **	0.77

Note: **, significant at 95 % level. CF = customer focus, SP = strategic planning, PM = process management, HR = HR focus, IN = information and analysis, LD = leadership, KP = knowledge process, KS = knowledge sharing, KC = knowledge creation, KA = knowledge application, ES = economic sustainability, SS = social sustainability, EN = environmental sustainability.

4.3. Hypotheses Testing and Measurement Model

We tested the hypotheses of the present study using the maximum likelihood method in AMOS. Firstly, we tested our measurement model for data fit. For this purpose, we examined different model fit indices such as CFI, IFI, GFI, RMSEA, NFI, and AGFI. All values of model fit indices showed statistical evidence of a better model fitting to the data. We also tested the χ^2/df ratio for less than 5 in order to accept the model for data fit. The findings are shown in Table 3.

Table 3. Model fit indices.

Indicators		Acceptable Range	TQM	OS	KM
Absolute fit index	χ^2/df	1~5	1.89 *	1.30 *	2.53 *
	GFI	>0.9	0.93 *	0.93 *	0.91 *
	AGFI	>0.9	0.96 *	0.94 *	0.90 *
	RMR	<0.08	0.050 *	0.031 *	0.022 *
	RMSEA	<0.08	0.061	0.042 *	0.038 *
Comparative fit index	NFI	>0.9	0.90 *	0.93 *	0.90 *
	CFI	>0.9	0.92 *	0.97 *	0.95 *
	IFI	>0.9	0.94 *	0.96 *	0.95 *
Parsimony-adjusted measures	PNFI	>0.5	0.72 *	0.76 *	0.68 *

* within the acceptable range.

4.4. Structural Model Testing

In order to take the analysis to a further level, we tested our hypothesized relations through SEM in AMOS software with the help of beta values and associated *p*-values. The results are shown in Table 4. According to these results, all hypotheses of the present study showed significant results, which means that all hypotheses were in an acceptable range. From the statistical results, it is evident that TQM significantly predicts KM (beta = 0.351, $p < 0.05$) and KM significantly predicts OS (beta = 0.47, $p < 0.05$); therefore, H2 and H3 are accepted.

Furthermore, we tested the mediation effect of KM in the relationship of TQM and OS with the help of Bootstrapping option in AMOS. The results showed that the indirect effect is 0.166, $p < 0.05$. BootLLCI = 0.127 and BootULCI = 0.439. Neither ULCI nor LLCI include zero, which means zero falls outside of ULCI and LLCI which means the indirect effect is significant and positive. Hence, KM is a significant mediator in the relationship between TQM and OS, so H4 is supported. Similarly, the direct effect of TQM on OS is also significant and positive 0.493, $p < 0.05$, which means that TQM significantly predicts OS, implying that H1 is also accepted. It is notable that the effect size is reduced (direct effect-C) from 0.493 to 0.166 (indirect effect -C′) but remained significant which is indicative of the fact that KM is a partial mediator in the relationship of TQM and OS. On a final note, the mediation effect explains more than 25% of the total variance in OS. This effect can be calculated from the formula given in Equation (1). The structural relationships are shown in Figure 2.

$$\text{Proportion of mediation} = \frac{\text{Indirect effects}}{\text{Total effect}} \tag{1}$$

Table 4. Hypotheses testing.

Hypotheses	Path	Relationship	Beta Value ($p < 0.05$)	LLCI/ULCI	Decision
H1	TQM → OS	+	0.493 ***	0.183/0.392	Supported
H2	TQM → KM	+	0.351 ***	0.762/1.138	Supported
H3	KM → OS	+	0.473 ***	0.199/0.537	Supported
H4	TQM → TL → SCA	+	0.166 ***	0.127/0.439	Supported

Note: *** $p < 0.000$.

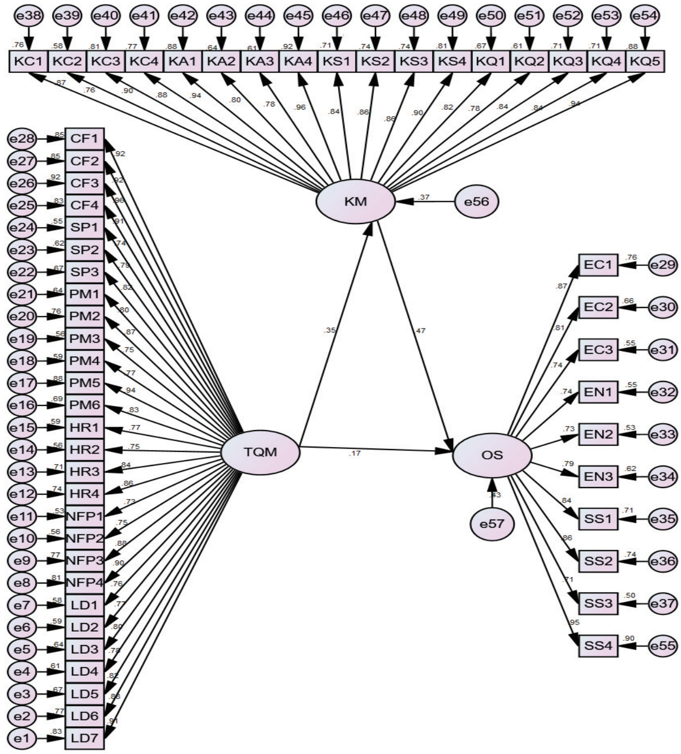

Figure 2. The structural model.

5. Discussion

The current study was carried out to serve two main objectives. Firstly, the study intended to investigate the relationship between TQM and OS from the perspective of a circular economy. To this end, the results of the current study validated that there is a direct relationship between TQM and OS. Successful use of TQM practices in an organization can lead to an enhanced level of OS. These results are in line with the study by Abbas [18], which found a significant impact of TQM on corporate sustainability. However, our results show a contradiction with the findings of Li et al. [91] in the context of Chinese enterprises, in which they indicated TQM does not affect the green performance of the organization. It can now be argued that the basis of TQM is a set of action strategies related to the sustainable development of enterprises.

Altogether, TQM not only reduces economic inefficiency but also protects the environment and nature by transporting them to the environmental permanence of the organization. Improving the level of customer satisfaction, reducing the error rate, and improving key performance indicators of the TQM program can be directly linked to the economic sustainability of enterprises.

The enterprises that are more aware of the impact of their work on the environment seem to be more interested in incorporating the TQM orientation in their business operations [92]. As TQM and environmental management share the same landscape, as they both focus on the efficient use of resources to reduce the level of waste during the value creation processes of a business; they are similar in terms of philosophy. In order to improve its environmental footprint, an organization should implement a TQM program core to its business operations. By combining quality with a competitive environment, a sustainable organization focuses on sustainable development. Moreover, TQM strengthens not only the organizational environmental initiatives but also boosts organizational repute and market share value which ultimately enhances the overall performance of the organization. Additionally, by applying the TQM approach to a wide range, companies can ensure the impact of green systems, such as low levels of harmful gases and minimal use of natural resources in order to be environmentally friendly. According to the results of Kang et al. [93], TQM had a significant and positive impact on a sustainable social environment. However, compared to economic and environmental sustainability, many companies have neglected social stability in their policies due to the low stability of the triple bottom line (TBL) model [94]. To sum, socially sustainable organizations aim to recognize the impact of their actions on society and the environment in order to take steps, to improve their environmental footprint, and to improve their community. Although social sustainability is complex to understand, it is easy to detect. Thus, the enterprises that understand the importance of social sustainability give prime importance to the initiatives that can reduce their negative impact on the environment. These results are in line with the findings of Andrade Arteaga, Rodríguez-Rodríguez, Alfaro-Saiz, and Verdecho [16], Chen et al. [95], and [96].

Another objective of the current survey was to investigate the mediating effect of KM between the relationship of TQM and OS. In this regard, the statistical findings of the current survey validated the mediating role of KM in the proposed relationship of TQM and OS. It is stated that if organizations implement the TQM program effectively, they will improve their performance of KM and this will also have a significant impact on OS. Moreover, our study confirmed that TQM leads to a higher level of KM activity in the organization. Intelligent organizations see TQM and KM as elements of collaboration, emphasizing the importance of individual employees for knowledge sharing, acquisition, and dissemination in an organization. The results have shown the efficacy of KM to enhance OS, i.e., social, environmental, and economic well-being. The analysis of the mediation role of KM between TQM and OS yielded significant implications and shows that the inclusion of KM in the proposed model is imperative to enhance the overall sustainability performance of an organization. On a further note, both TQM and KM share the same values in many ways; for example, one of the core value of TQM is continuous improvement for which the knowledge repository of an organization is of utmost importance. Likewise, to reduce the error rate, the role of the knowledge worker of an organization is critical. This line of reasoning can be seen in the work of Mendes [97]. In brief, our study brings it to the fore that to attain OS, the role of KM is of paramount importance, as our results proved that when KM is introduced in the model, it explained a significant amount (more than 25%) of the total variation in OS. Thus, the mediating role of KM between the relationship of TQM and OS is proven as per the statistical findings of the current survey.

Implications

TQM and environmental management have a common orientation for long-term goals as both of these concepts emphasize reducing resource utilization, reducing waste, and improving customer satisfaction. To achieve such long-term goals, organizations must focus on integrating good standards of quality system management and environmental management. By combining quality with the environment, a capable organization will be able to induce its continuous improvement in all three areas of sustainability (environmental, social, and economic). As TQM promotes environmental management practices, it can strengthen the organizational image and market share. In addition, by following TQM practices in a broader context, organizations can ensure the benefits of green manufacturing practices, such as low greenhouse gas emissions and wastewater and low consumption of energy and natural resources, making it a more environmentally friendly organization. These results are also in line with the findings of Green et al. [98] and Sriyakul et al. [99].

Similar to the sustainable environment, TQM has shown significant and positive effects on social sustainability in previous studies [93,100]. However, in comparison to the economy and the environment, many organizations have neglected social stability in their policies, due to the low level of stability in the TBL model. Smart organizations continue to recognize the impact of their actions on society, both positive and negative, and take steps to improve the quality of interaction with primary and secondary partners. Although it is difficult to classify activities for social care, they are easy to identify. Some of the generalizations develop a general policy for workers, consumer rights and workers' rights, rest of employment, volunteering, living standards, health and safety, welfare, community involvement, contributions, or participating in public development programs. Organizations that understand customer experience and relationships recognize the importance of maintaining relationships and being part of their business plans. Thus, a well-planned TQM philosophy not only considers environmental sustainability but also takes care of the social aspect of sustainability.

Our findings also show a positive relation between TQM and economic sustainability. These findings are consistent with various studies, such as García-Alcaraz et al. [101]. According to the results, TQM practices are also helpful in improving the economic health of an organization as the philosophy of TQM stresses efficient management of resources at each level which undoubtedly improves the overall economic efficiency of an organization. One of the main reasons for these results is that both TQM and KM systems improve company performance, such as time management, efficient use of equipment, training, and development, which has an impact on employees and customer satisfaction. Another important reason for improving the economic efficiency of organizations through TQM is that TQM systems reduce the cost of operations and inefficiency of operations, resulting in better and more stable services. While the quality of a product or service can build a brand and competition, firms need to ensure the quality of their operations and services. It is important to note that TQM practices are interdependent, and in order to receive the maximum benefit from them, organizations must supplement the entire process with proper knowledge management practices. In this regard, leadership can play an important strategic role, as leaders have a responsibility to plan and implement organizational plans.

The study has some important social implications, which we will explain one by one. For example, the findings of the current study highlight the importance of TQM and KM in achieving sustainability objectives. Specifically, the study unveils the importance of TQM and KM from the perspective of a circular economy. The notion of circular economy is at the heart of sustainable manufacturing in different developed countries. However, the situation in the context of the developing countries is very different because most of the developing countries (including Pakistan) do not have sufficient resources and knowledge to properly execute the crux of a circular economy. In this context, the current study adds to the discussion of a circular economy by arguing that a well-planned TQM approach supplemented by KM practices may be helpful for sustainable manufacturing. More specifically, the current study adds to the findings of Perey, et al. [102], who acknowledged the usefulness of TQM for waste management and sustainable practices but ignored the importance of KM in this process. Thus, the leadership and management of businesses should increase their commitment to implement TQM programs in the enterprises to ensure not only the achievement of financial stability but also the social and sustainable environment in line with the concept of TBL.

Moreover, it is central to implement the TQM mechanism in all enterprises that can adhere to one of the standard benchmarks such as MBNQA, EFQM, and SQA. However, in Pakistan, many ISO-certified companies only have Lean Manufacturing, Kaizen, Juran Training, and other quality management standards that do not properly acknowledge the philosophy of sustainable development and circular economy. The policymakers of the enterprises have to realize that in the absence of a comprehensive TQM program, achieving organizational sustainability will be a difficult task. The current study supports the basic fundamentals of the MBNQA model and leads to improved quality in organizational decision-making. The results show that TQM practices are important in the manufacturing sector; this study provides a guideline that the TQM philosophy along with KM should be fully applied in the manufacturing sector of Pakistan in order to get better and sustainable results.

Especially from the perspective of a circular economy, the findings of the current survey have some specific implications. To begin with, it is to be noted that the current pattern in most of the manufacturing organizations in Pakistan is a linear production pattern that follows the philosophy of 'take, make, and waste' without any significant consideration of the concept of a circular economy which is an antonym of linear economy. Although some organizations are striving to incorporate the concept of the circular economy into their business operations, up until now, such organizations could not reap the full benefits of a circular economy. For such organizations, realizing the importance of TQM and KM from the perspective of a circular economy is of utmost importance. More specifically, Pakistan is one of the nations in the world that is ranked high for waste production, as the country has been reported to generate more than 70,000 tons of solid waste on daily basis. In the given scenario, if the manufacturing sector of Pakistan assumes its responsibility and makes it a priority to follow the essence of a circular economy, there is every possibility to think of a better and sustainable future for the country. To that end, the findings of the current survey may be helpful as currently, several industries in Pakistan are ISO certified, but there is a need to shift the way the current organizations follow TQM philosophy in order to think of it as an enabler for a circular economy.

6. Conclusions

The current study is helpful for the manufacturing sector of Pakistan to achieve the sustainability perspective, especially from a viewpoint of a circular economy. It is to be noted that economic transformation is not an overnight process, nor does it depend solely on industrial restructuring. It is, in reality, a change in the mindset, behavior, and priorities of all the concerned stakeholders. Further, to achieve sustainable manufacturing, the circular economy is a way forward for Pakistani businesses. This view can also be seen in some recent studies. For example, the studies of Rahman and Kim [29] and Umer and Abid [103] are some relevant cases in this regard. Furthermore, the industries in Pakistan have to realize the potential of TQM to achieve sustainability and for a transition from a linear economy to a circular economy. Presently, different businesses in Pakistan have ISO standards (14000, 26000, and others); however, most businesses follow such standards to satisfy state laws or as a requirement imposed by the client organization. This is the time to assume TQM from a proactive approach, as the full potential of TQM is not just to satisfy state laws or clients, but beyond that, it can place an organization in a better competitive position through circular production. Similarly, the businesses in Pakistan need to realize the importance of a knowledge resource for achieving a successful transition towards a circular economy. More specifically, proper creation and acquisition of knowledge are critical for its successful application from the perspective of a circular economy [21]. There are some theoretical considerations of the present study as well; first, it enriches the gap between TQM and OS, especially in manufacturing companies of Pakistan. This supports TQM's position that effective implementation of TQM activities can significantly improve an organization's sustainable performance. This study emphasizes the importance of the KM role in the relationship between TQM and CS and confirms KM's principle that good governance not only has a positive impact on personal and organizational activities but also increases their ability to excel in a competitive landscape.

In sum, we have to think green before we can act green and ultimately go green. It is high time to start reimagining the relationship between resources in both our daily lives and the corporate sector and, as a result, reimagine the future we are creating for our next generations. On a final note, our study may generate the same findings in similar economies such as India and Bangladesh. However, in other economies, due consideration and care are necessary before implementing the findings of the current survey.

There are some limitations to the current research. First, the information collected does not include any operational staff. Their opinion may add important insights to the present research study, so future researchers are required to include operational staff as well in order to get better insights.

In addition, the information was based on the understanding of the participants and not on the financial statements provided in organizational documents, so the actual performance was not measured in the present study. Therefore, in addition to self-understanding, the real data of the organization, such as annual reports, may also provide other evidence of the impact of TQM activity on OS. Data were only collected from industries located in the Quaid E Azam industrial state and Sundar industrial zone of Lahore so the generalizability of the present study is under question. In order to better address the issue, future researchers are required to include more cities in Pakistan.

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From Waste Pickers to Producers: An Inclusive Circular Economy Solution through Development of Cooperatives in Waste Management

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Abstract: The world's global plastics waste crisis demands policy coordination and technological solutions to improve waste management systems, and organizations worldwide have created momentum around the concept of a circular economy. This paper advances a holistic, inclusive circular economy framework that aims to empower waste pickers with the following basic pillars: (1) build collaborative networks of stakeholders to enable inclusion of waste pickers; (2) establish cooperative enterprise models to integrate waste pickers into the formal economy; (3) build waste pickers' technical skills and capacity for entrepreneurship; and (4) provide access to technologies and markets that enable waste pickers to manufacture upcycled products.

Keywords: circular economy; inclusiveness; stakeholders; capacity building; entrepreneurship; cooperative business models; collaborative networks

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1. Introduction

The world faces a global plastics waste crisis that demands policy coordination and technological solutions to improve waste management systems at every stage, including the collection, transport, sorting, treatment, and final disposal or reprocessing of waste. International organizations, governments, and the private sector have created momentum behind rethinking the after-market plastics economy through a circular economy, defined as "keeping materials and products in circulation for as long as possible through practices such as reuse of products, sharing of underused assets, repairing, recycling and remanufacturing ... [and] restoring natural systems, designing out waste, and substituting non-renewable materials with biological and renewable ones" [1]. Circular economy solutions have the potential to drive economic growth [2] and create between 9 and 12 million new jobs worldwide [3] in addition to alleviating the environmental and economic consequences of plastic waste. Critically, circular economy solutions, if designed and implemented with an eye for the needs of vulnerable workers, also offer new opportunities to maximize social equity and economic inclusion.

This paper advances an inclusive circular economy solution that aims to empower waste pickers in the developing world. Waste pickers have the potential to act as environmental stewards by mitigating the effects of waste, contributing to the resilience of urban systems, reducing greenhouse gas (GHG) emissions through recovery of materials from waste streams, and saving energy and preserving natural resources by enabling recycling and reuse [4]. They play critical roles in waste management, but their full potential to contribute to the circular economy remains unrealized due to their marginalized social status, lack of recognition by authorities, and disconnection from the formal economy. Additionally, they face significant occupational hazards and social exclusion, and their livelihoods are at risk of being displaced by private-sector-led waste management approaches.

Due to the prevalence of plastic waste, combined with its unique harms and relative ease of reprocessing, this paper emphasizes the strong potential of plastics recovery and remanufacturing as an initial input for this approach to catalyzing greater inclusion and entrepreneurial capacity for waste pickers; however, the inclusive circular economy solution described here has wide applicability for nearly any other waste stream. After describing the global plastics crisis, we discuss the unique social, occupational, and economic challenges faced by waste pickers. We then propose a new strategy for empowering waste pickers through education and capacity strengthening that leverages cooperative enterprise models, along with low-cost micro-manufacturing technologies, that will allow waste pickers to create value-added products out of plastic waste—enabling new economic opportunities for waste pickers-as-producers while realizing their enormous potential to accelerate the transition to a circular economy.

2. The Growth in Plastics Use and Waste

Plastics are integral to the global economy, acting as an enabling technology in almost every sector of economic activity. For decades, the production of plastics increased at a compound annual growth rate of 8.4%, from 2 Mt in 1950 to 380 Mt in 2015—roughly 2.5 times the compound annual growth rate of global GDP during the same period. Only a relatively small share of plastics produced throughout history have ever been recycled. By one estimate, of the 6300 Mt of plastics produced from 1950–2015, 79% accumulated in landfills or in the environment, 12% was incinerated, and only 9% was recycled [5]. The fate of plastics is invariably intertwined with waste management systems that are poorly optimized for recycling and reuse. Globally 37% of waste is disposed in landfills, 33% is openly dumped, 11% is incinerated for final disposal, and only 19% is recycled. In low-income countries, 90% of solid waste is still burned or openly dumped, and low- and middle-income countries are expected to see a threefold increase in total waste production by 2050 [6]—a fact that is especially significant to the solution described here, given the large numbers of informal sector waste pickers in these countries.

3. Harmful Impact of Plastic Waste

The harms of plastic waste can broadly be categorized in environmental and economic terms. Regarding the environment, plastic waste contributes to the destruction of natural ecosystems, especially oceans and riverways. Ten rivers account for 88–95% of plastic debris that makes its way to the ocean [7]. Eight million tons of plastic waste are deposited into oceans each year—the equivalent of dumping a garbage truck full of plastic into the ocean every minute. By 2050, the rate of plastic dumping into the ocean will increase to four dump trucks per minute, and the volume of plastics by weight will exceed that of fish [8]. Plastics that litter the earth also disintegrate into microplastic particles that become atmospheric pollutants. One study recorded 365 microplastic particles per square foot falling from the sky [9]. The health consequences of microplastics inhalation and ingestion are unknown [10]. An additional environmental harm of plastics waste is the production of GHGs from after-use incineration, estimated at 390 Mt in 2012. From now through 2050, GHG emissions from the plastics sector will increase from 1% of global carbon emissions to 15%, contributing significantly to climate change [8].

The mismanagement of plastic waste also has significant financial impacts. Ninety-five percent of the material value of plastics packaging, estimated at 80–120 billion USD, is lost after a single usage cycle [8]. Plastics waste annually causes 13 billion USD in damages to marine ecosystems and 1.3 billion USD in losses to tourism, fishing, and shipping industries in the Asia-Pacific Economic Cooperation (APEC) region alone. The total after-use externalities created by plastic waste, accounting for GHGs emitted in production and incineration, are estimated at 40 billion USD annually [8].

4. Waste Picking as Informal Sector Labor

The informal sector accounts for 61% of employment globally—approximately 2 billion people—and comprises 90% of employment in developing countries [11]. Informal workers are most heavily concentrated in the agricultural sector, but many informal occupations exist ranging from housekeeping to construction. The International Labour Office estimates that in the developing world, 1% of the urban workforce, or 15 to 20 million people, is engaged in recycling [12]. Known as waste pickers, they collect, wash, sort, and process waste from streets, waterways, and landfills. Waste pickers are generally not compensated for collecting trash, but instead earn income through low-value forms of resource valorization through volatile commodity markets.

International organizations have attempted to determine the number of waste pickers from local to global scales, and although some data are available for cities, country-level and global data are scarce. Waste pickers comprise an estimated 0.1–0.4% of workers in seven West African cities; 0.7% of workers in South Africa; and 0.1% of workers in India [13]. These figures, although proportionately small, represent millions of workers. Some municipal and national governments, such as Brazil, have created employment classifications to monitor the waste picker population and track the economic impacts they create.

The level of organization and labor formality of waste pickers varies, and these two factors bear heavily on their ability to earn a living wage. Generally, waste pickers fall into three categories: unorganized (independent), organized (e.g., through a business collective or union), and contract laborers [13]. Local authorities often maintain informal arrangements with waste pickers who supplement formal private sector contracts by filling small niches in urban waste management. In Pune, India, municipal authorities offer formal recognition to waste pickers, providing identity cards and access to health insurance [14], but this is an exceptional case; in most cities, local authorities reap significant benefits from the contributions of waste pickers without formally recognizing or paying them [15].

5. Occupational Hazards of Waste Picking

Informal sector workers are uniquely vulnerable to exploitation and mistreatment and lack the security provided by connection to the formal economy, such as banking services, business licensure, and insurance. Waste pickers are no exception to these dynamics and face unique additional challenges. First, waste picking is an inherently high-risk occupation that brings significant health hazards, such as exposure to hazardous chemicals and biological waste; threats to occupational safety; and lack of access to basic sanitation amenities when working in landfills, such as drinking water, toilets, and places to wash [16]. In one study of waste pickers in Mumbai, India, the "prevalence of morbidities was significantly higher among the waste-pickers, particularly for injuries (75%), respiratory illness (28%), eye infection (29%), and stomach problems (32%), compared to the comparison group (17%, 15%, 18%, and 19% respectively)" [17]. Secondly, waste pickers face social alienation and exclusion, ranging from daily mistreatment and humiliation to police harassment and beatings [18]. Third, waste pickers face a variety of social problems including racial conflict, violence and infighting, theft, insecure living conditions, and substance abuse [16]. Finally, waste pickers are often deprived of opportunities for education and social mobility. In families that rely on waste picking for income, children are often put to work before they can finish school, reinforcing the cycle of social exclusion and poverty [19]. Importantly, women in waste picking may also suffer gender-based income discrimination: One survey showed that where there are larger concentrations of women in informal valorization, junk shops pay women lower rates for materials [14].

6. Economic Vulnerability of Waste Pickers

Waste pickers' livelihoods are constantly under threat due to their dependence upon volatility-prone commodity markets and the ever-present possibility of losing access to waste streams as municipalities adopt "cleaner" private sector solutions. Both problems are exacerbated by their lack of collective economic and political influence. Consequently, waste pickers are uniquely economically vulnerable and often live at the edge of subsistence: for example, in Mumbai, waste pickers earn between 2.71 and 3.62 USD per day [20].

Labor informality adds to the challenges that waste pickers face as service providers at the bottom of the global waste value chain. The primary value that waste pickers provide is in the highly labor-intensive tasks of door-to-door collection and segregation and preparation of materials for recycling, which are sold to middlemen who pay low prices—generally only about 10% of the acquired value of the materials, or one-third of what they would pay to actors in the formal sector [21]. In recent years, the livelihoods of waste pickers have also become increasingly vulnerable to displacement by the private sector, such as when cities establish contracts with waste management providers—sometimes at the behest of donor agencies [12]. For example, the Inter-American Development Bank and the World Bank have encouraged Latin American countries to adopt Integrated Solid Waste Management (ISWM) solutions that include source reduction, recycling and composting, waste transportation, and landfilling. These systems, if designed without an eye for inclusion of all stakeholders—including the informal sector—may limit waste pickers' access to the waste sources that are most profitable for recycling [19]. Although some municipalities have consulted with waste picker cooperatives in ISWM planning to create complementarities between waste pickers and the private sector, waste pickers are generally left out of deliberation and planning processes that shape their futures [1].

Importantly, top-down, private-sector-implemented approaches to waste management not only put waste pickers at risk financially, but also reinforce the linear economy. Private sector actors handle waste in whatever manner is most profitable, even if it means incineration—which creates 25 times the emissions of recycling [12]. In contrast, waste pickers are incentivized to maximize the quantity and quality of recyclable material for resale, and thus devote significant effort to segregating the waste and connecting to appropriate buyers using their local knowledge. One study of six cities found that where private sector recycling has replaced informal valorization, results have been inconsistent, and recycling plants have tended to show disappointing performance. The study concludes that, partially as a result of waste pickers' reliance on lower technology solutions (such as human and animal transport of waste), "an integration of the informal sector would contribute significantly to reducing GHG emissions, as it results in increases in the quantity of recovered material . . . [and] more material recovery at lower environmental cost" [14].

7. An Inclusive Circular Economy Solution for Waste Pickers

The transition to a global circular economy is often characterized as a solution to environmental problems, but this effort also presents opportunities to design solutions to alleviate inequity and social exclusion. Prevailing top-down approaches to waste management in developing countries, even if they mobilize waste picker cooperatives to facilitate recycling, encourage a race to the bottom in which waste pickers are squeezed by middlemen and left to the mercy of commodity market price fluctuations. Holistic, inclusive circular economy solutions would allow waste pickers to diversify their operations and develop new revenue streams; increase interdependency between waste pickers and conventional waste management actors to facilitate mutually beneficial cooperation that leverages their distinct competitive advantages; and achieve greater efficiency by shortening waste supply chain movements through decentralized waste processing.

An approach that starts from the bottom up and mobilizes collaborative networks to empower waste pickers with training, organization, and technology will allow them to ascend the value chain by utilizing recyclable materials to manufacture value-added products rather than limiting their role to collecting waste and brokering low-margin sales to commodity buyers. The integration of the informal sector into waste management systems can increase recycling rates, while eliminating child labor; provide waste pickers with the benefits of formalization such as healthcare, education, and social recognition; and create new jobs and improved livelihoods [3]. More broadly, an equitable transition to a circular economy will improve occupational health and safety for waste pickers, create opportunities for job and venture creation and skills development, and reduce economic harm and displacement.

Although the needs of waste picker communities vary from city to city and country to country, a holistic, inclusive circular economy solution should incorporate the following basic pillars: (1) foster collaborative networks of international, national, and local stakeholders to support waste pickers; (2) establish and support cooperative enterprise models to integrate waste pickers into the formal economy; (3) build waste pickers' technical skills and capacity for entrepreneurship; and (4) provide access to technologies and markets that enable waste pickers to manufacture upcycled products.

7.1. Pillar #1: Building Networks of Stakeholders to Include Waste Pickers

The waste management ecosystems of developing countries comprise multiple actors, including municipalities, waste pickers and waste picker cooperatives, private waste management companies, purchasers of recyclable material and products, academic institutions, international development organizations, and community-based organizations. Successful ISWM planning can ensure the inclusion of the informal sector by facilitating collaboration between these stakeholders through transparent, accessible, and participatory decision-making and policymaking. Identifying complementary and differentiated roles for waste pickers within ISWM systems can also improve waste diversion rates, such as by capitalizing on their natural incentives to maximize collection and sort waste effectively, and by leveraging their abilities to provide certain services with greater efficiency. Improving the working conditions and income potential of waste pickers—and realizing their full potential to increase recycling rates in order to reduce GHG emissions, improve landfill lifespan and utilization, and maximize the economic value of recyclable materials—requires raising awareness among diverse stakeholders of the benefits that waste pickers provide. Better understanding and measurement of informal valorization activities can contribute to national and international recycling goals [14] and facilitate effective, sustainable collaboration towards common goals related to the empowerment of waste pickers. Raising awareness among diverse stakeholders of the benefits that waste pickers provide, and identifying complementary and differentiated roles for waste pickers within ISWM systems, can ultimately improve waste system operational, financial, and environmental performance, while improving the working conditions and livelihoods of waste pickers.

7.2. Pillar #2: Forming and Strengthening Waste Picker Cooperatives

Waste picker cooperatives have proven to be a successful model for integrating waste pickers into the formal economy and domestic and global supply chains, but realizing their full potential requires targeted efforts to increase inclusion and empowerment, including from international non-governmental organizations and development agencies [3]. Cooperatives are critical to helping waste pickers to secure living wages by increasing their ability to negotiate with municipalities to maintain access to waste and with buyers to secure better prices [11]. They provide job security, improved working conditions and higher wages, resilience to economic shocks, and leadership opportunities for women. Most importantly, they provide connection to the formal economy, as cooperatives are legally recognized entities that are considered to be part of the formal sector [4]. Interventions aimed at empowering waste pickers must therefore invest in the organization of business cooperatives, especially in cases where cooperatives have not yet been formed or are weak [22]. To be effective, solutions should strengthen "the internal organization of waste cooperatives by providing better business skills [and] management training, with particular emphasis on the core values and principles particular to cooperatives" [19].

7.3. Pillar #3: Capacity Strengthening for Entrepreneurship

Engaging directly with cooperatives allows local and international stakeholders to work with waste pickers to establish comprehensive, community-based economic development mechanisms. An effective approach for catalyzing enterprise-building should address topics such as financial literacy, venture formation, business skills, technical skills, end market development, and cooperative formation and management. Addressing these issues will empower waste pickers to improve the profitability of their current activities and begin a shift towards diversified livelihoods, such as micro-manufacturing products from recycled materials, that give them a larger stake in national and regional economies. Capacity strengthening will also allow them to maximize their contributions to waste management systems [23].

7.4. Pillar #4: Access to Technology for Remanufacturing and Production

Critically, even waste pickers who are organized into effective cooperatives and trained in new business and entrepreneurship skills still find themselves at the mercy of volatile commodities markets. Recycling machinery is prohibitively expensive for many cooperatives, and even those that sell fully processed bulk recycled material will remain as small players in a vast global market as long as their contributions are limited to the base layer of the recycling value chain [11]. The value added from the work of waste pickers is in collection, sorting, washing, and reselling of waste resources, limiting their ability to secure and reinvest financial resources to expand the scope of their operations to engage in higher value activities.

International organizations can play an important role in helping cooperatives to ascend the value chain by helping them to obtain affordable, low-tech machines that utilize recyclable materials to produce marketable plastic products. They can work with waste picker cooperatives and local authorities to create networks of decentralized micro-manufacturing facilities in low-income and underserved neighborhoods, helping to create new revenues that revitalize communities. This approach has the added benefit of shortening waste supply chains, thereby reducing waste transportation costs and emissions, as waste pickers can process and remanufacture waste nearer to the areas in which they collect waste rather than at centralized materials recovery facilities. Several private sector companies in India have demonstrated that the production of upcycled products can be profitable, such as Aarohana Ecosocial Development, which produces crafts and clothing from recycled bags [24]. Examples of the kind of products that can be produced with plastic waste include yoga mats, shoes, clothing, jewelry, athletic gear, backpacks, tools, building materials, and furniture. Machines for micro-manufacturing upcycled products can be obtained at low cost, such as Precious Plastic USA's open-source machinery, which costs less than 10,000 USD for a full set including a shredder, compression oven, extruder, and injector [25].

If waste picker cooperatives can be equipped with the organizational and technological capacity to diversify into the production of value-added products, they can earn higher margins by selling upcycled goods locally, nationally, and even internationally. Local plastic picking and producing cooperatives could scale to become national cooperatives similar to agriculture-based ones, such as the Amul Dairy Cooperative in India, which supports nearly 1 million farmers and generates over 1 billion USD in revenue per year [26]. The revenues provided by waste reprocessing and micro-manufacturing, in turn, will allow cooperatives to be self-sustaining, generating revenues that can support increased member incomes, ongoing venture diversification, and reinvestment into community resources such as education.

8. Conclusions: Circular Economy as a Catalyst for Sustainable Development

Circular economy models are often characterized in terms of concepts such as technological innovation, policy change, industrial systems, and natural capital. These and other conceptual lenses are essential, but an intentional focus on equitable, inclusive economic development that creates new livelihoods and maximizes social value is also necessary to realize the full potential of the circular economy. The case of waste pickers demonstrates how top-down approaches—such as focusing on improving the recyclability of plastics, or companies collaborating to standardize packaging protocols—are insufficient to address the broader spectrum of socioeconomic concerns surrounding the transition to a circular economy, especially the working conditions and livelihoods of workers in developing countries. Although these approaches are necessary, the inclusive circular economy solution for waste pickers articulated here is an example of how a bottom-up approach can also ensure that vulnerable workers are not left behind.

Waste pickers have long been marginalized and treated with suspicion by governments around the world, holding them back from realizing their full potential to contribute to resilient urban ecosystems as key players in effective waste management strategies. Even where waste pickers have organized through business cooperatives, their reliance on traditional business models—based on low-value valorization activities and brokering the sale of recyclables at margins that barely turn a profit—limits their ability to earn a living wage. Cooperatives have proven effective in helping waste pickers to earn better livelihoods, improve their working conditions, and achieve formal recognition from local governments, but these efforts are limited in their ability to create enduring economic stability for waste pickers. For example, in Pune, India, the nearly 3000 members of the Solid Waste Collection and Handling (SWaCH) cooperative provide waste management services to 70% of the city [27]. However, SWaCH still faces threats from large scale, private-sector-led approaches that deprive waste pickers of income while driving environmentally unfriendly practices such as waste incineration [28].

A holistic, intentionally designed inclusive circular economy solution can build on the success of cooperatives like SWaCH by mobilizing broad networks of stakeholders from local to international scales to assist waste pickers in forming and maintaining cooperatives and in brokering sustainable arrangements with local authorities that secure their access to waste resources. With the training and technology to manufacture products that can be sold for significantly higher profits than bulk recyclables, these picker–producer cooperatives can diversify their revenues and realize higher returns for their members, catalyzing bottom-up economic growth that has the potential to help waste pickers thrive financially and transform the communities in which they live. Moreover, although plastic waste is an ideal initial focus for this approach, this solution can readily be applied to many other waste streams—including construction debris, textiles, and even organic matter.

Circular economy practices are critical to solving the global waste crisis, but with holistic design that prioritizes inclusion of the world's most vulnerable workers, they can also drive the achievement of sustainable development goals related to poverty, hunger, gender equality, and social inequality [1]. The approach described here is only one example of how the transition to a circular economy can be leveraged to maximize inclusion and equitable outcomes for the world's poorest and ensure that the benefits of the circular economy are accessible to all.

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Challenging Novelties within the Circular Economy Concept under the Digital Transformation of Society

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Abstract: The study makes, under a new configuration of the circular economy, a cross-country analysis based on the Competitiveness and Innovation Indicators in the E.U., i.e., two sub-criteria: private investments, jobs, and gross value added; and patents related to recycling and secondary raw materials as a proxy for innovation. The analysis proved that investments influence the number of patents, and participate in societal transformation. A further cluster analysis classified countries on the level of innovation. The cluster analysis in SPSS centres on significant potential, weaknesses, impact, and waste management control through blockchain technology. It is found that the factors that influence innovation, according to the Global Competitiveness Report, link the business dynamism and innovation capability with the capacity to sustain resilient ideas, such as competitive intelligence and social entrepreneurship. The discussions aim to prove that the efforts to rethink the circular economy principles contribute to its conceptual and societal transformation role through the implementation of innovative processes, inventive solutions, and blockchain technologies, and their social consequences to solve environmental problems. Once understood and accepted, CE will drive sustainable behaviour.

Keywords: circular economy; competitiveness; investments and patents governance; innovation and policy for sustainability; societal transformation

1. Introduction

The circular economy sustains economic return, and strengthens the quality of life through its multiple roles. Its principles can positively impact individuals, establishments, and economies. In 2020, the European Union set up the Action Plan for Circular Economy (CE) as the healthiest way to outline sustainability through respect and responsibility within the environment and society. The circular economy can drive systemic change, and sustain the value circulation within the ecosystem, eliminating the concept of waste. The circular economy represents a model to restore ecosystems. Both innovation and habit-altering define its implicative characteristics [1–4].

Many scientists consider the circular economy the best model for societal and economic benefit [1–3]. This is proved as a suitable solution regarding economic and social inequality, and deficient political strategies. If risks are in a falling trend in a country, the country's risk premium is also experiencing a fall, which positively influences society and the national economy [4]. The United Nations and OECD, as institutions of global recognition, highlight the circular economy as a significant social shift towards an original and inherently energetically efficient system; its general implementation will help competitiveness that will sustain the high technology use, and give a more effective response to global ecological challenges.

Digital and competitive intelligence skilled human resources are the driving factor in the circular economy. Adapted innovative human resources with transferable and digital competencies are trained in educational institutions using new technologies, such as blockchain, MOOCs, eXtended Reality (XR), etc. [5,6].

This article aims to analyse the elements of innovation and competitiveness of selected countries within the CE concept to measure the position of these countries. Firstly, the analysis utilises a regression model that shows that the number of patents correlates with the investments in innovation. Still, additional factors regarding innovation should be analysed. Secondly, we performed a cluster analysis to emphasise which countries are more innovative, and the factors that nudge innovation. This way, with an understanding of current positions, progress on their path to a circular economy and sustainable development could be measured.

Contributions of the study are reflected in measuring the "as is" situation in terms of selected circular economy criteria, identifying obstacles, and making recommendations for further efforts.

2. Background Research

The European Commission recommended four leading indicators (production and consumption, waste management, secondary raw material, and competitiveness and innovation) for all European countries to use in their national evaluations to take the appropriate measures to promote a sustainable circular economy [7]. However, although many qualitative types of research were performed on the circular economy, competitiveness, and innovation, only a few studies have quantitatively evaluated the circular economy concept and the elements included in the EU CE fourth indicator, as they are usually chosen as background [8–10].

Đurđević et al. believe that being competitive in the domestic, regional, or world market is set as an aspiration and the goal of doing business for many companies. However, current business conditions on the market impose the need for constant adjustment and a continual search for ways to raise competitiveness for companies. This is precisely because of the overproduction and oversaturation of the market [11–13]. Consequently, companies find it challenging to differentiate and position themselves in consumers' minds (i.e., market positioning). Although it is complex and difficult for companies to achieve competitiveness in the market in the mentioned business conditions, it is not impossible [14]. Ilić and Radnović find that companies constantly have to fight to keep existing leadership positions by winning new ones in the conditions of increased competition in numerous industries. For companies to cope with such increased competition, it is necessary to constantly reinvent and adapt their products and business processes to gain an advantage over the competition, thus securing the "best in class position". Today, it can be argued that innovation, i.e., the introduction and application of new ideas in companies' business across many industries, is a strategic ability. The companies with a low innovation index, i.e., the share of the sales generated by products (processes) existing for less than three years, can be neither competitive nor successful [15,16].

Janssens and the team address the need for quantity and quality competencies that are necessary for a circular transition to occur, and that "transversal competencies and valorisation competencies are equally important as technical competencies for a circular economy" [17,18].

The classical meaning of innovation, referring to the creation of new things, is redefined by Stošić as "renewal and expansion of products, services and markets", so those "new ways are set up in management, work organisation, conditions and skills" [19]. Miletić et al. find that innovations enable improved quality of products and services, increase security, and lead to increased competitiveness [20]. Gay and Szostak point out the importance of innovation and creativity for the small- and medium-sized enterprises (SMEs), accounting for more than 90% of companies worldwide, which have to be creative and innovative to survive in their market, and differ from the competition. They find that SMEs are not the scaled-down versions of large enterprises [21], a view also confirmed by Torres [22]. Adding that they have their specificities and laws and that, despite specific inherent difficulties, SMEs provide a favourable environment for developing creative ideas. However, specific characteristics are preventing them from implementing innovations. Gay and Szostak believe that innovation is of great importance for driving the competitiveness of an enterprise and the growth of a country, which is presented through a dilemma implying that, although necessary, it brings uncertainty, and is complex to understand and implement. The dilemma worries all companies regardless of the company size. The authors, however, note that SMEs are more exposed to uncertainty. Increasing competition and globalisation have put innovation at the forefront of industrial development. A lack of the capacity to successfully manage uncertainty risks is particularly detrimental to small firms [21].

Schiederig et al. identify six characteristics of an eco-environmental innovation as "an object which is characterised by its market orientation, its environmental benefit over its whole life cycle and which sets the innovative green standard to the company even if its primary intention may be environmental or economic" [23].

The technologies' development and innovative implementation in the market cannot be conceived outside societal life. They influence everything: work, development, life. Patents play a significant role in technology, from development as a concept, and marketing as a tool. Moreover, transferring innovative technologies to third parties opens up new development and financial opportunities. Gross domestic spending on research and development is the first link in the innovation chain. An important step has been taken by introducing in the Europe 2020 Strategy the leading indicator "research and development intensity", a measure that refers to the dimensions of production and output of innovation. The share of research and development staff in the workforce reached 1.2% of total employment in 2015, most of whom were employed in the business field. This was observed in reporting almost half of the EU enterprises' innovation activity in 2014. At the same time, the size of GDP per capita was significant; the states with the largest number of innovative enterprises also had this indicator relatively high. Moreover, one-third of them developed cooperative activities with other enterprises in 2012–2014 [24]. But, it is true that though some countries are spreading technologies [25], others use the know-how generated by other countries [26]. This suggests that research and development is not the only criteria underpinning innovation. Other factors need to be considered. Raghupathi V and Raghupathi W (2017) noted that the association between living standards and innovation suggests that to improve innovation and drive growth, countries need to focus on improving living standards in terms of high minimum wages, and better working conditions. At the same time, they point out that countries with high foreign patents have low tax revenues as a percentage of GDP, and this income is mobile. Patent ownership can be found in locations other than the country in which they were created [27]. Through answers to some questions about the proportion of patented innovations, the pace and continuity of this process in a country, how patenting affects the dissemination of knowledge, etc., Mosser shows that innovation measures are not influenced by local patenting [28]. Having a solid patent system is not the essential development policy for low- and middle-income countries, as Bronwyn H. (2020) shows [29]. According to the observation of Gold et al. (2017), the relationship between intellectual property and economic growth is a placebo effect rather than growth, valid locally, both at the level of companies and the macro level [30–33].

3. Experimental Data, Complex Analysis, and Significant Results

3.1. Data and Variables

The European Commission recommended four leading indicators for European countries to use in their national evaluations to take the appropriate measures to promote a sustainable circular economy. These are [7]:

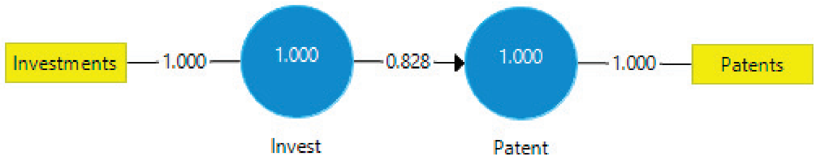
- The production and consumption indicator—consider households' and economic sectors' waste product, which has to be reduced as much as possible. It is measured through green public procurement, and the quantity of waste generation and food waste to reach self-sufficiency of raw materials for production in the EU [7].
- Waste management indicator—based on the reuse-recycle-repair principle to create value from treated waste, and is measured by two determinants: recycling rates; and specific waste streams, such as packaging waste, biowaste, e-waste, etc. [34].
- Secondary raw materials indicator—recycled materials bring added value once re-introduced into the economy circuits, saving natural resources consumption, mitigating the environmental footprint, and offering a continuous supply of raw materials. It is evaluated through the contribution of recycled materials to raw materials demand, and the trade of recyclable raw materials between the EU member states [28,35].
- Competitiveness and innovation indicator—creates continuously new types of jobs and sustainable activities, green forms of products, industries, agriculture. Innovation in technology, raw material, design, production, and methodology will facilitate the reuse of waste. Private investments, jobs, gross value added, and patents related to recycling and secondary raw materials as a proxy for innovation. The private investment and patents will be analysed in this paper.

The authors chose to analyse the competitiveness and innovation EU CE indicator, collecting Eurostat data [7] regarding the average investment (private investments, jobs and gross value added related to circular economy sectors—CEI_CIE010) and patents (patents about recycling and secondary raw materials—CEI_CIE020) for 2012–2018, by country in EU (Appendix A). We chose 2012 as the starting date for the analysis, referring primarily to the situation in Romania. In 2012, the industrial production stagnated after 2010, and in 2011, it registered uninterrupted increases, according to the National Institute of Statistics [36]. We then looked at how this aspect is found at the European level. Furthermore, in the following few years, the worldwide growth rate of gross world product fell to the lowest level since the global financial crisis, with significant losses, especially in the period 2014–2015. For example, in 2016, 49 countries saw a decline in per capita income [37].

Nevertheless, global growth reached 3.1% in 2017—the fastest pace since 2011. Subsequently, due to increased investment in several sectors of activity, the world economy experienced a revival. The United States, for example, was supported in 2018 by a fiscal expansion that offset the deficit of other economies [37].

3.2. Research Process

The analysis is based on public statistical data available, accessed and collected from the European official statistics databases (Eurostat WEF, Balance Innovation scorecard). In addition, we also accessed national authorities' data to understand the dynamics and impact of the CE policies in selected countries (Appendix A, Table 2). Finally, figures were used to present the descriptive statistics of the analysed data (Figure 1).



Mean, STDEV, T-Values P Values

	Original Sample...	Sample Mean...	Standard Deviation ...	T Statistics...	P Values
Invest -> Patent	0.828	0.825	0.104	7.929	0.000

Figure 1. Composite reliability coefficient.

Based on the data presented, we intend to prove the following hypotheses:

Hypothesis 1 (H1). *The level of investments influences the number of patents to some extent.*

Hypothesis 2 (H2). *The innovation level differs in EU countries mainly due to different levels of investments, but other factors might be analysed (such as cultural factors).*

In the first stage, a regression model was designed to evaluate the influence of investment over the number of patents in CE in 24 of the EU countries. Because of Eurostat's lack of reported data, Liechtenstein, Norway, Switzerland, Czech Republic, Ireland, Luxembourg, Malta, and Iceland were not included. These innovation patents, which now require 10% of ROI, will bring in the future 70% of ROI, proving the future sustainable impact of innovation on the economy [38–41].

In the second stage, for a clear insight into the impact of innovation on the sustainable economy in the EU, a cluster analysis was designed using the K-means algorithm, and each cluster's characteristics, challenges, weaknesses, and strengths in obtaining sustainable innovation were emphasised.

3.3. The First Stage—Regression Analysis for Evaluation Relations between Investments and Patents

Firstly, a regression model emphasising the importance of investments in innovation on increasing the number of patents for the EU applied to the fourth CE indicator will be used to obtain the CE outcomes in the EU. Our analysis excludes Liechtenstein, Norway, Switzerland, Czech Republic, Ireland, Luxembourg, Malta, and Iceland because they do not provide data on our variable. A strong positive correlation (0.828) is identified between the model's two variables (invest and patent). This correlation allows the authors to design the regression model. The R^2 coefficient is 0.68, indicating that the variation of causal investment variable determines 68% of the variable patent variance, and the model cannot explain 32% of this influence. As R^2 is not very close to 1, in a future analysis, we have to add some other factors that influence the number of patents, such as culture, technical facilities (hardware, software), the accuracy of knowledge, etc. Finally, the F-statistic offers arguments supporting or rejecting the null hypothesis (H0). Having a low value (0.00), the probability of making a mistake if accepting H1 is minimal. Thus, H1 is proven (the level of investments influences the number of patents).

R^2 (0.67)'s adjusted value is also close to the value of R^2, which proves that the influence of the independent variable (invest) is significant, and explains the variance of the dependent variable (patent). Since the adjusted R^2 value is close to the value of R^2, this allows the extension of the proposed regression model to the entire population surveyed. In this case, the variance of the dependent variable decreases with the difference between the two coefficients (0.685 − 0.671 = 0.015). This difference can be seen to be below 1%. The *t*-test generated for the *invest* variable validates the model, and contributes to the predictive power of regression. The variables' significance threshold (Sig.) should be less than or around 0.05. In our case, Sig. 0.00 is lower than 0.01 for investment, meaning that the coefficient of this variable is very well estimated, and Sig. 0.44 for constant is higher than 0.05, meaning that the constant could be better estimated.

Durbin–Watson's statistic strengthens the model, showing no autocorrelation between variables. Durbin–Watson tests the null hypothesis that residuals are not linearly auto-correlated. Though the test can take values between 0 and 4, the values around 2 indicate no autocorrelation. As a rule, values of $1.5 < d < 2.5$ show no autocorrelation in the data. The VIF value helps us make the collinearity diagnostics. If the VIF value is greater than 3, there is a chance of multi-collinearity between independent variables. If this value is above 5, then the chances of multi-collinearity are high. If this value is over 10, the independent variables indeed show multi-collinearity. In this case, the VIF is 1, meaning there is no collinearity between variables. In conclusion, the present model is valuable.

The regression equation it might be seen below (Tables 1–3):

$$\text{Patent} = 2.194 + 1.861 \times 10^{-3} \times \text{Invest} \quad (1)$$

Table 1. Regression results—Pearson Correlations *.

		Invest	Patent
Invest	Pearson Correlation	1.000	0.828
	Sig. (2-tailed)	0.0	0.000
	N	24	24
Patent	Pearson Correlation	0.828	1.000
	Sig. (2-tailed)	0.000	0.0
	N	24	24

* Correlation is significant at the 0.01 level (2-tailed).

Table 2. Model Summary.

R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
				R Square Change	F Change	df1	df2	Sig. F Change	
0.828	0.685	0.671	11.428	0.685	47.861	1	22	0.000	1.668

Predictors: (Constant), INVEST. Dependent Variable: PATENT.

Table 3. Coefficients.

	Unstandardized Coefficients		Standardized Coefficients	T	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	2.194	2.812		0.780	0.444		
INVEST	1.861×10^{-3}	0.000	0.828	6.918	0.000	1.000	1.000

Dependent Variable: PATENT.

Table 2 shows model Summary for the regression equation.

Table 3 presents Coefficients for the regression equation.

Furthermore, the authors used SmartPLS 3.0 software to calculate the composite reliability coefficient. The coefficient of composite reliability analysis strengthens our hypothesis, and shows good internal consistency because it is higher than the accepted limit of 0.7. In our case (Figure 1), the coefficient is 1 for both variables: investment and patent. Furthermore, the path coefficient (0.828 higher than 0.7) and *p*-Value (0.00 smaller than 0.1) and a very low standard deviation (0.09) also empowers us to consider that the model is very reliable.

3.4. The Second Stage—K Means Cluster Analysis

Secondly, a cluster analysis was performed to emphasise which countries are more innovative, and the factors that nudge innovation [42–44]. Studying the two criteria (patent, invest), one may observe that countries such as Italy (cluster 1), France (cluster 2), and Spain (cluster 6) form clusters by themselves (Table 4). France has almost the same number of patents as Poland, but France receives a higher investment amount. Spain and Italy have a small number of patents, under the average. Spain must review their innovation policy because of such low results while receiving a larger number of investments. Countries such as Belgium, Netherlands, Austria, Poland, and Sweden form cluster 3, representing the average sample: they have a medium investment amount and a medium number of patents. However, in this cluster, three countries, mainly the Nordic countries, show a higher degree of innovation due to significant investment, competitive human resources, and cultural background: pro-innovation attitude and the leadership mentality, which urges them to be creative, and find solutions in hostile environments. Germany and the United Kingdom (UK) form cluster 4 because they have a high investment, but the highest number of patents are obtained by Germany, being the most innovative European country. The complex infrastructure, technology, pro-innovation attitude, and competitive spirit make the difference in Germany's case. There is no doubt that the same countries show outstanding digitalisation and competitive intelligence outputs. This helps market actors to easier amass, study, and use information from all the fields of the market—competitors, decision-makers, or customers. Other countries, such as Romania, represent the extreme side, and form cluster 5. The low level of investment received reflects a small number of patents [45,46]. Still, other very complex factors are challenging to measure in figures/numbers, such as cultural patterns, self-esteem, lack of perspective, and lack of accurate and useful information that keep these countries far from innovation [46–48].

Table 4. Cluster membership, based on both criteria, Patents and Invest.

COUNTRY	Cluster	Distance	COUNTRY	Cluster	Distance
Italy	1	0.000	Denmark	5	1,414,072
France	2	0.000	Finland	5	1,149,118
Belgium	3	1,349,409	Cyprus	5	674,931
Netherlands	3	1,501,600	Estonia	5	607,931
Austria	3	668,430	Latvia	5	591,929
Poland	3	489,102	Portugal	5	529,071
Sweden	3	29,544	Lithuania	5	454,932
Germany	4	1,385,379	Romania	5	364,075
U.K.	4	1,385,379	Slovenia	5	332,934
Spain	6	0.000	Bulgaria	5	317,934
			Croatia	5	262,936
			Greece	5	200,939
			Slovakia	5	196,930
			Hungary	5	185,074

4. Discussion

The European Union conducted a competitiveness and innovation analysis based on Eurostat data: the eco-innovation index, R&D staff, and the product and innovative process enterprise (with its sub-criteria/items). Investments in human resources, and proper management of life cycle assessments (LCAs), based on blockchain technology, created new business models and innovations that ensured a sustainable economy. This assumption was validated by a regression model and K-means analysis [46]. We show that R&D promotes HR creativity, innovation, and collaboration, which positively affect eco-innovation and sustainable development. Product- and process-innovative companies have a limited impact on eco-innovation. We continue our previous research with this current article. The regression analysis shows a strong and positive correlation between investment and patents (0.828—when the investments increase by 1 unit, the number of patents increases by 0.828 units). Finally, the European Union countries were grouped based on investment and patent numbers in clusters. The results showed that all countries in cluster 5 have a poor track record of innovation. In contrast, clusters 3 and 4 countries are more innovative, having a good infrastructure, competitive human resources, and a pro-innovation culture [47–49].

The good and bad sides of how waste management and energy consumption are currently dealt with and treated are subjected to analyses and recommendations for future solutions. Promoting the CE indicators represents a recommended solution, to be woven into all educational programs in everyday communication until they become a concept familiar to all citizens, changing their mindset through ecological sustainability. Data analytics, digital technologies, and competitive intelligence are essential facilitators of the circular economy, changing development towards social entrepreneurship [47]. Competitive innovation sustains the idea that learning from what is happening inside and outside the business box helps increase both competitiveness and chances for catching any new opportunities. The more one understands, the bigger the profit and the chances to overcome competitors, satisfying customers, and facilitating operational management development for society and the environment. This also contributes to a new design of entrepreneurship to combine the classical and modern professions, develop new ways of business, and speed up decisions linked to environment preservation.

Executive decisions and societal wellbeing [48–51] could help those countries suffering because of insufficient investment, limited access to knowledge, and other constraints that stop their move for a better and more-accomplished life. Here, social entrepreneurs have an important word to say and a challenging task for the circular economy to drive the next level of development and impact their future.

Although this research has shown a strong positive correlation between investments and innovation, using the number of patents as proxy, the creation of patents solely does not guarantee their usability or an economic return or contribution to societal development. Indeed, there are many patents and innovations that never reach the market due to unfavourable economic and business conditions. An object of further study would be to assess the quality of patents, and their impact on society and the economy, as it is difficult to quantify the impact of these patents on the circular economy. It is indeed possible that some technologies prove to be unsustainable, and rather hinder the progress to a circular economy. As this study has only explained part of the causes of innovation growth through investments, further factors that affect this should be identified and included.

5. Conclusions

The CE influences national economies, organisations, and consumers. Given that fact, each actor participating in either social or business life, and every representative nominated by the Government, has to find their respective role and interest in sustainable behaviour to reach Green Deal objectives.

The regression model shows that investment proved the most crucial factor that stimulates patents in CE innovation. However, some other elements deserve to be added to the model for a sustainable economy, such as creating new jobs in the green economy, governmental support, green public procurement, education for understanding, and the implementation of digital and transferable knowledge and competencies.

Based on quantitative and qualitative analyses, the paper helps better understand Romania's current situation regarding innovation and competitiveness.

Some results confirm the hypotheses: (a) the level of investments influences the number of patents to some extent; (b) the innovation level differs in EU countries due to investment and cultural factors. Therefore, if Romania has an intention to approach the EU average, it has to increase in investments, which will be reflected in the number of patents and technology transfers, which would bring numerous benefits to the economy and society, as well as to sustainable development.

The importance of the article is subjective. However, the authors are highly motivated for their home countries to take a better course in their transition from linear to circular to follow the results of other countries in the lead. Sustainability is neither a race nor a competition; it might be a run through different shades of interest in science and professional education. Executive decisions considering societal wellbeing could help those countries in suffering because of insufficient investment, limited access to knowledge, and other constraints that stop their move for a better and more-accomplished life. Here, social entrepreneurs have an important word and a challenging task for the circular economy to drive the next level of development and impact their future. And they could be assisted by competitive intelligence to unlock the creation of new frameworks; help align targets, activities, and operations across information systems; and increase the speed of circular economy transformation into a resilient cornerstone for both people and society.

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Appendix A. Average of Investment and Patents for 2012–2018, by Country in EU

Table A1. Average of Investment and Patents for 2012–2018, by country in EU.

Country	Investments	Patents
Belgium	2856,585714	10,79428571
Bulgaria	530,2142857	0,642857143
Denmark	2262,257143	4,097142857
Germany	29732,47143	86,87714286
Estonia	240,4	0,804285714
Greece	646,9166667	0,428571429
Spain	11221,92857	25,29142857
France	21276,82857	43,99142857
Croatia	585,4714286	0,504285714
Italy	17974,21429	21,32
Cyprus	173,46	0,471428571
Latvia	255,6857143	1,628571429
Lithuania	392,5714286	0,827142857
Hungary	1033,085714	3,46
Netherlands	5708,085714	15,59714286
Austria	3537,657143	9,47
Poland	4695,042857	38,02714286
Portugal	1376,857143	2,488571429
Romania	1211,785714	4,092857143
Slovenia	514,8285714	0,635714286
Slovakia	650,9142857	1,8
Finland	1996,9	12,75857143
Sweden	4234,271429	5,308571429

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Article

Life Cycle Assessment of Electrodialytic Technologies to Recover Raw Materials from Mine Tailings

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Abstract: Currently, the development of new sustainable technologies to recover raw materials from secondary resources has shown a lack of available data on the processes and supplies involved, as well as their environmental impacts. The present research has conducted a life cycle assessment of electrodialytic (ED) technologies to improve critical raw materials recovery in the Portuguese mining industry. To critically appraise the activities from the mining sector and gather data on technical and environmental issues, three waste management scenarios were considered: (1) ED treatment with a deep eutectic solvent as an adjuvant; (2) ED treatment with simultaneous H_2 recovery; and (3) ED treatment with sodium chloride as an enhancement. The data presented were based on global databases, technical reports from official sources, and peer-reviewed published experimental outcomes. The estimated results indicated that one of the constraints in applying ED technologies is energy consumption and thus the impacts are highly dependent on energy source choices. On the other hand, as a consequence of the H_2 inherently produced by ED technologies, there is a direct potential for energy recovery. Therefore, considering an upscale approach of the ED reactor based on bench scale experimental results, the H_2 could be reused in the ED facility or stored. Additionally, according to experimental data, 22% of the tungsten from the fine mine tailings could be recovered. Finally, the possibility to remove 63% of arsenic from mine tailings could decrease contamination risks while creating additional marketable co-products.

Keywords: life cycle assessment; secondary mining resources; electrodialytic process; upscale; tungsten; arsenic; hydrogen

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1. Introduction

The European Union 2030 climate action targets aim to reduce 55% of the greenhouse gases emissions compared to the values in 1990 [1] and increase the total renewable energy share in energy consumption by up to 32% by 2030 [2]. Moreover, the Sustainable Development Goals include targets for water and energy consumption, waste and biodiversity management, and adaptation of mining operations to climate changing conditions [3].

The European Commission has recently launched the fourth critical raw materials list, where tungsten (W) continues, together with other 29 elements, to be included as a material of high risk of scarcity and economic relevance [4]. Strategies for sustainable reprocessing of mine tailings should be applied to extract valuable raw materials before their disposal or further reuse options.

Tungsten is a valuable transition metal that can be extracted from tungstate minerals [5], such as scheelite ($CaWO_4$) [6] and wolframite ($(Fe,Mn)WO_4$) [7]. Tungsten is applied to produce hard metal and metal carbide powder that can be further treated by powder metallurgical methods for hard metal tools production [8]. If Europe could take full advantage of its own resources, the dependency on other countries to produce hard metal tools could be overcome.

Panasqueira is an underground mine located in Portugal, on the southern edge of the Estrela mountain near the Zezere river, which has operated for more than 130 years. The Panasqueira ores are composed of a series of subhorizontal, stacked, and hydrothermal quartz veins, promoting the mineralization of wolfram-bearing schists and shales. The mineralized area at the Panasqueira mine is 400–2200 m wide, 2500 m long and 500 m deep. During the mining process two types of mine waste are generated: coarse aggregates derived from rock blasting and fine tailings conveyed into dams, both of which have accumulated for more than 100 years [9].

Storage and/or deposition of mine tailings constitute the main threat to the surrounding environment of Panasqueira, particularly via water contamination due to their physical, chemical and mineralogical characteristics and to the volume/area occupied by them. These residues, namely, the most ancient, may leach harmful elements from storage sites, designated by acid mine drainage [10]. These residues are more exposed to oxygen and water, increasing the chance of acids being formed due to sulfide minerals (e.g., pyrite). Other problems that may arise are related to high levels of cyanide and nitrogen compounds in waters at mine sites from heap leaching and blasting. Particulate matter can be released by the wind from mining activities, such as excavations, blasting, transportation of materials and wind erosion. Moreover, exhaust emissions of the vehicles from mining sites increase the levels of particulates [11]. To prevent and control the pollution from several streams, the Panasqueira mine has an environmental license that complies with limits and conditions for the management of the environmental pressures [12].

The current decrease in ore grade has prompted the assessment of existing resources, energy needs and environmental impacts of mine tailings in a life cycle overview, concerning a circular economy perspective. These approaches play not only an important role in supporting cleaner production, resource management and decision-making in the mining industry, but also in identifying new business opportunities. The current demand and metal prices have leveraged the interest in secondary mining resources for critical raw materials, where the recycling of W has lower-energy negative impacts (<6000 $kWht^{-1}$) compared to virgin production (10,000 $kWht^{-1}$), depending on the grade and cut-off [13].

The impacts from the processing of raw materials should be considered during the selection of the Best Available Techniques (BATs), which are the up to date technologies for preventing and minimizing emissions and impacts on the environment [14]. Generally, the BATs promote the improvement of the output and energy efficiency of the raw material production process through replacement of the old equipment with new apparatus, which is less energy consuming [15].

One feasible method to alleviate the impacts of rejected fractions from mining activities is the electrodialytic (ED) process, which consists of the application of a direct low-level current density (mA/cm^2) between pairs of electrodes, to remove substances from different environmental substrates. In the ED treatment of mine tailings, anion (AEM) and cation exchange membranes (CEMs) were used to separate the matrix from the electrodes' compartments [16]. This aimed at controlling the pH conditions of the electrolyte and the matrix, improving the selectivity of the removal of contaminants [17]. The membrane surface attracts dissolved ions with the opposite charge (counter-ions) from the pore water of membranes. Thus, the counter-ions are transported through the membrane due to the electrical current while co-ions, that have the same charge of the membrane, are rejected [17].

Research has been performed to assess the feasibility of applying the ED treatment to W mine tailings to (1) recover W contents and other elements of interest [16], (2) remove harmful compounds [18], (3) to recover H_2 that is inherently produced during the treatment [19,20], and (4) to provide a suitable matrix for further reuse in the construction sector as a supplementary cementitious material [21]. Furthermore, the ED process has demonstrated potential to extract W present in fine tailings (approximately 22%) in the presence of biodegradable acid adjuvants—natural deep eutectic solvents (DES) [18].

Life cycle assessment (LCA) is an analysis technique applied to assess potential environmental impacts of a product/service from, e.g., raw material acquisition to waste disposal. LCA provides an estimation of cumulative impacts under environmental categories such as global warming, ozone layer depletion, soil and water acidification, eutrophication, and abiotic depletion of non-fossil and fossil resources [22]. According to ISO 14040 [23] and ISO 14044+A1 [24], the LCA process is systematic and divided into four phases: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation [25]. LCA requires a detailed inventory analysis to ensure a representative assessment of all the inputs and outputs of mass and energy across the whole phases of the product life cycle, designated by life cycle inventory (LCI) [26].

The upgrades on technical processes should, therefore, consider the environmental, social, and economic consequences of managing mine tailings throughout the value chain. For instance, orebody characterization, mine planning, processing, disposal, reprocessing, recycling, and reuse should be integrated. From an economic point of view, decreasing mine tailings is a top priority, followed by reuse, recycling, recovery treatment and disposal. Circular business models supported by public policies could have strategic importance, where economic benefits/incentives could be essential to optimize the recycling management system while increasing recycling rates [27].

The trade-off between raw material extraction from secondary mining resources and the environmental harmfulness of mine tailings after the ED process, as well as the need to critically understand the information that LCA studies can offer, were the base of the present work. Thus, this research shows the potential environmental impacts that should be considered in an LCA when the ED technology is applied to Panasqueira fine tailings. In addition, an upscale hypothetical approach of the ED reactor, based on laboratory experimental results, was developed. The impacts estimated and determined in several scopes are presented in terms of mine tailing management scenarios (direct disposal vs. ED remediation prior to discharge/further reuse options). In this context, three different operational ED conditions were considered: (1) ED treatment with a deep eutectic solvent as an adjuvant; (2) ED treatment with simultaneous H_2 recovery; and (3) ED treatment with sodium chloride as an enhancement.

2. Materials and Methods

2.1. Case Description and Production System

The Panasqueira mine, located in the Centro region of Portugal (Figure 1) and described as the largest Sn–W deposit in Western Europe, has changed its layout over the years due to the W market downturns. In this way, the optimization of mechanical processes and the exploration of alternative ores were considered. The Panasqueira mine process is summarized in Figure 2. The mine has a production plan extending to 30 years in the future [9].

Wolframite, cassiterite and chalcopyrite are the minerals extracted and used to produce W, copper (Cu) and tin (Sn) concentrates, respectively. The extraction process consists of a room and pillar method, considering geo-mechanical and geological properties of the rock mass. The first stage for the production of W is crushing and milling of the ore, promoting the release of the W mineral from the material. Then, a heavy media separation (HMS) between fine and coarse fractions is performed. This stage promotes the removal of 80% of the ore that does not contain W. Then, the W preconcentrated fraction is subjected to a conventional gravity concentration technique, followed by magnetic flotation in the presence of sulfide and dry magnetic separation [29]. The process is mostly gravitational due to the relative density of the concentrated products in relation to the sterile material [30].

Additionally, there is a wastewater treatment facility, the Mine Water Treatment Station (MWTS), located in *Salgueira*. The MWTS was projected to treat a maximum of 500 m^3/h, where the wastewater comes from the mine, wash activities and heaps [30].

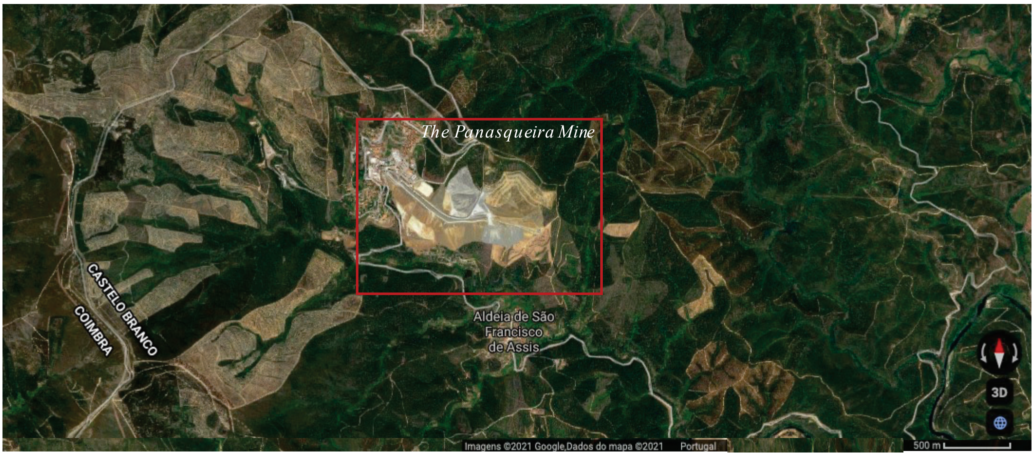


Figure 1. The Panasqueira mine geografic location—Covilhã, Portugal, 40°10′11.0604″ N, 7°45′23.8752″ W (source: Google maps).

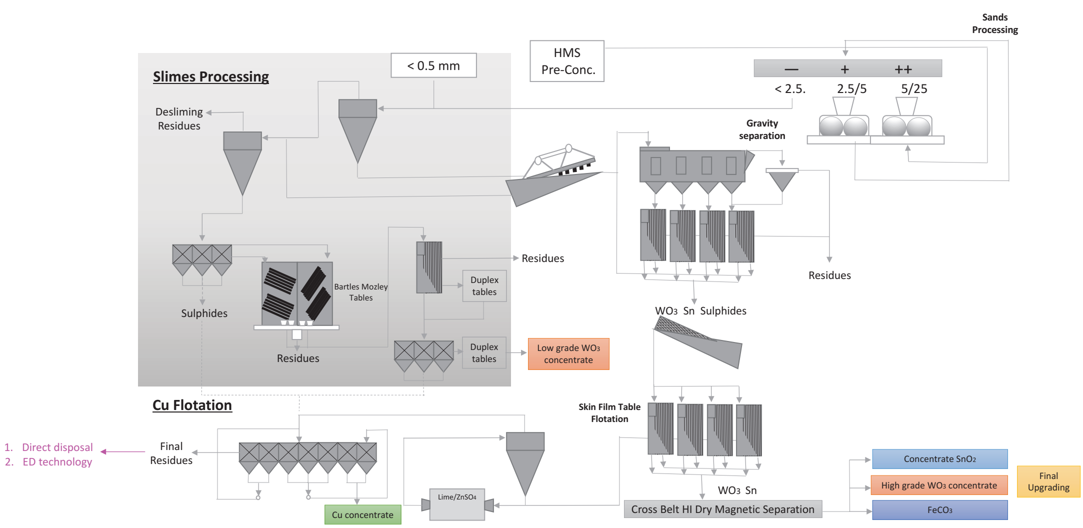


Figure 2. The Panasqueira mine process and scenarios considered for the management of mine tailings generated (based on [28]). HMS—Heavy media separation.

2.2. System Boundaries and LCA Road Map

Figure 3 shows the steps considered for the present LCA study. The analysis starts on the exploration of the ore for the W concentrate production. Then, for the rejected fraction of the mining process, three waste management scenarios were considered: (1) ED treatment with DES as an adjuvant; (2) ED treatment with simultaneous H_2 recovery; and (3) ED treatment with sodium chloride (NaCl) as an enhancement. Based on the analysis of the ED scenarios, an ED upscaling study was carried out that also coupled financial projections.

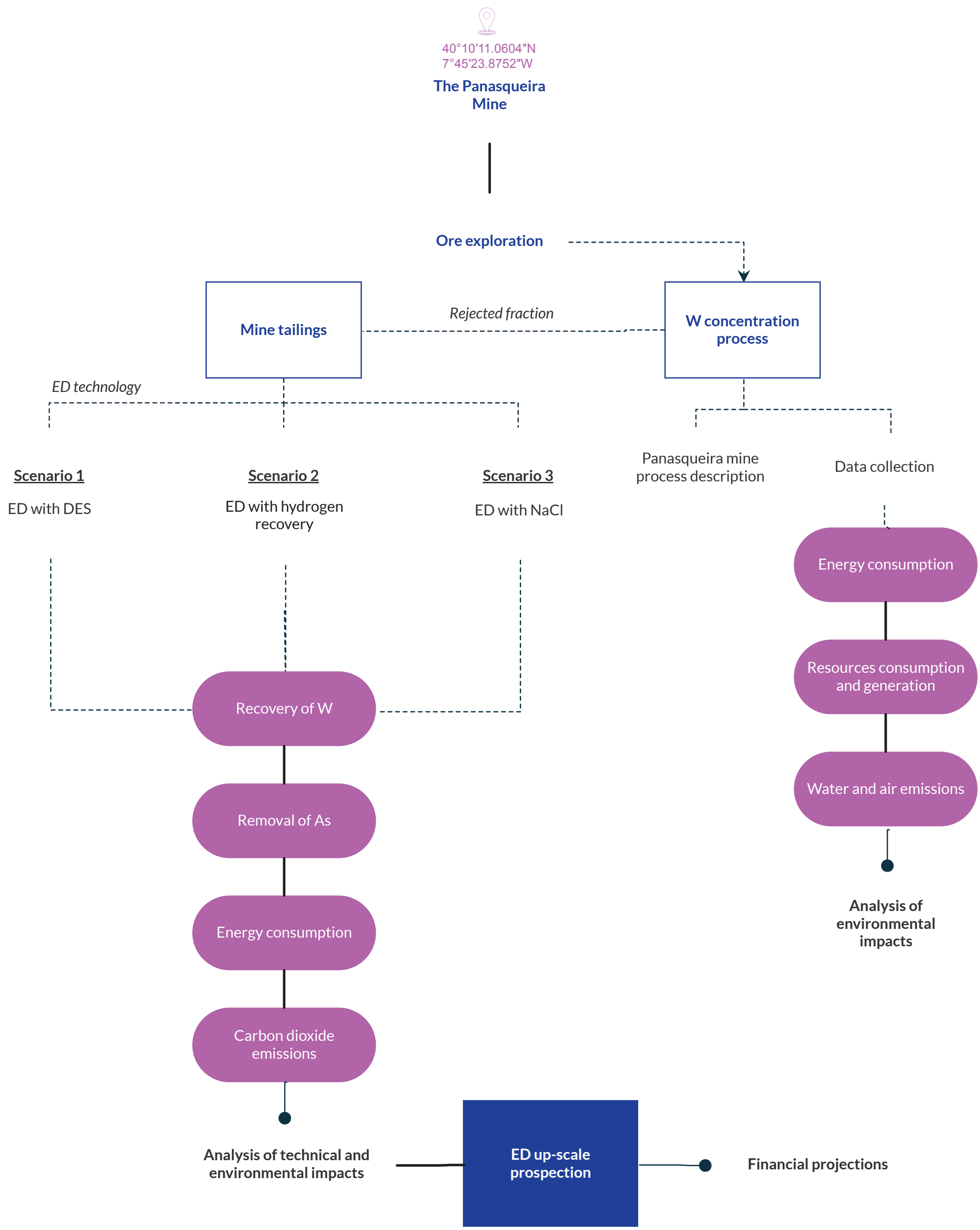


Figure 3. Flowchart of the life cycle analysis performed for the production of W concentrate and the electrodialytic treatment of mine tailings.

2.3. Data Collection

The data used to build the LCA were selected from three main sources: Ecoinvent database version 3.7.1, technical reports published from the European Commission and results from laboratory works published in international scientific journals (Table 1).

Table 1. Main sources used for the Life cycle assessment (LCA) data collection.

Source	Topic	Documents Consulted
Ecoinvent version 3.7.1	Tungsten concentrate production	- Tungsten mine operation and beneficiation [31]
European Commission technical reports	Mining industry operation	- Integrated Pollution Prevention and Control (IPPC) reference document on best available techniques in the nonferrous metals industries [8]
Research works published in international scientific journals	Electrodialytic process	- Exploring hydrogen production for self-energy generation in electroremediation: A proof of concept [20] - Electrodialytic hydrogen production and critical raw materials recovery from secondary resources [19] - Hydrogen recovery in electrodialytic-based technologies applied to environmental contaminated matrices [32] - Electrodialytic removal of tungsten and arsenic from secondary mine resources—deep eutectic solvent enhancement [18]

2.4. Mine Tailings Characterization

Considering the Panasqueira mine plant (Figure 2), the processing of 1000 kg of ore (from excavation activities) was considered as the functional unit for the LCA study. Table 2 presents estimations regarding W concentrate production and mine tailings generation from the processing of 1000 kg of ore. The calculations were based on scientific data available on Panasqueira resource compositions, as referenced in Table 2.

Table 2. Resources consumed and generated during the production of tungsten concentrate at the Panasqueira mine.

Item	Value per Functional Unit	Units	References
Panasqueira mine resources–ore	1000 (functional unit)	kg	-
W content in Panasqueira mine resources	3.0	kg/t ore	0.3% WO_3 [33]
W concentrate after the concentration process	2.3	kg/t ore	75% WO_3 [29]
Mine tailings generation	997.4	kg/t ore	-
W in mine tailings	0.8	kg/t ore	[29,33]
As in mine tailings	3.7	kg/t ore	[16]
W price	25,500	EUR/t	[34]
H_2 price	2.7–6.5	EUR/kg	[35]

Thus, concerning Table 2, from the processing of 1000 kg of ore, only 2.3 kg of W concentrate is produced, with grades of 75% of WO_3. This means that around 997 kg of fine tailings are generated from the processing of 1000 kg of ore. From the mine tailings it is possible to recover 0.8 kg of W/t of ore. The W price (25,500 EUR/t) makes the W recovery attractive from an economic perspective.

2.5. Water and Air Emissions and Resources Consumed

The processing of 1000 kg of ore was selected as the functional unit for the LCA. Water and air emissions during W concentrate production were determined based on Ecoinvent database [31]. In the Ecoinvent platform, the information is presented considering 1 t of W concentrate production. Thus, an extrapolation based on the W concentrate production at the Panasqueira mine was used to estimate its environmental impacts.

The resources consumed and generated during the production of tungsten concentrate at the Panasqueira mine were determined, considering the amount of fine tailings that results from the processing of 1000 kg of ore. In this sense, the amount produced from fine tailings generation was determined by subtracting the initial fraction (1000 kg ore) of the quantities of W, Cu and Sn concentrates produced. The W contents in mine tailings per functional unit were determined based on the concentrate grade of W trioxide (WO_3) produced in the plant—75% [29].

The plant also produces Cu and Sn concentrates. However, the amounts of Cu and Sn were only considered to estimate the fine tailings generation, and production impacts were not considered for this study.

2.6. Energy Consumption and CO_2 Release

To estimate the energy consumed by the ED system, Equation (1) was applied:

$$E\ (kWh) = \frac{V_i \times A \times t}{1000} \quad (1)$$

where V_i is the average voltage (Volts) in time i, A is the current intensity (Amperes) and t is the duration (hours) of the experiment. To convert the energy consumed into the quantity of CO_2 released for the environment, a conversion factor of 0.23314 kg CO_2 per kWh was considered [36].

3. Results and Discussion

3.1. Tungsten Concentrate Production at the Panasqueira Mine: Environmental Impacts

3.1.1. Energy Consumption

During the W concentrate production at the mining site, there are several high energy consuming phases. The overview presented in Figure 4 is based on data from technical reports. Herein, an average of the energy consumption of each processing step per ton of processed ore during the W production is shown.

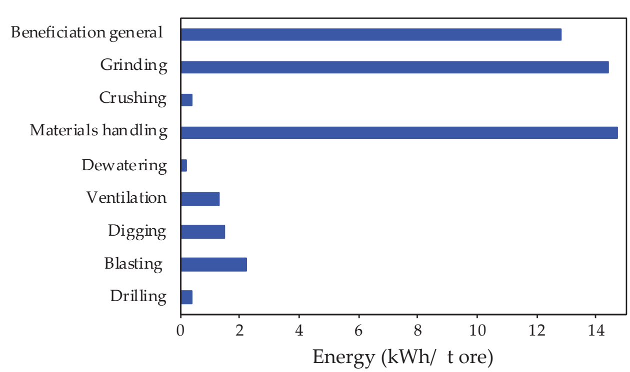


Figure 4. Energy consumption of mining processing activities (adapted from [37]).

The high energy consuming stages are materials handling (more than 14 kWh/t ore) and grinding (14 kWh/t ore). On the other hand, crushing, dewatering and drilling activities present lower energy consumptions (below 1 kWh/t ore). In addition, the environmental categories which are more affected by those processing steps are global warming potential (12.6 kg CO_2 eq/t ore), cumulative energy demand (133 MJ eq/kg), terrestrial acidification (0.29 kg SO_2 eq/t ore) and human toxicity (3.4 × 10^{-5} CTUh/t ore) [37].

3.1.2. Air and Water Emissions

During the processing of 1000 kg of ore, air and water emissions are generated, causing the main environmental pressures. Table 3 presents the emissions that were determined for Panasqueira mine processing based on Ecoinvent data from W concentrate production impacts.

Table 3. Emissions to the environment during the tungsten concentrate production (determined based on Ecoinvent data for tungsten concentrate production [31]).

Emissions	Value per Functional Unit	Units
Air		
Carbon dioxide, nonfossil	0.35	kg/t ore
Carbon disulfide	7.74 × 10^{-6}	kg/t ore
Particulates < 2.5 µm	0.01	kg/t ore
Particulates > 10 µm	0.13	kg/t ore
Particulates > 2.5 µm and < 10 µm	0.11	kg/t ore
Water		
Aluminum	9.26 × 10^{-6}	kg/t ore
Biological oxygen demand (BOD_5)	2.08 × 10^{-3}	kg/t ore
Chemical oxygen demand (COD)	4.15 × 10^{-3}	kg/t ore
Dissolved organic carbon (DOC)	1.54 × 10^{-3}	kg/t ore
Hydrocarbons	1.29 × 10^{-5}	kg/t ore
Iron	3.66 × 10^{-5}	kg/t ore
Nitrite	1.29 × 10^{-5}	kg/t ore
Phosphorus	1.29 × 10^{-5}	kg/t ore
Total organic carbon (TOC)	1.54 × 10^{-3}	kg/t ore
Tungsten	1.29 × 10^{-5}	kg/t ore
Water	0.26	m^3/t ore

Carbon dioxide is the major substance released to air (0.35 kg/t ore) and as observed in Figure 4, the materials handling and grinding are the main operations contributing to its release, in addition to the emission of particles. Regarding water load emissions per ton of ore, the chemical parameters that have higher impacts on aquatic systems are chemical oxygen demand (COD) (4.15 × 10^{-3} kg), biochemical oxygen demand (BOD_5) (2.08 × 10^{-3} kg) and total organic carbon (TOC) (1.54 × 10^{-3} kg).

COD is generally used to indirectly determine the amount of organic compounds in aquatic systems and is useful as an indicator of the degree of organic pollution in surface waters [38]. The COD is the most affected parameter by mining activities (4.15 × 10^{-3} kg/t ore), indicating that not all forms of organic matter (biodegradable and nonbiodegradable) are available.

The BOD_5 presents the second highest impacts (2.08 × 10^{-3} kg/t ore), meaning a decrease in the amount of oxygen consumed, by aerobic biological organisms, to decompose the organic matter in 5 days. An excessive microbial activity causes a reduction in the quantity of oxygen in the water, which may foment the growth of anaerobic organisms and decay the development of other existing communities [39].

The dissolved organic carbon (DOC), which is a potential source of carbon and energy for ecosystem metabolism, plays a central role in many limnological processes, since it is largely derived from terrestrial vegetation, deposited from lake catchments either by streams or by overland flow [40]. The mining impacts in terms of DOC are less pronounced (1.54 × 10^{-3} kg/t ore), although changes in DOC cycling can result in air–water exchange of CO_2 alterations [41].

Mining processes demonstrated the lowest impacts on the total organic carbon (TOC) (1.54×10^{-3} kg/t ore), mainly in the form of DOC. The TOC measures the amount of carbon found in an organic compound. A high organic content means a higher oxygen consumption and, consequently, an increase in the growth of microorganisms that deplete oxygen supplies [42].

The chemical water contamination is reflected in composition changes, while physical contamination results from the presence of fine material, affecting both surface water and aquifers. In the case of metallic ores, chemical contamination can be relevant due to the oxidation of pyrite producing sulfides that may leach heavy metals. In addition, yellowish to red $Fe(OH)_3$ precipitates are formed when acidic water meets neutral water in river basins. These precipitates affect the growth of aquatic plants [30]. Physical contamination by fines occurs when there is a discharge of treatment effluents in water courses. Contamination by suspended solids seriously affects fish communities [30]. In the case of the Panasqueira mine, the Zezere river is the main concern of water pollution.

Mining at levels below the water table will subsequently promote risks of evaporation of aquifers, water degradation by eutrophication and chemical contamination [43]. Acid mining drainage is characterized by a pH below 5 and is related to the sulfides (S^{2-} and $S_2{}^{2-}$), sulfur (S) or thiosulfate ($S_2O_3{}^{2-}$) being in contact with water and the atmospheric oxygen (oxidizing conditions). Acid water results from the oxidation of pyrite (FeS_2), usually catalyzed by bacteria. Other sulfides such as blends (ZnS), galena (PbS), chalcopyrite ($CuFeS_2$), pyrrhotite (Fe_7S_8) and arsenopyrite (FeAsS) can contribute to acidifying water resources. Generally, acidic effluents present high concentrations of Fe, manganese (Mn) and aluminum (Al) [30].

To decrease water resources contamination in the area, the Panasqueira mine has an in-house Mine Water Treatment Station (MWTS). The wastewater comes from the surface through infiltration and from the production process, since a significant amount of water is used during drilling and irrigation of the work fronts. The wastewater treatment facility has a volume capacity of 7000 m^3. The outlet and the receiving tank were designed to convert relatively soluble ions, such as Fe^{2+} and Mn^{2+}, into the respective less soluble oxidized forms (Fe^{3+} and Mn^{4+}). The treatment plant is composed of four tanks with mechanical agitation in which the addition of flocculant and lime is carried out. Lime is added to increase the pH of acidic water and prevent a possible drop in pH when ions such as Fe^{3+} and Mn^{4+} precipitate in the form of hydroxides. The solid hydroxides formed and in suspension are deposited at the bottom of the tank, being pumped into the mud dam [30].

3.2. Mine Tailings Management

3.2.1. Electrodialytic Scenarios

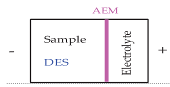
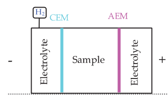
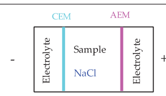
Following the assessment of air and water emissions during W concentrate production, the environmental pressures of mine tailings were studied in particular in terms of ED process efficiency for elements extraction and recovery, energy consumption and CO_2 emissions. This assessment was based on experimental data from previous works. In fact, the major impacts from waste disposal at mine sites can be divided into two categories [37]:

(1) the loss of productive land following its conversion to a waste storage area;

(2) the introduction of sediment, acidity, and other contaminates into surrounding surface water and groundwater from water running over exposed problematic or chemically reactive wastes, and the consequent soil contamination.

In this sense, alternative ways to direct disposal of mine tailings are desired. Table 4 presents three different scenarios where the ED technology was studied as an alternative to direct disposal. The systems defined have diverse extraction ratios of elements and other features, being important to compare the ED scenarios in terms of achievements and environmental impacts.

Table 4. Data from the electrodialytic treatment of mine tailings.

Scenario	ED Scheme	Duration (h)	Current Intensity (A)	Extraction (%/kg t ore)		H_2 Purity/ Recovery (%)
				W	As	
1. ED treatment with DES [1]		96	0.05	22/0.2	16/0.6	n.a.
2. ED treatment with H_2 recovery [2]		1	0.1	7.5/0.06	48/1.8	74/50
3. ED treatment with NaCl [3]		120	0.1	13/0.1	63/2.4	n.a.

[1] According to [18]; [2] according to [20,32]; [3] according to [19]; AEM—Anion Exchange Membrane; CEM—Cation Exchange Membrane; DES—Deep Eutectic Solvent; Electrolyte ($NaNO_3$ 0.01 M); NaCl—sodium chloride; n.a.—not applicable.

Scenario 1 involves the use of a DES in the sample compartment during the ED treatment. DES present advantages in terms of yield, costs and toxicity when compared to conventional ionic liquids [44], which are composed of strong acids and bases [45]. In this way, a two-compartment reactor was operated for 4 days at 0.05 A. The electrolyte and sample sections were separated by an anion exchange membrane [18]. The main outcome of this reactor configuration was the quantity of W extracted from the matrix. The use of choline chloride/oxalic acid (1:1) promoted a higher solubilization of the W and, together with the current applied, a synergetic effect on the recovery of this critical element was observed.

Scenario 2 includes a three-compartment ED reactor and the simultaneous collection of self-produced H_2 in an eco-friendlier manner. This configuration presented the lower W recovery, where only 7.5% of W was extracted. However, it should be noted that this system operated only for 1 hour at 0.1 A. Applying this current intensity was possible to access the production of H_2, an energy carrier, with 74% H_2 purity. Electrokinetics have been coupled with electrodialytic technology for H_2 production during the removal of pollutants [20], where the energy requirements for this system are considerably smaller owing to the higher conductivity of the matrix [46]. Additionally, regarding the As removal, a better performance was achieved (48%) in comparison with scenario 1 (16%). Considering the functional unit defined for this study, hypothetically, this system could avoid 1.8 kg of As contamination (Table 4).

Finally, in scenario 3, a three-compartment ED reactor was tested at 0.1 A for 5 days using NaCl to improve the current passage [19]. The main achievement of this system was a 63% As removal from a total of 3.7 kg As/t ore (Table 2), meaning less than 2.4 kg of As contamination per t of ore (Table 4).

Regarding different market segments and environmental concerns, the scenarios considered may show different potentials. In this way, the trade-off for the three scenarios was studied to understand the impacts on resources consumption and its economic feasibility. Table 5 presents an energy assessment for the three bench scale ED treatment scenarios. These tests were performed to treat 39 [18] and 22 g [16,20] of fine tailings in a two- and/or three-compartment ED reactor, respectively. The energy was determined according to Equation (1).

Table 5. Estimation of the energy consumed and CO_2 released during the electrodialytic laboratory treatment of mine tailings.

Scenario 1. ED Treatment with DES						
Measure	**Voltage (V)**	**Current intensity (A)**	**Energy consumed (kWh)**	**kWh/g W extracted**	**kWh/g As extracted**	**g CO_2**
Day 0	32.30	0.05	2.0×10^{-3}	1.0×10^{-2}	4.2×10^{-5}	0.38
Day 1	13.20		1.0×10^{-3}	5.0×10^{-3}	2.1×10^{-5}	0.15
Day 2	11.10		1.0×10^{-3}	5.0×10^{-3}	2.1×10^{-5}	0.13
Day 3	10.80		1.0×10^{-3}	5.0×10^{-3}	2.1×10^{-5}	0.13
Day 4	11.80		1.0×10^{-3}	5.0×10^{-3}	2.1×10^{-5}	0.14
		Average	1.0×10^{-3}	6.0×10^{-3}	2.5×10^{-5}	0.18
Scenario 2. ED treatment with H_2 recovery						
Measure	**Voltage (V)**	**Current intensity (A)**	**Energy consumed (kWh)**	**kWh/g W extracted**	**kWh/g As extracted**	**g CO_2**
0 min	35.00	0.1	4.0×10^{-3}	6.7×10^{-2}	2.8×10^{-5}	0.82
10 min	27.50		3.0×10^{-3}	5.0×10^{-2}	2.1×10^{-5}	0.64
20 min	25.80		3.0×10^{-3}	5.0×10^{-2}	2.1×10^{-5}	0.60
30 min	26.10		3.0×10^{-3}	5.0×10^{-2}	2.1×10^{-5}	0.61
40 min	28.00		3.0×10^{-3}	5.0×10^{-2}	2.1×10^{-5}	0.65
50 min	38.80		4.0×10^{-3}	6.7×10^{-2}	2.8×10^{-5}	0.90
60 min	59.50		6.0×10^{-3}	1.0×10^{-1}	4.2×10^{-5}	1.39
		Average	3.0×10^{-3}	6.2×10^{-2}	2.6×10^{-5}	0.80
Scenario 3. ED treatment with NaCl						
Measure	**Voltage (V)**	**Current intensity (A)**	**Energy consumed (kWh)**	**kWh/g W extracted**	**kWh/g As extracted**	**g CO_2**
Day 0	98.40	0.1	1.0×10^{-2}	1.0×10^{-1}	5.3×10^{-5}	2.29
Day 1	77.25		8.0×10^{-3}	8.0×10^{-2}	4.2×10^{-5}	1.80
Day 2	46.80		5.0×10^{-3}	5.0×10^{-2}	2.7×10^{-5}	1.09
Day 3	41.65		4.0×10^{-3}	4.0×10^{-2}	2.1×10^{-5}	0.97
Day 4	27.85		3.0×10^{-3}	3.0×10^{-2}	1.6×10^{-5}	0.65
Day 5	14.70		1.0×10^{-3}	1.0×10^{-2}	5.3×10^{-6}	0.34
		Average	5.0×10^{-3}	5.2×10^{-2}	2.7×10^{-5}	1.19

The highest energy consumption occurred in scenario 3, where a three-compartment reactor and NaCl were used. An average of 5.0×10^{-3} kWh was consumed, with a release of 1.2 g CO_2. In fact, this system was operated at a higher current intensity (0.1 A) and thus, it was expected to have a higher energy consumption, and consequently, higher amount of CO_2 release. However, the addition of NaCl promoted the control of the power consumption once it led to an increase in media conductivity and therefore lower resistance [47].

On the other hand, scenario 1, performed with natural extractants (DES), demonstrated a decrease in the energy consumption of more than 80%. In this set-up, a current intensity of 0.05 A was applied, which was the main contributor to the energy consumption decrease (1.0×10^{-3} kWh) when compared to the other two scenarios. This means approximately 0.9 g of CO_2 emissions to the environment. In fact, this scenario presented the lowest energy consumption per mass of elements extracted (6.0×10^{-3} kWh/g W and 2.5 E $\times 10^{-5}$ kWh/g As).

Scenario 2, which includes H_2 recovery, demonstrated an intermediate energy consumption. In scenario 2, as in scenario 3, a current intensity of 0.1 A was applied. However, due to the use of a totally sealed reactor (to ensure no leakage of gases), a decrease in the voltage occurred and thus a decrease in the resistivity inside the reactor was observed. Based on Ohm's law, if the current intensity is constant, the voltage and the resistivity (or conductivity) are strongly related. The decrease in the ED cell voltage is linked to a conductivity increase in the electrodes' compartments [20].

This may explain the lower energy consumed (3.0×10^{-3} kWh) compared to scenario 3 (ED with NaCl). Additionally, the possibility to recover the self-hydrogen produced by the ED treatment and reuse to feed the reactor in terms of energetic requirements could provide energy savings of up to 50% [32].

Regarding the water needs for sample suspensions and electrolyte preparation with sodium nitrate ($NaNO_3$), ED configurations that have three compartments require 700 mL (32 times the sample weight) and the two-compartment systems require 600 mL (15 times the sample weight). However, the reuse of secondary water resources during the ED treatment (e.g., secondary effluent) have shown promising results [16] that may contribute to alleviate tap water needs.

Summing up, the laboratory experiments could follow structural designs, such as a central factorial design. However, it is pivotal to properly assess the industrial interest. In a scale-up perspective, the experiments should be carried out sequentially, followed by a process analysis and economic evaluation. Even in the first steps of the research, which can affect the experimental domain of interest, the quality of the information provided could be improved and be key factor for a pilot unit.

3.2.2. Electrodialytic Treatment Upscale Prospection

In order to increase the understanding of the scenarios studied, a perspective of a full scalable ED reactor model to support commercial roll-out was carried out. The implementation of the theoretical ED pilot reactor would result in a full running removal and recovery of the target compounds from the fine mine tailings, hypothetically aiming zero liquid or solid discharges. A full closed-loop of residues would change the perspective of mine tailings, which would become a valuable resource instead of a costly waste stream.

The ED plant, which can be either vertical or horizontal, is presented in Figure 5, showing a simplified flow sheet of a loop reactor. It is important to point out that the design of the reactor does not need to be similar to the laboratory scheme. However, it has to be designed to achieve the best data, both in terms of fluid dynamics and transport properties. In Figure 5, the design of the reactor is used as an example of the concept, and merges the best parts of both scenarios 1 and 2:

(1) two-compartment reactor design, which is easier to operate;
(2) DES as enhancements, alleviating the consumption of strong acids and bases while incrementing the W recovery;
(3) cation-exchange membrane, which allows H_2 recovery for depreciation of implementation and maintenance costs, as well as flexibility in different market segments.

A balance between the ED treatment plant and downstream units needs to be ensured in order to decrease environmental pressures from the disposal of mine tailings. The final product (after the ED treatment) needs to have such a quality that consecutive ED phases will work optimally at minimal operational costs. Since the Panasqueira mine has available land, the installation of solar panels in the south direction with 144 cells at 400 W ($2025 \times 996 \times 40$ cm) [48] will promote the use of renewable energy and overcome the environmental pressures and costs regarding ED technology. The use of solar panels decreases the investment cost by avoiding the use of batteries, solar inverters, and power supplies and the maintenance cost since there is no battery waste to manage [49].

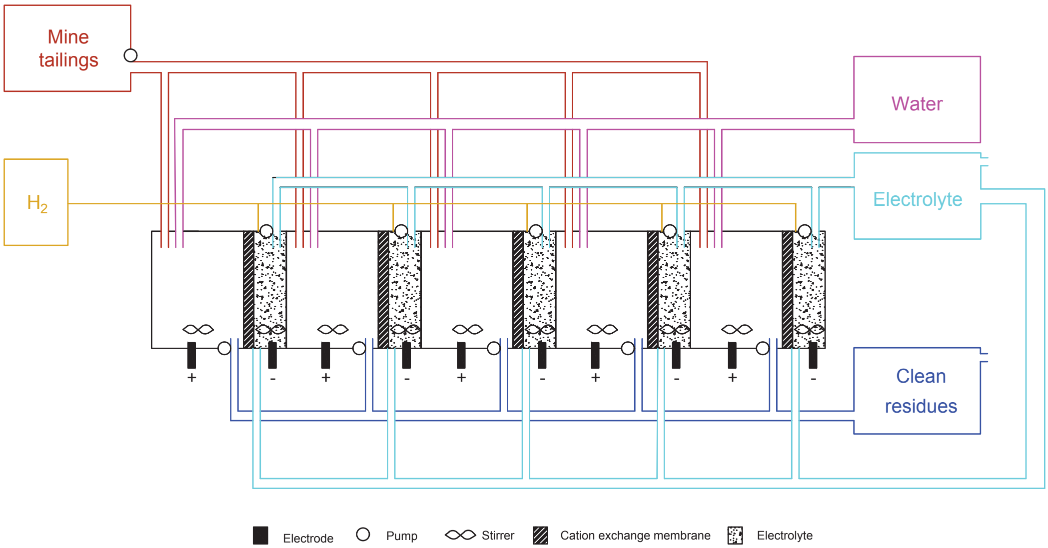


Figure 5. Theoretical electrodialytic plant facility based on bench scale experiments.

Additionally, the scaled-up reactor was dimensioned addressing issues related to a seamless operation with minimal needs for cleaning. The material selected for the reactor was polyethylene due to its chemical and impact resistance, electrical properties and low coefficient of friction. In addition, polyethylene is lightweight, easily processed and offers near-zero moisture absorption [50]. The reactor was dimensioned to treat 10 m^3 per day (8 h running time, based on average labor schedules in Portugal) in five conjugate sequential units. The capacity of each block is 2 m^3, as reported by other pilot studies [51]. These dimensions promote the treatment of the volume of mine tailings produced per day (0.4 m^3), considering: (1) mud's density of 3031 kg/m^3 [52]; (2) 997 kg volume of mine tailings; (3) water needs both for the electrolyte ($NaNO_3$ 0.01 M) and sample suspensions. The ED facility was projected to be fully distributed by individual blocks. Each section includes pumps (when gravity transport is not possible), membranes, and sample and electrolyte compartments. Additionally, it includes reservoirs for ED treated and nontreated mine tailings (before the ED process), water, electrolyte and H_2, to either reuse or storage. This simplifies the maintenance of the reactor and, consequently, reduces the problems during the treatment.

Scaling in ED occurs due to inorganic species, e.g., PO_4^{3-}, NH_4^+, Mg^{2+}, Ca^{2+} and CO_3^{2-}, forming low-solubility minerals. The more effective the process is at removing these elements, the less scale will be formed and therefore the maintenance costs for the ED unit will be lower [53].

A constraint of the ED facility is the goal of achieving total reuse of water, since there is a need to treat and/or crystallize the salt from the brine stream ($NaNO_3$) and the effluent suspension produced. There are several technological options for waste brine crystallization. The projection of the ED facility intends to concentrate and crystallize the salts in the brine solution. Crystallization plays an important role in many industries where water recycling is implemented. If it is not possible to perform the purification of brine solutions, the Panasqueira MWTS (capacity = 500 m^3/h) [30] could also include the treatment of both brine solution and effluent suspension. In addition, treated water resources from the Panasqueira MWTS could be used to prepare the mine tailings suspensions, aiming for circularity of by-products. This step would promote savings in water consumption by the generation of suitable mixtures to reuse in the ED system.

Moreover, the proposed ED unit combines a reservoir for the collection of the self-produced H_2, increasing the value proposition of the ED pilot. Lead-acid batteries are the most useable storage systems, as well as rechargeable batteries, supercapacitors, and redox flow batteries. The most promising systems for renewable energy storage are the lithium-ion batteries and redox flow batteries [49]. Coupling a unit for H_2 recovery at the mine can direct the site towards a clean energy transition [54]. In fact, the implementation of H_2 as a flexible energy carrier in future energy systems is a top priority in the new EU Green Deal. The smart integration across sectors is encouraged and promotes investments on cutting-edge research and innovation for clean energies [1]. Together with W recovery and As removal, the H_2 transfer to be used in the mine ED facility could have socio-economic impacts both on recovery of raw materials and clean energy transition, since it addresses applicable solutions to industries. This stimulates the fostering of synergies in industrial sectors, the creation of new services and the transition and adaptation to eco-innovated systems. The ED treated fine tailings can be further used in construction materials with compatible applications with conventional concrete and fired brick masonry walls [21]. On the other hand, the As can be used in purification processes of zinc leach solutions [55], and residues containing As could be recovered by glass industries, since arsenates can be turned into silicoarsenates during vitrification [56].

Further roll-out may be hampered by the lack on financial commitment to implementation in a declining industry, where investments in utilities are not seen as strategic to the core business. However, low investment solutions with limited capital expenditures (CAPEX) and operating expenditures (OPEX) costs are required. Table 6 presents the financial projections of the ED plant for the initial investment, as well as the first and the fifth years of ED operation.

Table 6. Financial projections of the expenditures of implementing the theoretical electrodialytic plant facility presented in Figure 5.

Item	Quantity	Cost/Uni (EUR)	Initial Investment (EUR)	1 Year of ED (EUR)	5 Years of ED (EUR)
Stirring	10	1986.00	19,860.00		
Reactor in polyethylene (diameter = 1.6 m; length = 1 m)	5	650.00	3250.00		
Block compartments (diameter = 1.6 m; length = 1 m)	20	149.00	2980.00		
Electrodes Ti/MMO (0.5 × 0.1 m; width = 3 mm)	10	100.00	1000.00		
Membranes CEM–CR67, MKIII, Blank (diameter = 0.8 m)	5	499.00	2495.00		
$NaNO_3$ * (1 kg per unit)	29	151.90	4405.10	1,101,275.0	5,506,375.0
Natural deep eutectic solvents (choline chloride. 1 kg per unit + oxalic acid. 25 kg per unit) *	6	143.00	858.00	214,500.00	1,072,500.00
Pumps	11	489.00	5379.00		
Tubes	36	1.89	68.04		
Power boxes	10	383.81	3838.10		
Crocodiles + wires	20	0.99	19.70		
Solar Panels (2025 × 996 × 40 cm)	5	476.00	2380.00		
Implementation	10% of the total reactor price		4653.29		
Maintenance	5% of the initial investment (every 3 months)			10,237.25	51,186.23
Cleaning of Membranes	15 EUR/m^2 (twice per month for 2 m^2 of membranes area)			3600.00	18,000.00
Replace of Membranes	Every 4 years				2495.00
Cleaning of Reactor	2% of the initial investment (once per year)			1023.72	5118.62
Total investment			51,186.23	1,330,635.97	6,655,674.86

* Number of packaging to buy. Costs were based on: stirring—[57]; reactor—[50]; compartment block—[58]; electrodes—[59]; membranes—[60]; $NaNO_3$—[61]; Adjuvants—[62,63]; pumps—[64]; tubes—[65]; power box—[66]; crocodiles + wire—[67]; solar panels—[48]; implementation—[68]; maintenance; cleaning of reactor and membranes; changing membranes lifetime—[69,70]. Ti/MMO—titanium/mixed metal oxide.

It should be noted that Table 6 shows a simplified economic approach of the ED concept, considering only its physical implementation. Through this assessment it is possible to understand the impact of these figures on the broad uptake potential in the mine industry. This section does not cover the fully CAPEX or OPEX estimating procedures. Nevertheless, it provides concepts that can be used in the project evaluation to help the understanding of its application in a full implementation mode. Moreover, Table 6 also details the costs of the components needed for the ED facility. The materials for the ED plant construction (e.g., electrodes, membranes, pumps, tubes) and the reagents needed for the electrolyte and sample suspensions ($NaNO_3$ and DES) are the main contributors of the costs reported in the first- and fifth-year projections. Together with the costs for the manufacturing, and, therefore, the total investment in the first year, a set of other expenses to guarantee the success of the ED process during its lifetime is also foreseen. The total investment before developing the ED facility in a full run mode is approximately 51,000 euros, increasing from around 1 to 7 millions of euros in the first and fifth years, mainly due to $NaNO_3$ and DES consumption.

The investments can be considered high, although further optimization of the processes and research could decrease the values presented. Additionally, the up-scaling theoretical approach should be further optimized, based on a pilot study, to decrease inputs related to energy and resources in a more positive way. This strategy may promote minimization of the negative pressures in the environment and the adaptation of industrial sectors to eco-innovative markets. In particular, the ED plant presented could leverage new market possibilities, the requalification of mining areas after close and the development of new technologies with regard to achieving the Sustainable Development Goals [3].

4. Conclusions

Mining industries have been stimulated to operate in a more sustainable way, reducing their environmental burdens and improving resource management. In this way, eco-efficient processes and alternative scenarios to direct waste disposal of rejected fractions are desired.

This research work evaluated the impacts on the environment that may come from mining processes and three potential scenarios that involve the ED treatment of fine tailings from the Panasqueira mine.

Regarding the impacts of mining processes, materials handling and grinding presented the highest energy consumption and, consequently, CO_2 release (0.35 kg/functional unit). A carbon footprint of 12.6 kg CO_2 eq/t ore is associated with mining activities. On the other hand, the chemical parameters that have the highest impacts on aquatic systems are COD (4.15×10^{-3} kg), BOD_5 (2.08×10^{-3} kg) and TOC (1.54×10^{-3} kg).

The analysis of previous ED data at the bench scale was a key factor to estimate the potential environmental burdens involved in an ED plant conception. In particular, energy consumption is a major concern at an industrial scale. Herein, the ED technology could have a central role in the recovery of metals below 45 microns, a main challenge for the mine. In addition, the mine has a project spanning more than 30 years, which means that new market segments could be explored to keep the development and the requalification of the Panasqueira area after its closure. In this context, aligned with the removal of As contents, the recovery of W and H_2 seems to be attractive for the development of the Centro region of Portugal, considering a circular economy perspective, both in terms of raw materials recovery and sustainable energy production. These aspects might decrease the risk associated with mining activities and leverage new business opportunities in the mining sector in the upcoming years.

Thus, concerning the three scenarios studied, different advantages were pointed out. Scenario 1, which involves the use of DES, exhibited a better performance in terms of the quantity of W extracted from the matrix (22%). Scenario 2 considers self-produced H_2 recovery during the ED treatment with 74% H_2 purity. Scenario 3 presents an approach with conventional reagents and the main achievement of this system was the As removal (63%).

Based on the best features of the scenarios analyzed, a sequential theoretical ED facility was presented. The dimensioning of the reactor was based on the quantity of mine tailings that need to be treated and laboratory data. An investment of approximately 51,000 euros was estimated, increasing from 1 to 7 millions euros in the first and fifth years due to maintenance and operational costs. Nevertheless, the upscaling effect may reduce the inputs—namely, those regarding operational costs and energy consumption. In future works, a pilot study of the ED treatment should be performed to assess the scaling-up influence on technical aspects and to determine the economy of scale's percentage.

This study provides new insights for the life cycle of mine tailings and a basis for environmental decision-support in the application and roll-out of ED technologies.

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Circularity in the New Gravity—Re-Thinking Vernacular Architecture and Circularity

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Abstract: The mounting climate change crisis and the rapid urbanization of cities have pressured many practitioners, policymakers, and even private investors to develop new policies, processes, and methods for achieving more sustainable construction methods. Buildings are considered to be among the main contributors to harmful environmental impacts, resource consumption, and waste generation. The concept of a circular economy (CE), also referred to as "circularity", has gained a great deal of popularity in recent years. CE, in the context of the building industry, is based on the concept of sustainable construction, which calls for reducing negative environmental impacts while providing a healthier indoor environment and closing material loops. Both vernacular architecture design strategies and circular economy principles share many of the same core concepts. This paper aims at investigating circular economy principles in relation to vernacular architecture principles in the built environment. The study demonstrates how circular principles can be achieved through the use of vernacular construction techniques and using local building materials. This paper will focus on Egypt as one of the oldest civilizations in the world, with a wide vernacular heritage, exploring how circularity is rooted in old vernacular settlements and how it can inspire contemporary circular practices.

Keywords: circular design; circularity; circular economy; vernacular architecture; Egypt

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1. Introduction

The growing climate change crisis and urbanization have urged more government decision-makers, urban planners, architects, and private investors to develop new policies, processes, and methods for leading more sustainable lifestyles [1]. According to the United Nations Environment Programme (UNEP) [2], cities consume 75% of the world's primary energy capacity (such as crude oil, coal, wind, natural gas, etc.), produce 60–80% of global greenhouse gas emissions, and produce 50% of the world's waste [3,4]. Buildings are considered among the main contributors to harmful environmental impacts, resource consumption, and waste generation [5]. According to UNEP [6] and the World Resarch Institute (WRI) [7], buildings account for 40% of all waste generated by volume, 40% of all material resources use by volume, and 33% of all human-induced emissions. Furthermore, the construction industry and the built environment are among the greatest contributors to natural resource depletion [3,8,9]. Thus, it is imperative for governments to start adopting more sustainable practices in the construction industry.

The concept of the circular economy (CE), also referred to as "circularity", is one of the sustainable concepts that has been gaining traction in recent years as an approach for reducing the environmental footprint of different industries, including the building sector [5,10–13]. While there is no standard definition for the CE model, it has been defined by several organizations as the opposite of the linear economy (LE) and its "make-take-waste" model [12,14]. The linear production-consumption model is concerned with producing and consuming goods made from raw materials, selling them, using them, and then disposing of them as waste [3,5]. This model, however, has become ineffective due to the increase in global populations and depleting natural resources [12]. In the building industry, CE calls for reducing the negative environmental impacts on the environment while providing a healthier indoor environment and closing material loops [15]. CE is not necessarily considered a new concept but rather one that combines several pre-existing principles for closing material loops, reducing energy and raw material waste [16,17], and prolonging the lifespan of products through maintenance and repair [18,19].

Vernacular architecture can also be linked to circular sustainable concepts. Vernacular architecture is defined as the design of buildings based on local needs, using local materials, and reflecting the local culture and traditions. In addition, they are usually built by inhabitants without any formal design training (architecture without architects) [20–22]. Vernacular buildings provide optimal solutions for local problems [22] that are in harmony with nature, in a durable, healthy, and sustainable manner [23]. Furthermore, vernacular buildings all over the world are dependent on the use of low-impact natural materials and construction techniques. Such techniques have proven to be resilient to weather conditions and fulfill the locals' needs at minimal cost and with a minimal impact on the environment [24–26]. Thus, the importance of local architecture is quite evident, along with the need to return to many of the simple, sustainable solutions that have been devised in the past [22].

2. Literature Review

2.1. The Circular Economy in the Built Environment

CE in the built environment has gained academic, governmental, and organizational recognition over the past few years [3]. The EU has developed a series of actions and legislative proposals for future reuse and recycling targets for construction and demolition waste [27,28]. Shifting to CE provides several opportunities for reducing primary material usage and carbon footprints [29], and can positively impact economic, environmental, and social sustainability [30]. Circular economy concepts can be integrated in the scale of buildings, products, and components, in two main aspects: circular material usage, and circular design [12]. The use of circular materials is concerned with the selection of materials that are renewable (biological cycles), or that are reusable after first use (technical cycles), while the circular design is defined as the design of products and components that can be easily disassembled at the end of their use, facilitating their reuse in other projects [12]. Furthermore, circular building design (CBD) is concerned with buildings that are designed, planned, constructed, operated, and maintained with CE principles in mind [31]. To be able to shift toward CBD, CE principles need to be applied to the different life cycle stages of the building, managing the building and its component parts from cradle to cradle [30]. This also entails ensuring that all materials used in the building can be recycled or composted at the end of its lifecycle [32].

Previous studies have approached CE in the built environment from different points of view. A few examples of recent studies on this topic are outlined in this section. Akhimien et al. [30], for instance, provided a review for circular economy interventions in buildings under seven main circular economy principles or strategies and highlighted the possible gaps in research on this topic. Similarly, Cimen [33] and Eberhardt et al. [5] presented a review of the literature on the circular economy in the construction and built environment sector, highlighting key findings and gaps in the reviewed studies. Munaro et al. [3] provided a state-of-the-art review on CE research and focused on analyzing what has already been done in terms of circular practices in the construction value chain. The study also proposed a theoretical framework to be used as a starting point by designers, researchers, and stakeholders for introducing circular practices in the built environment [3], while Amory [12] developed a framework (guidance tool) for the design of circular buildings, based on the "circular design" and "circular material usage" strategies. Furthermore, Cambier et al. [34] presented an overview of the available design tools related to circular design that can be implemented at different stages of the design process. Eberhardt et al. [35] conducted life cycle assessment models that compared linear and circular building components, suggesting the potential benefits of the re-use and recycling of building components in the circular approach. Huuhka and Vestergaard [36] presented a comparison between building conservation and CE concepts, addressing the relationships among them, their commonalities, and their differences. However, there was a gap in studies that linked the CE with vernacular architecture.

Moreover, despite the efforts being made, the wide-scale adoption and implementation of CE in building design and construction strategies still lack a common direction, often implemented through small-scale and fragmented approaches [3,5,33]. Buildings are complex and dynamic, involving many different systems and components, each with its own life cycle, functions, and characteristics. The environmental performance of buildings depends on several different attributes, such as building design, materials choice, operation, and maintenance [5,37]. The literature also indicates that CE initiatives are directed toward different focus areas and use different tools [38]. Thus, it is argued that these fragmented initiatives prevent the universal adoption of CE in the building industry [33,35]. Studies indicate that there is also a lack of knowledge on the definition of CE, its fundamental principles, and its implementation in an innovative manner in the building sector's business model [27,36], while Kirchherr and Van Santen [39] indicate that most CE studies focus on developed countries, making many of the CE studies irrelevant to construction in less-developed countries. This is due to differences in policy environments, access to funding, and infrastructure [39]. Cambier et al. [34] have also asserted the need for more practical examples, such as case studies and best practices for circular buildings. All of this indicates the importance of providing more studies that investigate CE in the building sector. In addition, it highlights the need for more studies on best practice in developing countries [39].

2.2. Circular Design Principles

Various CE design principles were highlighted in the literature in different classifications. These principles include adaptive design and reuse, design for disassembly (DFD), and design for repair and manufacturing [17,40–42]. Adams et al. [27] classified the CE principles regarding: designing for disassembly, flexibility and the reuse of secondary materials, the reuse of components, and the use of secondary materials in the construction value chain [5]. Likewise, Akhimien et al. [30] concluded that there were seven main circular economy principles in buildings: design for disassembly, design for recycling, building materiality, building construction, building operations, building optimization, and the building's end-of-life. Akhimien et al. [30] also highlighted that most studies were focused on two main aspects: the recycling of waste components and end-of-life. Buildings that can be disassembled are more adaptable, according to CE principles, since their parts can be reused, renewed, optimized, or exchanged for others while maintaining their value. Lastly, UNEP [43] classified CE according to four main principles. These are: (1) reduce by design, (2) refuse, reduce and re-use, (3) repair, refurbish and remanufacture, and (4) repurpose and recycle. From these classifications, four main principles were summed up to be adopted throughout this study. The concluded principles combine most of the principles discussed in the different sources reviewed and are rooted in vernacular architecture principles. These are (1) reduce by design, (2). refuse, reduce, and re-use, (3) repair, refurbish, and remanufacture and (4) repurpose and recycle. Table 1 summarizes the various classifications mentioned and highlights the circular design principles that are adopted in this study.

Table 1. A summary of the circular design principle classifications in the investigated literature.

	Circular Design Principles' Classification		Sources
A	1. Adaptive design and reuse 2. Design for disassembly	3. Design for repair and manufacturing	[17,40–42]
B	1. Design for disassembly 2. Flexibility and the re-use of secondary materials	3. Reuse of components 4. Use of secondary materials in the construction value chain	[27]
C	1. Design for disassembly 2. Design for recycling 3. Building materiality 4. Building construction	5. Building operations 6. Building optimization 7. Building end of life	[30]
D	1. Reduce by design 2. Refuse, reduce, and re-use	3. Repair, refurbish, and remanufacture 4. Repurpose and recycle	[43]
	1. Reduce by design 2. Refuse, reduce, and re-use	3. Repair, refurbish, and remanufacture 4. Repurpose and recycle	**The Concluded Design Principles**

2.3. Vernacular Architecture and the Circular Economy

It has been noted that vernacular architecture shares many of the core concepts of sustainable buildings. Vernacular architecture is concerned with climate-responsive buildings that are made from local materials and technology and reflect the local customs and lifestyle of a community [44]. Using vernacular concepts can create environmentally conscious designs that respond to climatic conditions, usually using passive and low-energy strategies for human comfort [44]. Vernacular buildings correspond to local materials and the economical use of building resources [44]. Many studies highlight the importance of learning from vernacular buildings for designing contemporary sustainable buildings and of returning to local approaches that are most suitable for their local environments [44–46]. Furthermore, vernacular solutions are usually low-cost since they adhere to their local contexts. This is particularly important for developing countries, such as Egypt.

Research into vernacular architecture design concepts reveals that they coincide with many CE concepts. According to several studies [47–50], there is still a need for more research that addresses the use of vernacular knowledge in contemporary architectural examples. Although CE has been linked to sustainable concepts in the past, a gap was noted, however, in studies that linked CE to vernacular architecture. In Egypt, sustainable and circular design solutions are fundamental for addressing climate change. Egypt has multiple examples of vernacular and neo-vernacular buildings, thus providing many opportunities to learn from their techniques. Several studies have also highlighted the value of learning from vernacular buildings in Egypt. For example, a study by Ahmed [51] investigated three vernacular buildings constructed by Bedouin residents in Siwa Oasis, highlighting best practices and appropriate systems that were implemented for climate-responsive low-carbon buildings. The study also highlighted the lessons learned from environmentally friendly approaches in terms of building with local materials, passive cooling techniques, natural daylighting, and the best use of available natural resources [51]. Dabaieh [49] investigated energy-efficient and low passive strategies in a contemporary vernacular building in Saint Catherine, Sinai, Egypt, highlighting how vernacular design concepts were integrated when designing modern contemporary buildings. Fouad and Mostafa [52] discussed the potential benefits of adapting aspects of vernacular architecture for a more sustainable quality of life in arid regions in Egypt. Fernandes et al. [53] investigated strategies used in Mediterranean vernacular architecture by analyzing cases from southern Portugal and Northern Egypt, identifying key vernacular climatic strategies that can be used for improving contemporary buildings' energy performance. However, more studies are still needed that explore how learning from vernacular concepts can be useful in the future adoption of CE in contemporary buildings.

3. Methodology

This study uses an investigative and exploratory methodological approach. A literature review initially supported the identification of gaps in research that explore the link between concepts and examples of circular economy and circularity within vernacular architecture. After these gaps were identified, two cases were examined using an exploratory approach. The first case is a vernacular settlement that shows examples of circular design and construction techniques, while the second case represents a contemporary settlement that aims to revive vernacular architecture with respect to context. Four main circular design principles were elected as indicators of circularity from the literature review and were used in the case study analysis. The principles are: (1) reduce by design, (2) refuse, reduce, and reuse, (3) repair, refurbish and remanufacture, (4) repurpose and recycle. The principles were summed up from the reviewed classifications to include many of the key circular principles indicated in the investigated literature. In addition, these principles also share many of the ideas that were found to be rooted in vernacular architecture concepts. Two of the principles were merged together in our investigation as they resemble the principle of the 5 Rs, which are: refuse, reduce, reuse, repurpose, and then recycle. The methodological steps followed in this study are shown in Figure 1.

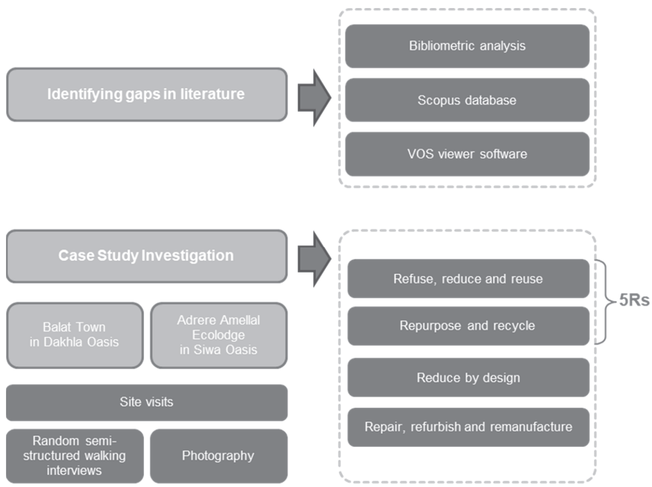

Figure 1. The methodological approach and steps followed in this study.

3.1. Identifying Gaps in the Literature Connecting the Circular Economy with Vernacular Architecture

To identify gaps in the literature that make the connection between the circular economy and vernacular architecture, this research used bibliometric analysis, searching Scopus database results from the last 10 years. To illustrate the bibliometric analysis, VOSviewer software was employed to depict the most used keywords within the field of the circular economy in relation to architecture, as shown in Figure 2. The first keywords used were "circular economy" and "vernacular architecture". There were only two publications that have a close connection to the circular economy. Both publications were based more on "shape grammar" and product design than on architecture. Shape grammar is considered a generative and algorithmic language and design tool that was established by George Stiny and James Gips in 1971 [54]. Yet, when replacing the search phrase "vernacular architecture" with "architecture" and "built environment", more links and publications appeared, with 141 for "architecture" and 200 for "built environment". Most of the papers related to architecture and the built environment mentioned topics related to sustainability, waste management, building materials, life-cycle assessment, economics, and ecology. These results concretely demonstrate the gap in research that links the circular economy and vernacular architecture, compared to research focused on circularity and architecture in general.

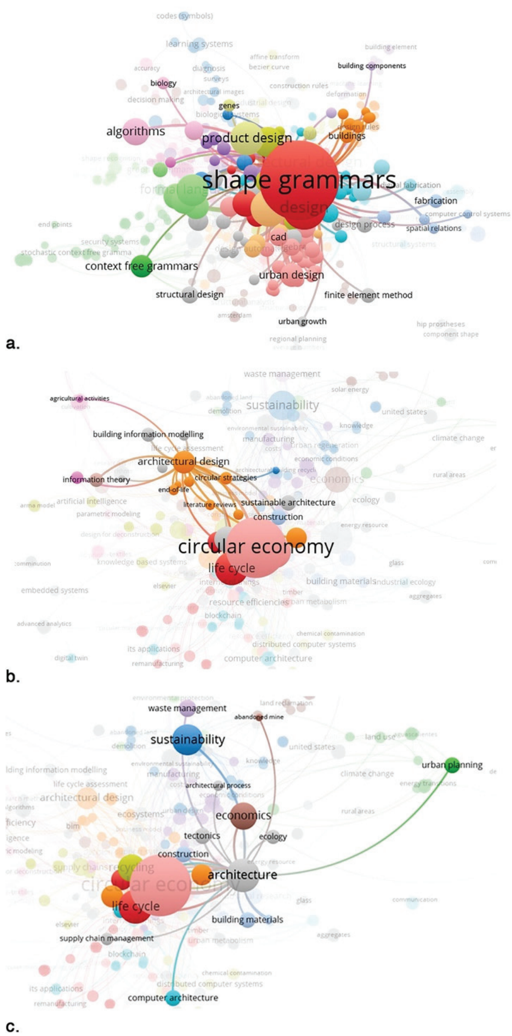

Figure 2. The gap between research on the circular economy and vernacular architecture is shown in (**a**), while (**b**) and (**c**) show the connection between research on the circular economy and the built environment/architecture.

3.2. Case Study Investigation

The two case studies chosen are located in the Western Desert of Egypt. The traditional vernacular case study that was selected is in Balat Town in Dakhla Oasis, whereas the contemporary case study is Adrere Amellall Ecolodge in Siwa Oasis. Following suggestions from [55–57] to select a single case study location to maximize what can be learned in terms of comparability in the period of time available for the study, field trips to the Western Desert were conducted in 2016 and 2017 to visit the two case-study sites. Several tools were used during these visits, including field notes, field observations, random semi-structured walking interviews with 20 locals, structured interviews with two architects, and photography. After a year of site visits, the data was analyzed using circular economy approaches from the literature review to assess the vernacular architecture.

3.3. Case Study Description

The town of Balat, built at the eastern entrance of the Dakhla Oasis, is situated at the junction of two old caravan routes in the Western Desert of Egypt [58]. Records refer to Balat as early as the 14th century [59]. Ancient Balat was a significant kingdom in the oasis [60] and was considered the chief town and headquarters for the governor of the oasis in Egypt at the end of the Old Empire (2350-2150 BCE) [61]. The main economic activity in Balat was and still is farming. They have a self-sufficient system for growing their local crops, given their remote location. Balat residents rely on underground fossil water for irrigation and drinking, as there is no water supply or drainage infrastructure. Furthermore, dry toilets are used, where organic wastes are composted to be used as soil fertilizers or as bio-fuel dunk cakes. This is one example of "closing the loop". Inhabitants have long adapted their dwellings to the tough, hot dry desert climate. Balat's inhabitants are accustomed to using passive techniques, especially for cooling. This is evident in the use of air shafts, shading, cross-ventilation, and high-thermal-mass building envelopes. In addition, the construction solutions adopted, using locally available materials, decrease the processing and transportation costs of building materials. Thus, the building outcomes are less energy-demanding and more environmentally friendly than many modern solutions. The main construction materials in Balat are clay, palm reeds, and acacia wood, as shown in Figure 3. Bearing-wall construction using sun-dried adobe mud bricks is the typical building technique. Such applications in building design and construction are based on cumulative previous experiences and tacit knowledge through trial and error.

Figure 3. The usage of adobe clay bricks, together with reeds and acacia wood, in construction at Balat Town in Dakhla Oasis.

Adrere Amellal Ecolodge was built in 2000 and is located in Siwa Oasis. It faces the salty lakes prevalent in the Western Desert and is surrounded by the white mountains of Siwa. The Oasis offers materials such as limestone, palm and olive trees, salt rocks, and clay that are unique compared to the typical materials available in the surrounding environment [62]. One of the most significant resources in the Oasis is the salt extracted from the salt lakes and the therapeutic mud, which is considered a unique geological phenomenon of the area [63]. The lodge includes residential units, a restaurant, and a healing center, which are all built from local salt "kershif" and clay for bearing-wall building, as shown in Figure 4. In addition, there is a water spring, as well as an organic farm that produces crops for self-sufficient farming. Adrere Amellal applies circular thinking and self-sufficiency, inspired by traditional and vernacular thinking. For example, the ecolodge depends on growing and cultivating its own crops, and the use of locally sourced natural materials in building construction and for furniture pieces. The eco-lodge has a local waste management station for treating wastewater and garbage, as well as an organic waste composting station, as shown in Figure 5. The architectural design of the building includes many passive strategies, like solar orientation, high thermal mass through the thickness of the wall, shading, passive cooling, and cross-ventilation.

Figure 4. The usage of kershif, and palms plastered with salty mud, at Adrere Amellal Ecolodge in Siwa Oasis.

Figure 5. Self-sufficient farming and the water spring in Adrere Amellal Ecolodge.

4. Results

4.1. Refuse, Reduce, Reuse, Repurpose and Recycle

From the field observations and investigations using the UNED circular economy's four principles, the researchers noticed that indigenous vernacular communities tend to apply the "5 R" principles, firstly, "refuse and reduce", using materials from outside their local context. They have learned from experience that importing non-local materials causes more problems than benefits in the long term. If non-local materials are necessary, they are reduced to a minimum and only brought in for essential needs. After the "end of life" stage of vernacular buildings, the building's materials can be easily recycled again. For example, mud bricks can be easily reused and molded again into new, fresh mud bricks. Wood used in the construction of roofs, if in good condition, can be repurposed again for roofing or can be reused for doors, windows, stairs, farming tools, or other homemade furniture, or upcycled for other functions. As a last option, if the wood is not of good enough quality for any other use, it can be used as charcoal for heating or cooking. Furthermore, it is possible to allow wood to rot/biodegrade if it has no further functionality. Similarly, mud bricks can also be broken down as clay in the soil. One outcome from the interviews with the locals, from a user-to-user perspective, is that in both the Balat and Adrere Amellal case studies, reused palm reeds were employed in construction. They were particularly useful in constructing the ceiling and roof, as well as being integrated into the design of other products. With almost no extra cost, the use of palm reeds is highly recommended due to their compressive strength and good resistance to the harsh desert climate.

4.2. Reduce by Design

Vernacular settlements were constructed in a minimalistic way. Indigenous vernacular communities are used to the principle that "forms follow resources". Taking Balat as an example, the main architectural design solutions are based on the concept of reducing the quantity of raw natural materials used in construction to the greatest extent possible. Reducing the quantity of materials used in construction and reducing the quantity of waste materials was a conscious decision. Vernacular dwellers are aware of how precious raw materials are, and they know from their accumulated experience how they can most effectively and efficiently use raw materials. Almost no waste is produced during construction, and any leftovers are used for other functions. From interviews with locals in Balat, an example of this can be seen in the way the components of palm trees are used in vernacular construction. The palm wood trunks, for instance, are used as the main beams in the roof construction. Furthermore, palm reeds are used as secondary beams by bundling them together as mats and then placing them over the main wood trunk (wood logs). Lastly, the leaflets around the palm reeds, when taken away, are used in furniture manufacturing or in weaving different sorts of household utilities, like food baskets and even bags. The palm fibers, located around the tree trunk, are also taken away and used for weaving baskets.

Adrere Amellal Ecolodge implemented construction methods reflecting the local vernacular architecture of the region, where the emphasis was on materials that are available in the desert. This helps avoid using harmful materials that pollute the environment or that consume more energy, either through construction machinery, transportation, or kiln-firing. From the interview with the two principal architects who designed Adrere Amellal, they mentioned that the design morphology of Adrere Amellal Ecolodge is based on thick kershif (a biodegradable combination of salt-rock and mud mixed together) walls that can vary between 40 and 80 cm and act as a thermal insulator. Kershif was selected in the early stages of the design for both the construction of the building and for built-in furniture design. Raw salt, extracted from the salt lakes in Siwa Oasis, as well as palm reeds from the site, were also used to construct the built-in furniture. Salt and palm reeds cost close to nothing to use and helped reduce the embodied carbon in both the construction process and in lifetime energy usage. Using both kershif and salt that were extracted from the same site allow reducing the transportation of the materials to the site. It was also observed that kershif can be easily disassembled as blocks, to be used again in construction or decomposed in the soil.

4.3. Repair, Refurbish and Remanufacture

Vernacular buildings in Egypt, especially those constructed from earthen materials, need regular maintenance and repair throughout their lifetime. From our interviews and field observations, we found that the locals use seasonal celebrations as opportunities to perform quarterly, annual, or sometimes bi-annual maintenance. Families festively gather to help each other conduct maintenance on the interior or the exterior of buildings. These activities keep their buildings fresh and reduce the possibility of any damage or deterioration due to harsh desert weather conditions. Regular repair and maintenance help increase the lifespan of buildings and reduce the need to replace parts. When needed, major repairs, such as the replacement of a structural element, patching walls or roofs, or the replacement of doors and windows, can also be conducted outside of celebration periods. Heavy rains can cause earthen building deterioration, thus requiring regular maintenance.

From the interview responses that were received, one interviewee mentioned that in the high rainy seasons in winter, rain and evaporation cause damage to some buildings, which then require maintenance. For instance, in Adrere Amellal, the crystallization that occurs in salt particles due to humidity in the summer can lead to the evaporation of some salt particles, while during winter, the rain can cause cracks and damage to the building. Accordingly, depending on the state of damage, annual repairs and renovation work are required to restore the building to its original state. In this case, two treatments are performed, either filling the cracks with a new mixture of kershif and plastering it with clay, or in the case of the total destruction of a wall, an entire wall can be replaced with a new one.

5. Discussion

From this explorative study, we can deduce that circularity in design should look at the building as a kit instead of looking at the building as a traditional structure. Design and building should be considered from the lens of disassembly, easy maintenance, and being easy to upcycle or reuse. Architects should design buildings to be easily taken apart so their materials can be reused in another building. Increasing not only a building's life span but the life span of its materials is another essential part of circular thinking and the circular economy. This might sound a bit challenging, but designers have to not only get used to working with smaller palettes of reusable materials but also design building components for disassembly as well as assembly. Yet design for disassembly, or, as some call it, "Design for Deconstruction" (DfD), offers other concerns that need to be considered. For instance, the circular design process itself requires new skills; it needs more flexibility in drawings and designs and more flexibility in terms of deadlines for assembly and disassembly.

Design for disassembly or for re-building was the primary method of conceptualizing vernacular architecture in Egypt. Designs differ from one building type to another and depend on the availability and use of construction materials. Earth, reeds, straw, wood, woven textiles, and jute are raw building materials that are easy to disassemble as small components and re-assemble again. As shown earlier in this paper, the focus is on earthen construction, mainly in the form of sun-dried mud blocks and mud-brick (Adobe) construction. Bricks are modular units that are easy to cast and assemble and easy to disassemble for rebuilding. The only design drawback of mud bricks is the time it takes to disassemble them for re-use. The use of mud bricks in construction can be labor-intensive and time-consuming in terms of casting and drying. However, nowadays, there are several methods for mechanical casting using hydraulic machines, which is a fossil-free process. Nevertheless, they are not as fragile as fired bricks, which can later be broken up easily during disassembly. Additionally, if any damage happens to sun-dried adobe bricks, they can be easily repaired using mud paste or clay mortar.

Both case studies in this paper were rich in showing the different usage of the local materials in many ways, whether in construction or in products. In addition, using adobe and kershif as traditional building techniques through time opens new doors for integrating many advanced techniques in construction, from 3D printing or robotics to traditional techniques, to enable faster building. For reducing the maintenance of adobe and kershif buildings, new additives can be integrated into the mixture that will prevent or reduce structure cracks and shrinkage with time, like adding lime and natural fibers.

Some circular materials also rooted in vernacular architecture are bio-based materials. Very soon, natural substances, such as weeds, algae, bacteria, enzymes, and even proteins, will be used to grow materials that will replace today's plastics and other industrial building and construction materials. The main goal of the development of these nature-based materials is to avoid the production of toxic waste during materials manufacturing processes and during their reuse and disposal. Ideally, these biomaterials can have positive impacts once they are no longer used in construction. For example, at the end of their lifespan, they could be used as animal feed or compost. It is worth mentioning that bio-fabrication is the future for circular design and soon, a supply chain will be integrated into the materials for building construction. Figure 6 illustrates a linear way of thinking, using industrial materials, and a circular way of thinking, using natural and renewable materials.

Still, there are challenges facing circular design and construction. Firstly, even if buildings are designed and constructed with circularity in mind, we cannot always build everything from new. Transforming existing old buildings through rehabilitation or adaptive reuse must be the number-one alternative, and rehabilitation can be performed with circular design concepts. One other challenge, depending on the size of the building, is that the process of assessment for reclaiming old materials can be time-consuming. It can also be hard to identify every single building component and decide which materials are reclaimable or not, especially when the issues of toxicity and the carbon footprint have to be considered. This chain of decision-making can hinder material reuse. Another challenge is the lack of standardization, in terms of how different architecture firms and contractors assess and reclaim materials for reuse. Labor cost is another issue, as experienced workers can be expensive and could be considered an economic burden on the project during the assembly and disassembly process. Quantifying designs for reconstruction or deconstruction can still be very undefined since there are not many well-recognized conventional methods. Moreover, there is a need for professionals who are able to judge which parts of a building can be reused as reclaimed materials. At this point in the process, circularity needs a strong desire and a will for change, necessitating dedicated and enthusiastic actors in the building sector to step in.

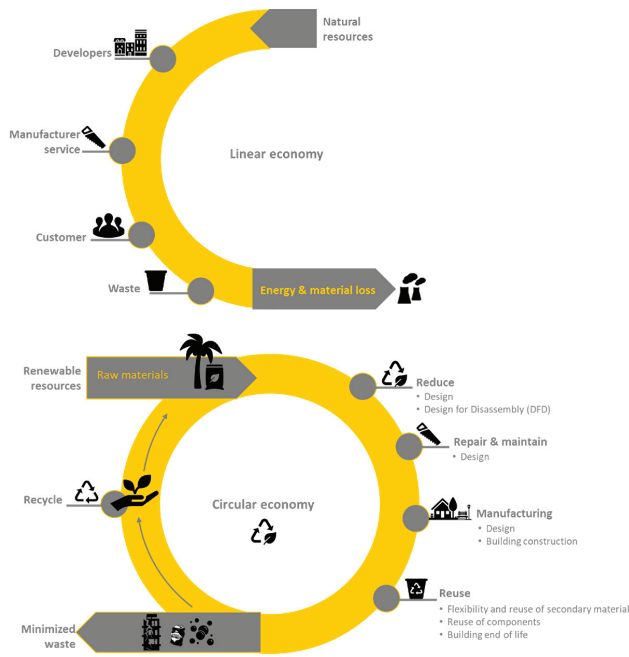

Figure 6. Comparison between a circular and linear economy in design and construction. The graphic summarizes the differences in thinking and the impact on the environment.

6. Conclusions

This study discussed four main circular building design concepts in vernacular architecture. Two cases in Egypt were chosen for this study's investigation: a traditional vernacular settlement and a contemporary project that was inspired by vernacular CE principles. Points of analysis for the two cases stemmed from key CE approaches that were found to be common to both circular design and vernacular design.

The focus was on four concepts: reduce by design; refuse, reduce and reuse; repair, refurbish and remanufacture; and repurpose and recycle. Based on the exploration of these concepts, this paper posits that the negative environmental impacts of buildings and the overuse of natural resources can be considerably reduced by drawing inspiration from vernacular architecture. However, most contemporary buildings are still not designed according to the principles of circular design, or even close to the concept of circularity. Available literature focuses primarily on topics such as life cycle assessment for building materials or the efficiency of innovative materials with low impact and potential for recyclability. A research gap remains on the hands-on design process of circular design and circular buildings and how architects can integrate circular economy concepts in their designs.

We hope this paper has shown how CE principles are rooted in vernacular heritage and can still be applicable in contemporary practice. We focused only on four principles but there are many others that can still be a good source of inspiration. We were limited in making the comparative work between a contemporary case study and a traditional case study. This research is part of ongoing work on investigating more hands-on circularity strategies in vernacular architecture. Although case studies from Egypt were displayed in this investigation, the study findings can surely be applied to other climatic zones and geographical locations. The methodological approach is holistic and will be applicable in different contexts.

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An Exploratory Study of the Policies and Legislative Perspectives on the End-of-Life of Lithium-Ion Batteries from the Perspective of Producer Obligation

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Abstract: European self-sufficiency in the battery sector is one of the major EU needs. The key lithium-ion batteries (LIBs) materials demand is expected to increase in the next decade as a consequence of the increment in the LIBs production and a massive amount of spent LIBs will flood global markets. Hence, these waste streams would be a potential source of secondary raw materials to be valorized, under the principle of circular economy. European governments first, and then companies in the battery sector second, are addressing many efforts in improving legislation on batteries and accumulators. This study explores the current legislative aspects, the main perspective from the producer's point of view, and the possibility to guarantee a proper recycle of spent LIBs. A monitoring proposal by means of a survey has been carried out and the Italian context, which has been taken as an example of the European context, and it was used to evaluate the practical implication of the current legislation. The main result of the survey is that a specific identification as well as regulations for LIBs are needed. The benefit from a cradle-to-cradle circular economy is still far from the actual situation but several industrial examples and ongoing European projects show the importance and feasibility of the reuse (e.g., second life) and recycle of LIBs.

Keywords: lithium-ion batteries (LIBs); energy storage; Extended Producer Responsibility (EPR); European Union (EU) legislation; critical raw materials (CRM)

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1. Introduction

The demand for lithium-ion batteries (LIBs) is increasing worldwide due to their high efficiency as well as due to the versatility of rechargeable batteries [1]. This steep increase has called attention to several challenges that must be faced: on the one hand, the supply of raw materials, and on the other hand, the valorization of end-of-life products. In the case of the electric vehicles (EVs) market, the registration of passenger cars in the European Union (EU) has seen a double-digit growth in most of the Member States. In 2016–2018, EVs comprised from 8.5% (Poland) to 33.4% (Norway) of passenger cars in European Free Trade Association (EFTA) countries [2]. Figure 1 summarizes the total global volume of EVs predicted for 2050 as well as under different scenarios. In 2019, the number of electric and plug-in hybrid cars reached 2 million (3% of the fleet) and it is predicted that it will hit 28 million in 2030 (31% of the fleet) [3,4]. However, the estimations vary because of the several legislative perspectives, the different simulation analyses, and the probable technological evolution.

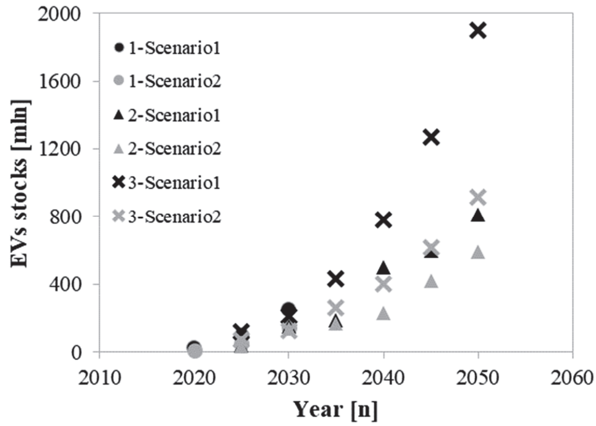

Figure 1. Worldwide stock provision of EVs: 1-Scenario1 and 1-Scenario2 data available in [5], 2-Scenario1 and 2-Scenario2 data available in [6], and 3-Scenario1 and 3-Scenario2 data available in [7].

Thus, as the LIB technology advances, many end-of-life products will flood into global markets. The increment is already growing; in Italy, for example, the waste stream of lithium-based accumulators increased from 11% to 25% [8] during 2014 to 2019.

Within the EU, in 2016, it was reported that only 5% of LIBs had been reintegrated into the market after recycling [9], thus revealing incomplete regulation and leading to a non-sustainable scenario. This was also due to the criticality of the raw materials employed [10] to manufacture LIBs. From this point of view, the last revision of the list of Critical Raw Materials (CRMs) by the European Commission included lithium as a strategical CRM [11] and it should be added to the list of elements critical for the EU, such as cobalt or natural graphite [12,13]. This emergency exists worldwide; in fact, Co and Li in electrodes have also both been considered significant strategic and economic values. Hence, because of the increase in LIB production, in 2018, the price per kg of Co reached USD 81 [14]. With the rapid inflation of the new energy vehicles market, the supply of these raw materials from natural resources may be unable to satisfy the future demand unless proper recycling of the retired LIBs is assessed [15].

European self-reliance in the battery field is a major EU objective but the actual market is far from this point because of the high dependency on the supply of both raw materials and battery cells [16]. Table 1 shows the main components of CRMs that are used in batteries and the percentage of reliance of the EU market on the main global producers.

Table 1. List of main CRMs used in batteries [17].

Raw Materials	Stage	Main Global Producers	Main EU Sourcing Countries *	Import Reliance **	EoL-RiR ***
Cobalt	Extraction	Congo DR (59%) China (7%) Canada (5%)	Congo DR (68%) Finland (14%) French Guiana (5%)	89%	22%
Coking coal	Extraction	China (55%) Australia (16%) Russia (7%)	Australia (24%) Poland (23%) United States (21%) Czechia (8%)	62%	0%
			Germany (8%)		

Table 1. *Cont.*

Raw Materials	Stage	Main Global Producers	Main EU Sourcing Countries *	Import Reliance **	EoL-RiR ***
Lithium	Processing	Chile (44%) China (39%) Argentina (13%)	Chile (78%) United States (8%) Russia (4%)	100%	0%
Magnesium	Processing	China (89%) United States (4%)	China (93)	100%	13%
Natural Graphite	Extraction	China (69%) India (12%) Brazil (8%)	China (47%) Brazil (12%) Norway (8%) Romania (2%)	98%	3%
Phosphate rock	Extraction	China (48%) Morocco (11%) United States (10%)	Morocco (24%) Russia (20%) Finland (16%)	84%	17%
Phosphorus	Processing	China (74%) Kazakhstan (9%) Vietnam (9%)	Kazakhstan (71%) Vietnam (18%) China (9%)	100%	0%
Titanium	Processing	China (45%) Russia (22%) Japan (22%)	n.a.	100%	19%
Heavy Rare Earth Elements	Processing	China (86%) Australia (6%) United States (2%)	China (98%) Other non-EU (1%) UK (1%)	100%	8%
Light Rare Earth Elements	Processing	China (86%) Australia (6%) United States (2%)	China (99%) UK (1%)	100%	3%

* Based on domestic production and import (export excluded). ** IR = (import − export)/(domestic production + import − export). *** The End-of-Life Recycling Input Rate (EoL-RIR) is the percentage of the overall demand that can be satisfied through secondary raw materials.

The LIB recycling industry is working on the batteries from EVs, electronics, and portable instruments nearing their end-of-life. The EU has set a target to improve the collection rate and recycle percentage of LIB raw materials, as shown in Table 2.

Table 2. European Li-ion battery collection rate and percentage of materials recycling [18].

Key Performance Indicator	2020	2030 Target
Portable battery takeback	45%	65%
EVs and industrial battery takeback	100% (obligation)	100%
Recycling efficiency: overall	50%	60%
Recycling efficiency: Cobalt	90%	95%
Recycling efficiency: Nickel	90%	95%
Recycling efficiency: Lithium	35%	70%
Recycling efficiency: Copper	90%	95%

Actually, the EU is a net importer of nickel-cadmium (NiCd), nickel metal hydride (NiMH), and lithium-based cells; the volume of these products manufactured in the EU is around 5% of the global output, which is lower than the EU's share of the global gross national product (GNP) [3]. The waste stream of these products is increasing year by year and it is critical that this becomes a new source of raw material.

It must also be considered that the performance of new LIBs usually decreases with use. In the case of EV batteries, for example, when the performance drops to 75–80% of its original value, the battery should be replaced. This means that the battery could have several usages also after these percentages, as technically proven by research projects and industrial application [19].

The absence of raw material and the need to guarantee a sufficient supply of batteries suggest that operators (recyclers) and producers should be directly involved in the treatment and recycling of waste batteries and accumulators. As far as an EU directive is concerned, according to Directive 2006/66/EC on Battery and Accumulators (BaAs), producers of BaAs and associated products are responsible for the related management of wastes in proportion to the products that are introduced into the market, even in the case of LIBs [20]. The corresponding directive was consolidated in 2013 [21] and 2018 [22] as part of larger intent to promote circular economy. Recently, a new document was provided by the European Parliament that established the new EU regulatory framework for batteries. Directive 2006/66/EC is currently under revision and the exponential growth of the LIB market as well as its unique features during recycling processes were considered [23].

A circular economy approach can be summarized in several steps, following the process from cradle-to-cradle. It begins with the design of the battery (standard formats and materials, international and standardized methodology for material labeling, and assembly strategy); followed by a review of the different possibilities of raw materials mining (from traditional extraction to secondary raw material mining, such as recycled materials); next, LIB production and use (implementation of new chemistry and technology for the production of LIBs); post-use collection of spent LIBs (minimum battery collection rate requirement also from EU directives); re-use (the valorization of end-of-life products can represent new business opportunities for second-life applications); and the process ends with recycling (LIB recycling allows for reducing energy consumption and CO_2 emissions, saving natural resources by avoiding virgin materials mining and imports, minimizing environmental toxicity, creating an economic gain, decreasing waste, and managing safety issues) [24].

Several promising implementations have already been applied at an industrial scale by producers and recyclers all over the world [24]. The most representative examples, according to the authors' knowledge and in the interest of this specific research study on industrial scale and patent, adopted by the major companies in the LIB field are listed below:

- Honda Motors Europe and Snam: are studying the feasibility of re-using end-of-life batteries (NiMH batteries) deriving from hybrid vehicles.
- The Volkswagen group (production site in Salzgitter) is designing a pilot plant for the direct production of LIB cells with a specific section for recycling.
- Fortum, BASF, and Nornickel are planning a pilot plant for the recycling of LIBs in Harjavalta, Finland.
- The Sony-Sumimoto process represents one of the best examples of a circular economy approach where the recovered $Co(OH)_2$ from Sony's spent LIBs from electronic devices is directly re-used in the fabrication of new cells. The process involves the calcination of spent cells and utilizes the cogeneration resulting from burning electrolytes [25].
- Northvolt recently approved the recycling program Revolt that will aim to source 50% of recycled material by 2030 in the recycling plant in Västerås, Sweden, and will target an initial recycling capacity of 100 tons per year due to a hydrometallurgical treatment of LIBs.
- Chinese Green Eco-Manufacture (200,000 ton/year) and Bangpo Ni/Co (30,600 ton/year) obtain regenerated cathodic materials through a hydrometallurgical process (992 MJ/ton) that are required for organic material incineration [24].
- Riciclo Made in Italy is a new patented technology (2018) developed by the collaboration of the Italian consortium COBAT (COBAT RIPA) and CNR ICCOM (Istituto di Chimica dei Composti Organometallici, Firenze) since 2014.
- Umicore patented a pyrometallurgical process to recover Co-alloy (WO, 2011/035915 A1) and a hydrometallurgical process to recover LIB electrolytes (US, EP 2 410 603 A1).
- Duesenfeld (Germany) patented a recovery process for LIBs electrolytes (US, 2018/0301769).
- Avestor Limited Partnership patented a combined process (pyro and hydrometallurgical) to recover high grade purity of Li2CO3 (US 7192654 B2) [24].

Many automotive companies are investing in projects involved in the reuse batteries from EVs for a second life in different applications, as reported in Table 3.

Table 3. Project of second-life applications of EVs batteries [26].

Company	Second-Life Application
BMW	Energy storage farm
BYD	Energy storage
Chevrolet	Data center
Eaton	Energy storage
EcarACCU	Solar energy storage
EVgo	EVs charging
Florida Power & Light	Grid management
Nissan/Sumitomo	Street lighting, large scale power storage
Nissan/Eaton/Mobility House	Renewable Storage, backup power for elevators
Renault	Street lighting, large scale power storage
Renault/Connected Energy	EVs charging

The clusterification of recycling facilities in a few countries as well as limited areas raises many challenges, including the transportation of significant quantities of spent LIBs, which represents the highest effort [27] among them.

This study reports on the current and future European vision of more sustainable waste prevention and management legislation for LIBs, beginning with an analysis of the producers' legislative obligation to a practical checklist for its application in several EU Member States to better satisfy both the demand of the European market and the sustainability requirements.

2. Materials and Methods

EU directives on BaAs were considered and analyzed to extrapolate the basic principles for all the EU Member States.

After an analysis of the European legislation, several national laws were taken as examples of significant representations of the issue, at least for the EU countries most historically consolidated (i.e., from 1995, before the inclusion of central and eastern Europe); for this reason, only the current regulations of Finland, France, Germany, Italy, the Netherlands, Portugal, and Spain have been compared.

The practical implication of the legislative acts was assessed by means of a survey and was applied to the collective schemes (consortia) associated with the (Italian) National Coordination Center for Batteries and Accumulators (Centro di Coordinamento Nazionale Pile e Accumulatori (CDCNPA), https://www.cdcnpa.it/) (accessed on 4 September 2021). The Italian case was chosen as it is descriptive at the European level: the legislation has not undergone a substantial change in recent years. Furthermore, the sample is representative because the answers were collected from consortia, but the collection was coordinated by CDCNPA, an independent center. Currently, the consortium CDCNPA includes 16 members, 14 of which are collective systems and two are individual systems. The answers were collected from both oral interviews and online surveys. Comprehensively, 43% of CDCNPA members' systems completed the survey and both their competent answers and comments represent a very useful contribution to the legislative issue.

This survey was prepared following the most recent EU directive proposal in terms of both legislative adaptation and scientific development, and the practical implication of the legislative acts was assessed and applied to the collective schemes associated with the national CDCNPA. The answers were both oral and from an online survey.

The survey was organized into two main parts: the first was correlated to the relevance of the European Waste Code (EWC) 160605, while the second explored the effectiveness of an efficient valorization of the waste stream by means of a circular economy approach to the battery value chain. The survey is available in the Supplementary Materials.

Then, the current EU project and main initiatives were compared.

3. Results and Discussion

Several EU directives and regulations aim to manage wastes from electric and electronic equipment (WEEE), namely end-of-life vehicles containing LIBs and BaAs. In most cases, a clear regulation connected with Directive 2006/66/EC (and corresponding updates) on managing spent battery flows is missing, hence, it represents a limitation to the industrial treatment mostly because of the lack of data sharing, the uncertainty about extended producer responsibility, and the unrealistic targets for collection and recycling. In fact, LIBs are actually classified as industrial batteries and their take-back, collection, and recycling procedures are regulated as products whose safety issues, market availability, and logistic frameworks are totally different [24]. Following the directive, it appeared appropriate for us to define industrial battery or accumulator, automotive battery or accumulator, and portable battery. More precisely, industrial battery or accumulator is defined as any battery or accumulator that is designed exclusively for industrial or professional uses or is used in any type of electric vehicle; automotive battery or accumulator is defined as any battery or accumulator that is used for automotive starters, lighting, or ignition power; and portable battery or accumulator is defined as any battery, button cell, battery pack, or accumulator that (a) is sealed, (b) can be hand-carried, and (c) is neither an industrial battery or accumulator nor an automotive battery or accumulator [20].

3.1. Analysis of the EU Legislation

The key points of the EU active legislation are summarized as follows:

- Collection scheme for the waste of portable BaAs is ensured by the Member State, wherein producers of industrial BaAs or third parties acting on their behalf will not refuse to take back industrial BaAs waste;
- Producers of automotive BaAs or third parties will set up schemes for the collection of waste automotive BaAs from users or from an accessible collection point in their vicinity;
- Member States shall ensure that producers or third parties acting on their behalf will finance any net costs;
- Producers and users of industrial and automotive BaAs may conclude agreements stipulating financing arrangements (and organizations);
- Member States shall ensure that all economic operators and all competent public authorities may participate in the collection, treatment, and recycling schemes they are referred to;
- These schemes will also apply to BaAs imported from third countries under non-discriminatory conditions and will be designed to avoid barriers to trade or distortions of competition;
- Member States shall ensure that each producer is registered; and
- The technical development of new types of batteries that do not use hazardous substances should also be considered.

It is worth noticing that despite the research progress and development in this field, there are still no common labels or codes for the identification of different types of BaA and their chemistry.

Producers must be registered on the national list, even if they originate from a different country, and the number of registrations should be evident. Furthermore, the total volume of the product that is introduced into the national market should be communicated to evaluate the financial support of the recycling net.

The proposal for the revision was published on 10 December 2020 [28]. The requirements relating to sustainability would become mandatory, for example, concerning the carbon footprint rules, content of recycled materials in being higher than the minimum percentage and durability criteria, and requirements for end-of-life management, safety, and labelling for marketing. The proposal also includes due diligence obligations for economic operators with respect to the sourcing of raw materials. The main goal is to ensure the sustainability and competitiveness of the European battery value chain [23,29]. In fact, the relationship between the BaAs manufacturing and recycling companies is becoming increasingly strong in view of a circular economy approach, guaranteeing a cradle-to-cradle life cycle for LIBs. From this perspective, the newly proposed concept of a Battery Identity Global Passport (BIGP) represents a viable and economic way to manage the forthcoming waste flows, offering the chance to precisely identify battery supply chains from the cradle-to-cradle approach. Furthermore, it perfectly fits within the expected new EU directive for BaAs, although it should be globally implemented so as not to reduce the chances to recycle LIBs in responsible and profitable ways [30]. Nowadays, the management of LIB waste streams in the EU is regulated by the strong connection between the producer and the recycler. This connection is then translated in the Extended Producer Responsibility tool.

3.2. Analysis of the Legislations of the Target Countries

Each EU country can decide how to organize the collection scheme to comply with the Extended Producer Responsibility tool. It is regulated in each Member State law, which represents a translation of the EU directives by their own legislative body. The latest updates for BaAs legislation and the types of adopted collection schemes are shown in Table 4.

Table 4. Last legislative update and organization of the BaAs collection scheme of the target countries.

Country	Finland	France	Germany	Italy	Netherlands	Portugal	Spain
Last legislation on batteries (year)	2014	2015	2020	2017	2017	2017	2021
Take-back collection scheme	Individual, collective public	Individual, Approved body	Individual, with more than two producers	Individual, collective	Individual, collective	Individual, licensed management entity	Individual, collectiv epublic scheme

All the analyzed countries have a strict definition regarding the Extended Producer Responsibility tool and how to register is precisely described even if the producer is outside the national borders; in that case, it is considered to be an import. The total quantity of materials introduced to the market should include both products and wastes. All countries must provide instructions for the financial scheme that supports the take-back collection schemes, which must permit the free-of-charge return of spent batteries from the end users.

- Finland

'Valtioneuvoston asetus paristoista ja akuista (520/2014)' and corresponding updates.

Last Finnish waste decree on BaAs was passed in 2014, but the WEEE Directive 2012/19/EU is employed to manage the responsibility of battery producers. However, it is specified that if a producer has a responsibility that pertains to several areas (for example, electronic and electrical appliances as well as packaging), the company must organize its producer responsibilities separately for each area. Authors have described this as relatively advanced environmental legislation and regulation for e-waste management [31], and the legislative bodies decided to merge both laws. The costs of the producer's share of the organization must be covered pertaining to their sold product volume and category. Moreover, the decree is also explicit about their responsibility for the portion or its equivalent of so-called orphan products. The portion is determined based on each producer's market share and the producers are proportionally responsible (based on the sold market volume) for the specific type of products. Spent LIBs are treated at the Akkuser plant in Nivala. According to the Finnish regulation, BaAs should be designed and manufactured as far away as possible to improve their environmental performance throughout the life cycle. To reduce harmful substances, the Pirkanmaa Center for Economic Development, Transport, and the Environment monitors the collection rates of discarded portable batteries and accumulators in accordance with the monitoring system.

Maximization of the separate collection of BaAs is also promoted. All separately collected, identifiable BaAs are recycled to minimize the possibility of the disposal of BaAs as municipal solid waste. An arrangement for the disposal of spent BaAs following a minimum service and accessibility level must be guaranteed with a minimum of one reception point for each municipality.

- France

'Décret n° 2009-1139 du 22 septembre 2009 relatif à la mise sur le marché des piles et accumulateurs et à l'élimination des piles et accumulateurs usagés et modifiant le code de l'environnement (dispositions réglementaires)' and corresponding updates.

The annual declaration of the quantity of products placed on the market is mandatory. Batteries must meet removal and treatment requirements through individual systems approved by the public authorities or by collective arrangements approved by the public authorities of two eco-organizations. Costs should be sustained by the producers and there should be no costs for end users. In France, there are the treatment operator's representative (FEDEREC, FNADE, and SFRAP1), the approved producer responsibility organizations (Corepile and Screlec) and the approved individual system (MOBIVIA Groupe). The information for producers is given by a non-profit organization in order to comply with the legislation. For the industry, it is possible to extend the responsibility individually or to delegate it to a professional end user. Obligations are distributed between the producers in proportion to the number of products placed on the market and the permission must be reviewed and approved by the ministry every six years. The collection of the waste is a principle of the legislation that is intended to improve the collection rate.

- Germany

'Bundesgesetzblatt Teil I2020Nr. 50 vom 09.11.2020 Erstes Gesetz zur Änderung des Batteriegesetzes'.

In this case, the producers must set up, operate, and declare their own collection systems, requiring the authority's approval to guarantee the take-back network. Additionally, the take-back systems must publish the following information annually on their websites, in compliance with trade and business privacy:

- the ownership and membership relationships;
- the financial contributions made by the members per battery placed on the market or per mass of batteries placed on the market;
- the procedure for the selection of the disposal service; and
- the recycling efficiencies achieved in their own system.

The responsibilities of the public waste management authorities are also defined. If the authorities offer the option of returning the waste in the case of automotive batteries, this must proceed free of charge for the end user.

Clear and public information is an evident priority.

Within the aim of assessing each contribution made by the producers, the take-back systems are obliged to create incentives. Additionally, there is a strong valorization of the recycling. In fact, the producer's obligation is considered complete only if it can guarantee the recycling of the take-back material. It is considered to be an effective supporting scheme to correct the lack of critical sources that are necessary for sustainable development [32].

- Italy

'Decreto Legislativo 20 novembre 2008, n. 188' and corresponding updates.

In 2008, Italian CDCNPA published a guideline for producers, in which they defined a checklist of the main issues for compliance with respect to the Extended Producer Responsibility tool.

According to the definition of a consortium in the Italian regulations, these bodies have the main objective of helping to solve the problem of collecting and recycling scraps [33].

In this legislation, there are no specific obligations for LIB recyclers, nor are there any in the European Waste Code (EWC) for LIBs. Only the separate management and a specific definition for secondary battery (rechargeable one) are indicated.

- Netherlands

'Regeling van de Minister van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer van 9 september 2008, nr. K&K 2008088170' and corresponding updates.

Since 2008 in the Netherlands, battery producers have been obliged to report on how the batteries are collected and processed during their end-of-life. The industrial waste must be collected individually or by delegated professional end users. Moreover, in this case, the Batteries Foundation Stibat, a non-profit organization, helps the producer to comply with the legislative obligations.

Producers should also take measures to design the battery with the smallest possible amounts of substances that are hazardous to human health or the environment, and they must ensure that end users of batteries and accumulators are fully informed about the possibility of returning waste portable batteries or accumulators.

- Portugal

'Decreto-Lei n.° 152-D/2017' and corresponding updates.

In Portugal, the legislation currently mandates that the costs of the collection scheme are proportional to the type and quantity of battery (used within the country). A financing system is the obligation of the producers. In the case of third parties, the responsibility is transferred to an integrated licensed system. Portugal increased the collection rates with an emphasis on the role of management entities [34].

There is an indirect diversification of the type of batteries and an explicit request for providing a selective collection service of BaA.

In Portugal, there are currently five entities that manage waste batteries and accumulators with different areas of activity. The producers should promote research and development towards improving the environmental performance of BaAs.

The obligation to receive the respective waste is extended to both traders and retailers.

- Spain

'Real Decreto 106/2008, de 1 de febrero, Vigente desde 21/Enero/2021'.

Spanish legislation allows for an additional way to operate collection schemes that uses the public scheme already established. This policy can be adopted only if the additional costs derived from the collection and management of batteries and accumulators are assumed by the producer. The procedures are used together with that implied in the collection policy of WEEE but with a separate collection.

The last update of the Spanish legislation has defined spent LIBs as a hazardous waste and a specific European Waste Code (EWC) was assigned to this stream.

Rules are established that must be followed due to a selective collection process established throughout the treatment and recycling process. Rules and standards for the collection are also cited. Economic instruments and research studies are identified as useful tools to promote the collection of spent batteries and ensure environmental sustainability. The recovery or the controlled disposal of used BaAs should be facilitated by means of networks of selective collection points for used batteries. The collection points are managed by the authorities or private parties. Research studies were also conducted in order to choose the appropriate location points in Spain [35].

Limits from the Analysis of the EU Legislative

The most important limitation is related to the obvious and very rapid development of new technologies and products that are not yet specified in the legislation. In addition, the current minimum collection targets and minimum recycling requirements for waste portable batteries are not defined appropriately [36]. At this time, LIBs have no technology specification (except in the Spanish legislation) and they are assimilated into lead-battery specifications. Along with the specifications of the types of battery (rechargeable or not), the specific chemistry [37] of LIB materials has also been reported. This possibility can also bring a higher flexibility to the collective schemes that are nowadays incomplete. Additionally, the lack of a specific definition for LIB waste leads to their misplaced classification as industrial batteries and their take-back, collection, and recycling are regulated as products whose safety issues, market availability, and logistics framework are totally different [24].

Besides battery classification, an appropriate definition of the financing scheme needs to be established. Current schemes are not suitable for the actual spent LIB stream and they are evaluated based on the quantity of batteries placed in the market by a producer without any differences between LIS and lead acid batteries (LAB) because the financing scheme is the same for both type of batteries, despite the substantial differences between them. Thus, when evaluating the best financing scheme, an analytical comparison should be done by considering the efficiency and effectiveness. This problem is also related to the lack of data sharing or a clear and explicit source, as noted previously.

3.3. The Italian Case: Answers from the Survey

The lack of a specific EWC led the consortium to two main conclusions. On one hand, the spent LIB classification as hazardous waste can improve the management of this waste stream when collection, transportation, storage, and the following specific treatments are carried out. On the other hand, the specification of the chemistry can improve the efficiency of the recycling system.

The lack of a specific EWC also has an impact on quantifying the flow of waste from LIBs that are managed by the consortium members, even if CDCNPA asserts that the largest collection flow derives from municipal centers and from the sorting of small equipment such as laptops, telephones, electronic tools, etc.

Moreover, the overall national value chain seems unable to adequately respond to the incoming waste stream, which was also foreseen. Concerning this, the locations of the main global companies operating in battery recycling (lithium recycling) consist of 61% outside the EU and 39% in the EU. Figure 2 shows the precise locations and it is evident that no plants are in Italy. These data were collected from an industrial analysis conducted to identify the main worldwide companies that recycle batteries, i.e., LIBs in this case. This was confirmed by the survey, which highlighted that at least the 90% of the waste is exported to other countries to be recycled, since in Italy, there are only plants that sort battery materials, which is itself a critical step to pre-treat spent batteries. Furthermore, the volume of the recycled material is negligible.

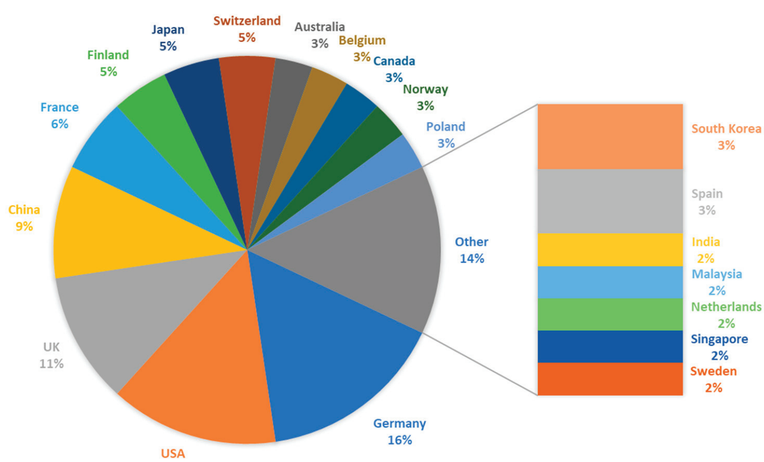

Figure 2. Lithium-ion battery-recycling companies worldwide.

3.4. The European Challenge: Ongoing Projects

The European limits described above can be overcome through careful studies and research processes. Battery2030+ represents the large-scale and long-term European research initiative within the battery field, which also maintains an eye on the forthcoming technologies (not only on LIBs). However, this is just one of the European initiatives/actions and projects are ongoing in the EU. The importance of recycling was defined as a strategic pillar of the European Battery Alliance [29]. Table 5 reports the main ongoing European projects concerning energy storage systems technologies.

This table depicts the flourishing environment of European in the battery field. In disclosing the future perspectives in the sector of energy storage systems, European governments and research centers are making many efforts towards the post-lithium-ion batteries. Indeed, many projects, launched beginning in 2017, are focused on the development of innovative materials aimed to reach higher energy and capacity levels (e.g., 057534–LiAnMAT, 950038—Bi3BoostFlowBat, 771777—FUN POLYSTORE, 770870—MOOiRE, and 864698—SEED). Moreover, along with the challenges regarding the future technologies, more efficient battery systems for electric vehicles and smart grids need to be developed (895337—BatCon, 101009983—ORION PROJECT, 731249—SMILE, and 770019—GHOST). In tandem with scientific innovations, European funds have been allocated to projects focused on sustainability and environmental evaluations (894063—GEVACCON and 875514—ECO2LIB). Thus, as mentioned above, the future challenges in the energy and environmental sectors for Europe, as well as for the whole world, will produce the most diverse fields. Indeed, far from being entirely covered by European governments, a profound transition will materialize in the approach to this progress, focusing on the scientific side and promoting public partnerships with and within universities and research centers. Thus, the ongoing projects within Europe are clear evidence of this trend.

The list of projects proves how important both the search for new technological solutions and the need for proper management truly are. Italian consortium members also monitor the lack of valorization concerning second-life use for batteries and this kind of use is only now the objective of an innovation project in the framework of the EIT Climate KIC (https://erion.it/it/ricerca-e-innovazione/lions2life/, accessed on 4 September 2021).

If the project outcome increases the battery durability, health, safety, and life, the pillars of a circular economy will be completely satisfied. Member States should also consider the Circular Economy Business Model when writing the legislation that will soon be necessary.

Table 5. Ongoing and recent projects in lithium-ion battery efficiency implementation technologies.

Program	Grant-Acronym-Agreement	Main Objectives	Start–End (yyyy)
H2020-EU.1.1.-EXCELLENT SCIENCE-European Research Council (ERC)	680070-BATMAN-Development of Quantitative Metrologies to Guide Lithium Ion Battery Manufacturing	Implement quantitative methods to study LIB inner processes and elaborate on guidelines for understanding their origins	2016–2021
	963281-SOLVOLi-Solvometallurgy for battery-grade refining of lithium	Develop a more sustainable method to deliver battery-grade lithium salts	2020–2022
	853133-Worlds of Lithium-A multi-sited and transnational study of transitions towards post-fossil fuel societies	Study how strategies of transition from fossil fuel transport to electric mobility powered by lithium-ion batteries are deployed in three key countries: Chile, China, and Norway	2020–2025
	057534 – LiAnMAT-Ultra-high energy storage Li-anode materials	Create a step change in Li-ion battery anode production, significantly reducing additives and manufacturing steps while minimizing capacity loss	2020–2021
	835073-BATNMR-Development and Application of New NMR Methods for Studying Interphases and Interfaces in Batteries	Propose a nuclear magnetic resonance-based approach to measure the dynamics of the multiple electrode–electrolyte interfaces and interphases in batteries	2019–2024
	948238-NANO-3D-LION-Nanoscale 3D Printing of a Lithium-ion Battery: Rethinking the Fabrication Concept for a Revolution in Energy Storage	Develop and employ advanced nanoscale 3D printing techniques to fabricate active battery materials with ultrasmall structural features	2021–2026
	772873-ARTISTIC-Advanced and Reusable Theory for the In Silico-optimization of composite electrode fabrication processes for rechargeable battery Technologies with Innovative Chemistries	The aim of this project is to develop and demonstrate a novel theoretical framework dedicated to rationalizing the formularization of composite electrodes within the next-generation chemistries for high-energy density secondary batteries	2018–2023
	950038-Bi3BoostFlowBat-Bioinspired, biphasic, and bipolar flow batteries with boosters for sustainable large-scale energy storage	Develop novel bioinspired materials as cross-over additives to produce cost-efficient processes for the production of a novel flow battery to be implemented for large-scale energy storage	2021–2025
	771777-FUN POLYSTORE-FUNctionalized POLYmer electrolytes for energy STORagE	Aimed at exploring functionalized alternative polymer hosts for mechanically robust block-copolymer systems; for alternative cation chemistries; for high and low electrochemical potentials; and for easy dissolution of electrode materials	2018–2023
	949012-DeepProton-Deep multi-scale modelling of electrified metal oxide nanostructures	Develop a novel deep-learning empowered multi-scale modeling framework to understand the functioning and degradation of electrified metal oxide nanostructures at the microscopic level	2021–2025

Table 5. *Cont.*

Program	Grant-Acronym-Agreement	Main Objectives	Start–End (yyyy)
H2020-EU.1.1.-EXCELLENT SCIENCE-European Research Council (ERC)	770870-MOOiRE-Mix-in Organic-InOrganic Redox Events for High Energy Batteries	Utilize metal organic compound frameworks (MOC/Fs) to build novel electrode materials, engineering their performance by in-operando analytical inspection tools	2018–2023
	864698-SEED-Solvated ions in solid electrodes for reversible energy storage based on abundant elements	Explore the usage of solvated ions as an active species to be intercalated into the electrodes	2020–2025
	759603-IMMOCAP-'If immortality unveil . . . '–development of the novel types of energy storage systems with excellent long-term performance	Develop a novel type of electrochemical capacitor with high specific power (up to 5 kW/kg) and energy (up to 20 Wh/kg) preserved along at least 50,000 cycles	2017–2022
H2020-EU.1.2.-EXCELLENT SCIENCE-Future and Emerging Technologies (FET)	957225-BAT4EVER-Autonomous Polymer-based Self-Healing Components for high performant LIBs	Design novel self-healing materials for NMC-based cathodes and electrolytes	2020–2023
	957202-HIDDEN-Hindering dendrite growth in lithium metal batteries	Develop self-healing thermotropic liquid crystalline electrolytes and piezoelectric separator technologies, and upscale from laboratory to industrial manufacturing processes	2020–2023
H2020-EU.1.2.1.-FET Open	899659-I-BAT-Immersed-cooling Concepts for Electric Vehicle Battery Packs using Viscoelastic Heat Transfer Liquids (I-BAT)	Introduction by synthesis of mineral oil-based compounds as novel coolants to double the power of battery cooling systems	2020–2024
H2020-EU.1.3.1.-Fostering new skills by means of excellent initial training of researchers	765828-POLYTE European Industrial Doctorate in Innovative POLYmers for Lithium Battery TEchnologies	The project will research the development of new polymeric materials to increase the performance and security of actual and future batteries	2018–2021
H2020-EU.1.3.2.-Nurturing excellence by means of cross-border and cross-sector mobility	894042-NanoEvolution-Nanoscale phase evolution in lithium–sulfur batteries	Aims to develop novel strategies in lithium–sulfur batteries technology as the most promising candidate for next-generation energy storage systems	2020–2022
	892916-Electroscopy-Electrochemistry of All-solid-state-battery Processes using Operando Electron Microscopy	Improve all-solid-state battery technologies by in-operando TEM and SEM investigations on specially assembled micro-cells	2020–2022
	896195 – LiBTR-Modelling of thermal runaway propagation in lithium-ion battery packs	Develop a thermal-runaway model by simulation on LibFOAM (for single cell and packs), FireFOAM (fire simulation), and OpenFOAM (open source CFD code)	2021–2023
	797295-eJUMP-Organic Ionic Plastic Crystals Nanocomposites for Safer Batteries	Aims to develop innovative nanocomposites electrolytes based on Organic Ionic Plastic Crystals (OICPs), which is a novel class of solid-state electrolytes with intrinsic safety and high ionic conductivity	2019–2021

Table 5. *Cont.*

Program	Grant-Acronym-Agreement	Main Objectives	Start–End (yyyy)
H2020-EU.1.3.2.-Nurturing excellence by means of cross-border and cross-sector mobility	895337-BatCon-Lithium-ion battery control for faster charging and longer life	Make step changes in the research and innovation of battery management by developing health-aware fast charging strategies that will benefit from an integrated advanced mathematical modeling	2020–2022
	894063-GEVACCON-Geographies of Value Chain Construction in Emerging Complex Technologies: A Compparative Study of the Electric Vehicle Lithium-ion Battery Industry in China and Germany	Develop a comprehensive analytical framework for disentangling the value chain construction in complex technology industries mainly in China and Germany	2020–2022
	841937-3D-PRESS-3D PRintable glass-based Electrolytes for all-Solid-State lithium batteries	Design glass-based compositions to obtain printable glass-based electrolytes with superior conductivity and functional properties	2020–2022
H2020-EU.2.1.3.-INDUSTRIAL LEADERSHIP-Leadership in enabling and industrial technologies-Advanced materialsH2020-EU.2.1.2.-INDUSTRIAL LEADERSHIP-Leadership in enabling and industrial technologies – Nanotechnologies	814471-LISA-Lithium–sulphur for SAfe road electrification	This project aims to solve the lithium–sulfur technology bottlenecks concerning metallic lithium protection, the power rate, and the volumetric energy density	2019–2022
	875029-ASTRABAT-All Solid-sTate Reliable BATtery for 2025	Identify the optimal solid-state cell materials, components, and architecture to be implemented in electric vehicle technologies while being compatible with mass production	2020–2023
	861962-NanoBat-GHz nanoscale electrical and dielectric measurements of the solid-electrolyte interface and applications in the battery manufacturing line	Develop a solid basis of GHz-nanotech instrumentation to implement nanoscale imaging of the SEI and advanced impedance spectroscopy in industrial battery production	2020–2023
	814389-SPIDER-Safe and Prelithiated hIgh energy DEnsity batteries based on sulphur Rocksalt and silicon chemistries	Enhance Li-ion battery performances, production costs, and life cycle durability, and esign novel recyclable battery architectures	2019–2022
	875557-SOLiDIFY-Liquid-processed Solid-state Li-metal Battery: development of upscale materials, processes, and architectures	Fabricate a prototype in a pilot line of Lithium-metal solid-state batteries made by sol-gel reaction to produce a composite cathode and solid-electrolyte separator	2020–2023
	875189-SAFELiMOVE-Advanced all Solid stAte saFE LIthium Metal technology tOwards Vehicle Electrification	The aim is the development a new lithium-metal battery cell technology based on a safe, reliable, and high-performance solid-state electrolyte, improving energy density batteries to 450 Wh/kg	2020–2023
	875514-ECO2LIB-Ecologically and Economically viable Production and Recycling of Lithium-Ion Batteries	Extend LCA cradle-to-grave study to judge the environmental impact of the different options in the LIB market	2020–2023
	814464-Si-DRIVE-Silicon Alloying Anodes for High Energy Density Batteries comprising Lithium Rich Cathodes and Safe Ionic Liquid-based Electrolytes for Enhanced High VoltagE Performance.	Develop the next generation of rechargeable Li-ion batteries encompassing amorphous Si coated onto a conductive copper silicide network as the anode with polymer/ionic liquid electrolytes and Li-rich high voltage (Co-free) cathodes	2019–2023

Table 5. *Cont.*

Program	Grant-Acronym-Agreement	Main Objectives	Start–End (yyyy)
H2020-EU.3.- PRIORITY 'Societal challengesH2020-EU.2.3.- INDUSTRIAL LEADERSHIP- Innovation In SMEsH2020-EU.2.1.- INDUSTRIAL LEADERSHIP- Leadership in enabling and industrial technologies	101009840-WATTELSE-High energy density modular batteries for a sustainable construction industry	Propose a versatile and modular lithium-ion battery system using patented state-of-the-art technologies to provide original equipment manufacturers with tailored solutions	2020–2022
	101009983-ORION PROJECT-A first step towards aviation decarbonization with smart lithium batteries	LIMATECH, a unique partner of this project, will introduce a novel lithium battery by developing protective electronics that integrate all the safety functions required with exceptional reliability and precision	2021–2022
	954593-Addionics-Innovative 3D electro-printing method to improve power, capacity, and safety of lithium ion-batteries	Develop a 3D battery architecture (from current collectors to electrode materials) that significantly improves battery performances regardless of the battery chemistry	2020–2022
H2020-EU.3.3.4.-A single, smart European electricity grid	731249-SMILE-SMart IsLand Energy systems	Demonstration of different innovative technological and non-technological solutions in large-scale smart grid projects in the Orkneys, Samsø, and Madeira islands: the technological solutions vary between the integration of battery technology, electric vehicles, aggregator approach to demand side management, and predictive algorithms	2017–2021
H2020-EU.3.4.- SOCIETAL CHALLENGES- Smart, Green, and Integrated Transport	875548-SeNse-Lithium-ion battery with silicon anode, nickel-rich cathode, and in-cell sensor for electric vehicles	Aimed at enabling next-generation lithium-ion batteries with a silicon-graphite composite anode and a nickel-rich NMC cathode to reach 750 Wh/L, wherein the main target is to reach more than 2000 deep cycles	2020–2024
	770019-GHOST-InteGrated and PHysically Optimised Battery System for Plug-in Vehicles Technologies	Enhance Li-ion technologies by implementing light materials and novel thermal management architectures, and develop innovative and integrated solutions for mass production	2017–2021
	769929-IMAGE-Innovative Manufacturing Routes for Next Generation Batteries in Europe	Develop generic production techniques for next-generation battery cells (Li-metal cathodes); identify energy and resource efficient cell manufacturing technologies; and develop a progressive, multiple-tier technological and production framework that can cope with the inherent technological changes and advancements characteristic of this dynamic field	2017–2021

Table 5. *Cont.*

Program	Grant-Acronym-Agreement	Main Objectives	Start–End (yyyy)
H2020-EU.3.4.-SOCIETAL CHALLENGES-Smart, Green, and Integrated Transport	875527-Hydra-Hybrid power-energy electrodes for next generation lithium-ion batteries	Aimed at developing a new generation of Li-ion technology with improved energy, power, and low costs utilizing sustainable materials; to reach this target, HYDRA mobilizes a strong industry commitment	2020–2024
	963903-Current Direct-CURRENT DIRECT – Swappable Container Waterborne Transport Battery	Propose an innovative lithium-ion cell optimized for waterborne transport using novel manufacturing techniques for a consistent cost reduction	2021–2023
H2020-EU.3.5.4.-Enabling the transition towards a green economy and society through eco-innovation	776851-CarE-Service-Circular Economy Business Models for innovative hybrid and electric mobility through advanced reuse and remanufacturing technologies and services	Demonstrate new enabling technologies and service to systematically perform innovative reuse and remanufacturing practices as key processes to provide value to customers and to minimize the environmental impact	2018–2021

4. Conclusions

In order to guarantee the sustainability and the optimum EU management of LIBs, the unification and communication among the different stakeholders within the whole value chain are of utmost importance.

This goal becomes fully clear considering that the needs and the challenges of the legislation in various countries acquire more relevance if tied to the generalized overview of circular economy needs/challenges. In 2015, the European Commission adopted "The missing link: a European action plan for the Circular Economy", in which the interdependence of all the processes in the value chain were analyzed, from the extraction of raw materials to product design; from production to distribution; and from consumption to reuse and recycling, inserting measures aimed precisely at designing products in an intelligent way. The commitment of the European Commission to these issues is also contained in the European New Green Deal presented by the new president of the European Commission in September 2019. Subsequently, on 11 March 2020, the Action Plan was updated and, in this version, the European Commission identified some production sectors as priorities, including the sectors of batteries and vehicles.

In this context, indeed, electric mobility represents one of the main areas requiring the implementation of circular economy logic, making it necessary to develop best practices to achieve sustainable mobility.

There is a clear need to apply a "Life Cycle Thinking" type approach that covers the entire life cycle of the vehicle and its components, and not only that of the LIB. The main issues to be addressed for a transition to a circular economy by the electric mobility sector consist of interventions along the entire electric mobility chain, such as (i) the development of charging infrastructures; (ii) the adoption of an eco-design logic through the choice of materials on the basis of their availability, recyclability, and ease of reprocessing; (iii) the spread of innovative and sustainable technologies based on "product as a service" business models, sharing platforms, and auxiliary services ("vehicle to grid" technology); (iv) an effective end-of-life management and regeneration system of the equipment and components; and (v) the development in each national territory of skills throughout the value chain (production of new vehicles, systems for assistance and repairs, and end-of-life treatment, where a second-life battery use system as well as LIB recycling and disposal processes are only one of the issues).

The Extended Producer Responsibility is recognized as an optimum tool to summon the various parties operating in the LIBs sector. However, after an analysis of the legislation (both European and of the target state), the following limits were detected:

- the financing systems for the collection schemes are not unique and a comparative analysis must be performed in order to identify the most effective and efficient systems;
- there is an absence of identification or codes that easily recognize LIBs, thus difficulties in sorting and recycling them are increasing; and
- there is an absence of specific regulations dedicated to LIBs, implying the loss of volume that is potentially detectable and valorized.

The upload of directives has been devoted to increasing the sustainability of LIBs but, at the same time, a revolution in the industrial sector is needed to guarantee the benefit of a cradle-to-cradle cycle for LIBs. Urgent innovation and legislative adaptation have been made more difficult considering the awareness that the use of accumulators cannot be the definitive or long-term solution.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su132011154/s1, Main point of the survey.

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Biotechnology for Metal Recovery from End-of-Life Printed Circuit Boards with *Aspergillus niger*

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Abstract: The growing production and use of electric and electronic components has led to higher rates of metal consumption and waste generation. To solve this double criticality, the old linear management method (in which a product becomes waste to dispose), has evolved towards a circular approach. Printed circuit boards (PCBs) are the brains of many electronic devices. At the end of their life, this equipment represents a valuable scrap for the content of base metals such as Cu and Zn (25 and 2 wt %, respectively) and precious metals such as Au, Ag, and Pd (250, 1000, and 110 ppm, respectively). Recently, biotechnological approaches have gained increasing prominence in PCB exploitation since they can be more cost-efficient and environmentally friendly than the chemical techniques. In this context, the present paper describes a sustainable process which uses the fungal strain *Aspergillus niger* for Cu and Zn extraction from PCBs. The best conditions identified were PCB addition after 14 days, Fe^{3+} as oxidant agent, and a pulp density of 2.5% (*w/v*). Extraction efficiencies of 60% and 40% for Cu and Zn, respectively, were achieved after 21 days of fermentation. The ecodesign of the process was further enhanced by using milk whey as substrate for the fungal growth and the consequent citric acid production, which was selected as a bioleaching agent.

Keywords: printed circuit boards; biotechnologies; circular economy; *Aspergillus niger*; copper; zinc; food waste

1. Introduction

In recent years, the production of electrical and electronic equipment (EEE) has substantially increased with the development of science and technology [1,2]. At the same time, the average lifetime of electronic products has also been drastically reduced (to around 2 years), resulting in a massive generation of waste from electrical and electronic equipment (WEEE) (around 44.7 million tons in 2016) [3,4]. Printed circuit boards (PCBs) represent about 3–5% of the total WEEE collected every year [5]. They are composed of metals (around 40 wt %), ceramics (around 30 wt %), and plastics (about 30 wt %) [3,6–9]. The metal fraction includes 20% Cu, 5% Al, 1% Ni, 1.5% Pb, 2% Zn, and 3% Sn (*w/w*) [2,4,10,11]. The presence of considerable amounts of metals represents a very critical issue for their possible release into the environment in the case of incorrect management [12]. Nevertheless, this aspect also represents an opportunity for a transition towards a circular approach following the principle "resource–product–regenerated resource", where the waste is converted into a resource (urban mining) [13,14]. The most conventional options used by industries to extract metals from PCBs are pyrometallurgy and hydrometallurgy [6,15]. Pyrometallurgical approaches produce pollutant emissions (dioxins and furans), and they usually involve high operation costs. Hydrometallurgy is a low energy-cost process which needs large amounts of chemical agents. Alternatively, biohydrometallurgy is often simple, environmentally friendly, and economical, responding to the sustainability principles essential for the development of a circular economy [15–17].

Several studies have described metal extraction from PCBs using bacteria, mainly *Leptospirillum ferrooxidans*, *Acidithiobacillus thiooxidans*, *A. ferrooxidans*, and *Sulfobacillus thermosulfidooxidans*, principally for the recovery of Cu and other metals such as Zn, Sn, Pb, and Ni [18–30]; *Chromobacterium violaceum*, *Pseudomonas fluorescens*, and *Bacillus megaterium* have also been used for Au recovery [31–35]. On the other hand, fungal bioleaching has several advantages since fungi show a greater ability to tolerate toxic materials, a faster leaching action than bacteria, and the ability to grow in both alkaline and acidic mediums [36]. *Penicillium simplissimum*, *P. chrysogenum*, and *Aspergillus niger* are the most common eukaryotic microorganisms used for metal leaching from different solid residues such as electronic scraps [10,15,20,36], contaminated soil [37], spent catalyst [38–40], flay ash [41–43], and red mud [44,45]. Citric, oxalic, and gluconic acids are the organic acids produced in the highest quantities by *A. niger* and are used for waste exploitation [37,46,47]. In detail, bioleaching with *A. niger* uses PCBs [10,20] or batteries [15,36] as substrate for metal extractions. High leaching efficiencies of 60% and 100% for Cu and Zn, respectively, were achieved after 21 days of fermentation with low pulp density of 0.1–0.5% (*w/v*).

Considering the current end-of-life PCB availability and the relevant content of Cu and Zn, the present paper aims to improve the sustainability of the process compared to the current state of the art. The possibility to increase the quantity of treated PCBs makes the treatment more attractive for stakeholders and suitable for industrial scale-up. Many conditions were investigated, including the possible inclusion of food industry waste as fungal growth substrate to improve the environmental sustainability of the treatment.

2. Materials and Methods

2.1. Preparation of Waste Printed Circuit Boards (PCBs)

PCBs used in this paper were obtained from computer devices. They were shredded by stainless steel blades and pliers after manually removing the main parts of electronic components (e.g., capacitors, batteries, and resistors). Finally, the residue was crushed to obtain a granulometry smaller than 0.5 mm, suitable for the bioleaching experiments. The metal fraction was separated from the plastic and flame retardants by density and the PCB powder was washed with NaCl-saturated water. The resulting PCBs had mean metal concentrations of 25% Cu and 2% Zn.

2.2. Microorganisms and Inoculum

Fungal microorganisms, classified as *A. niger*, were isolated in the laboratory from environmental samples. The inoculation of fungi was carried out inside sterile Petri dishes with a diameter of 100 mm in YPD broth (10 g/L yeast extract (Y), 20 g/L peptone (P), and 20 g/L D-glucose (D)), where 1.5% agar was added. The medium, before being used, was stirred and heated to 60 °C to achieve a homogeneous amber color and subsequently autoclaved. Finally, 100 mg/L of antibiotic (rifampicin) was added. The inoculated plates were incubated at room temperature for about 7–10 days. One-milliliter aliquots of the prepared inoculums were inoculated to 100 mL of the glucose medium. The glucose medium was prepared with the following composition: solution A was composed of 2.5 g of $(NH_4)2SO_4$, 0.25 g of $MgSO_4{\cdot}7H_2O$, and 0.025 g of KH_2PO_4 dissolved in 450 mL of distilled water; solution B was composed of 1 g of yeast in 50 mL of distilled water; solution C was composed of 150 g of D-glucose dissolved in 500 mL of distilled water; and solution D was composed of 1 g/L $ZnSO_4{\cdot}7H_2O$, 0.05 g/L $MnSO_4{\cdot}H_2O$, and 0.1 g/L $FeSO_4{\cdot}7H_2O$. The solutions A, B, and C were mixed and autoclaved, and 1 mL of the solution D was added to the resulting solution. The pH of solution was adjusted to 6.5 in the first day and readjusted to pH 3 during the bioleaching experiments. The bioleaching tests were carried out in 250 mL Erlenmeyer flasks which were incubated at 30 °C and shaken at 120 rpm. Each treatment was performed in duplicate. The pH was recorded by a pH meter inoLab Multi 720 (WTW).

2.3. Bioleaching Experiments

The bioleaching processes were conducted to verify the effect of two factors: the PCB addition at different fermentation times and the addition of two oxidant agents (Fe^{3+} or Mn^{7+}). The first factor was monitored by adding PCBs at three different times: at the beginning, after 7 days, or after 14 days of fermentation. The bioleaching process was carried out for 7 days after the PCB addition. In the case of PCB addition at the beginning, the longest time of 14 days allowed the fungal growth and acid production. The pH of medium was continuously monitored and readjusted to 3 using a 2 M NaOH solution. The second factor (the oxidant agent) was tested by adding Fe^{3+} (40.67 g/L of $Fe_2(SO_4)_3$) or Mn^{7+} (6.14 g/L of $KMnO_4$) simultaneously with the PCB addition at all tested conditions. The Fe^{3+} and Mn^{7+} amounts were determined by stoichiometric ratio with Cu, following Equations (1) and (2) [8,48,49]:

$$Cu^0 + 2\,Fe^{3+} \rightarrow Cu^{2+} + 2\,Fe^{2+} \quad (1)$$

$$5\,Cu^0 + 2\,Mn^{7+} \rightarrow 5\,Cu^{2+} + 2\,Mn^{2+} \quad (2)$$

The PCB concentration in bioleaching experiments was 2.5% (*w/v*). At regular time intervals, both citric acid production (2, 7, 14, and 21 days) and metal concentration (2, 4, 7, 10, 14, 16, 18, and 21 days) were monitored.

A chemical control test was carried out at the same bioleaching conditions to confirm the effect of the citric acid with or without oxidant agents. The operative conditions were PCB concentration 2.5% (*w/v*), pH 3.0, 30 °C, and 7 days. The citric acid concentration chosen was the same as that of the organic acid produced by *A. niger* in the bioleaching experiments (15 g/L), and the same amounts of Fe^{3+} and Mn^{7+} were used.

Additional tests were carried out to test the possibility of producing citric acid using an alternative carbon source to reduce the environmental load due to the glucose consumption for the fungal growth. Two kinds of agriculture and food residues were used, olive wastewater and milk whey (a cheese production residue). Both kinds of waste were used without or with an ozonation pretreatment (30 min and a flux of 7 gO_3/L·h). The choice of these residues was due to their high COD content (around 150 g COD/L). Furthermore, these waste flows represent a relevant management problem in the Mediterranean area [50,51]. Their use allows for the solution of a double problem by decreasing the consumption of raw materials and the reducing the amount of food waste disposed, in agreement with the circular economy pillars.

2.4. Analytical Determination

The concentrations of Fe (Fe^{3+} and Fe^{2+}), Mn^{2+}, Zn^{2+}, and Cu^{2+} were periodically analyzed in the leaching solutions. The concentrations of Mn, Zn, and Cu were measured by an atomic absorption spectrophotometer (Techcomp, AA6000). On the other hand, the quantification of the Fe content was performed by a UV/VIS spectrophotometer by the colorimetric thiocyanate method (Jasco Model 7850). The total Fe concentration was determined by oxidizing Fe^{2+} to Fe^{3+} with potassium permanganate, and consequently the Fe^{2+} concentration was calculated as the difference between total Fe and Fe^{3+} concentrations. The concentration of citric acid produced by *A. niger* in the medium was quantified by the Water HPLC instrument.

2.5. Statistical Analysis

In order to verify the effect of oxidant agents (Fe^{3+} or Mn^{7+}) and the best time for both PCB and oxidant agent addition (at the beginning, after 7 days of fermentation, or after 14 days of fermentation), a two-way analysis of variance (ANOVA) was carried out. When significant differences were observed, an SNK post hoc comparison test ($\alpha = 0.05$) was also performed. An additional statistical analysis was also conducted aimed at confirming the leaching role of both citric acid and oxidant agent.

3. Results

3.1. Bioleaching Experiments

Figure 1 shows the Cu and Zn leaching profiles in the bioleaching tests with PCBs. These results demonstrated that the leaching efficiency for both Cu and Zn increased when the PCBs and oxidant agent were added 14 days after the beginning of fermentation. This was achieved thanks to the highest citric acid production by *A. niger* when PCBs/oxidant agent were added at the end of fungal metabolism (Figure 2). In detail, the citric acid reached the concentration of 13.8 ± 4.5 g/L at these conditions, even though 0.033 ± 0.002 and 1.6 ± 0.7 g/L of citric acid were produced when PCBs and oxidant agent were added at the beginning of fermentation and after 7 days after the start of fermentation starting, respectively. The lowest citric acid production by *A. niger* was due to both the metal toxicity and the PCB inhibition on fungal metabolism due to the high substrate concentration [5,10,20].

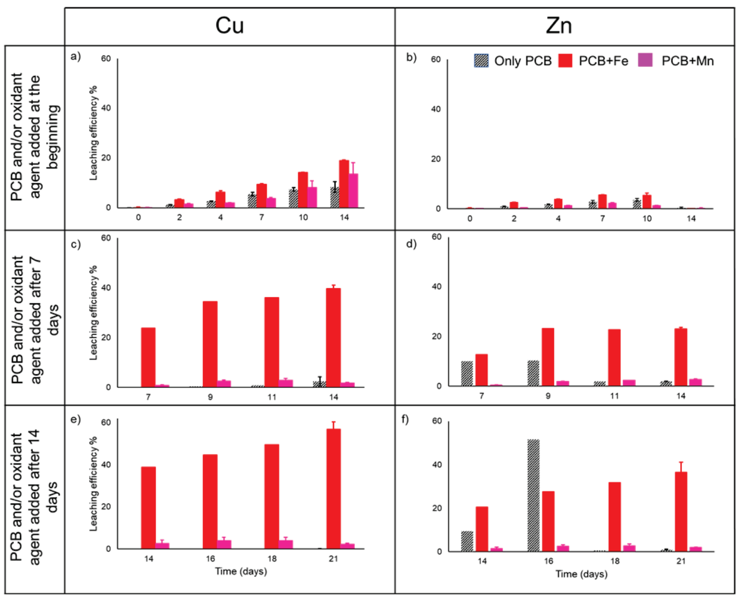

Figure 1. Cu (**a**,**c**,**e**) and Zn (**b**,**d**,**f**) leaching efficiency time profile in the bioleaching tests with *A. niger* and with the printed circuit boards (PCBs) and/or oxidant agent (ferric iron or potassium permanganate) added at the beginning (**a**,**b**), after 7 days (**c**,**d**), or after 14 days (**e**,**f**) of the fermentation period.

The results proved the positive effect of Fe^{3+} as an oxidant agent, with an increase of both Cu and Zn leaching (Figure 1). On the other hand, the Mn^{7+} were not relevant at all to the tested conditions. In further detail, Cu leaching rose from 19.0 ± 0.2% when Fe^{3+} was added at the fermentation beginning to 57.0 ± 3.0% when it was added after 14 days. The same trend was observed for Zn leaching efficiency, from 5.6 ± 0.1% to 36.5 ± 4.8%. The highest recovery efficiency of PCBs and Fe^{3+} added after 14 days was explained by the highest citric acid concentration, which increased the Fe dissolution from 10.6 ± 2.6% to 60.5 ± 5.3% (Figure 3). Moreover, the Fe speciation demonstrated that the total dissolved Fe reacted with PCB powder at the highest citric acid concentration [52]. Therefore, at the end of the experiment, Fe was completely in the reduced form (Fe^{2+}) due to the reaction with Cu and Zn (Equation (1)). In the other tested conditions, around 50% of the dissolved Fe reacted with PCBs to leach metals. The statistical analysis (ANOVA) confirmed the positive effects of both the PCB and the oxidative agent (Fe^{3+}) addition after 14 days with a P value lower than 0.05. The Fe^{3+} use produced an additional advantage. In the tests without Fe^{3+}, the Zn leaching efficiency after 2 days decreased from 2.8 ± 0.5%, 10.3 ± 0.7%, and 51.5 ± 0.5% to around 0% when PCBs were added at the beginning, after 7 days, or after 14 days of the fermentation period, respectively. Fe created a stable complex able to prevent the Zn precipitation in oxalate form [53,54]; this was due to the oxalic acid present as a by-product of citric acid synthesis by *A. niger* metabolism [36,46].

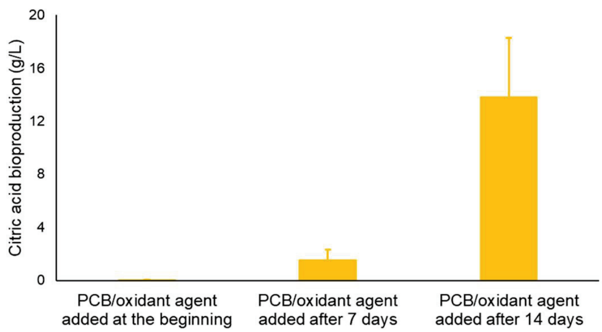

Figure 2. Citric acid concentration in the bioleaching experiments with *A. niger*.

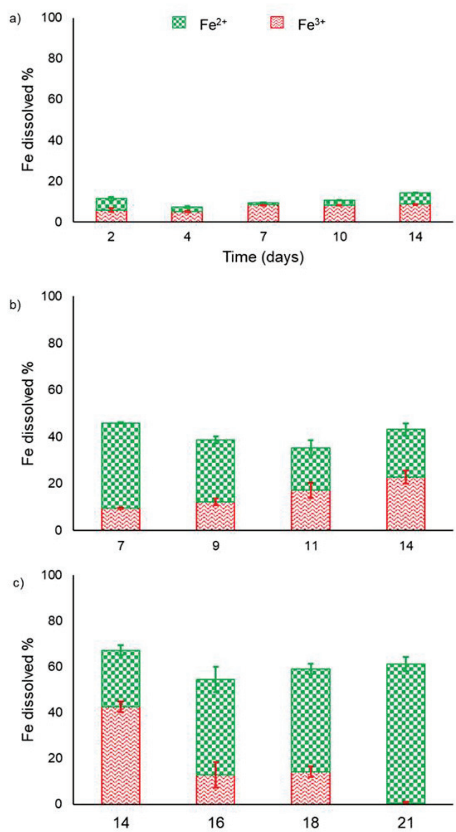

Figure 3. Fe dissolution and speciation in the bioleaching experiments: PCBs and Fe^{3+} added at the beginning (**a**), after 7 days (**b**), or after 14 days (**c**) of the fermentation period.

3.2. Chemical Controls and Statistical Analysis

To verify that both the Cu and Zn extractions were due to the citric acid produced by *A. niger* and to the oxidant agent added (Fe^{3+} or Mn^{7+}), chemical controls were carried out reproducing the bioleaching conditions. The results in Figure 4 confirmed the positive effect of Fe^{3+} addition with final yields of 59.4 ± 0.9% and 24.6 ± 5.0% for Cu and Zn, respectively. The statistical analysis, carried out to compare the chemical results with the corresponding bioleaching ones, demonstrated that the results were not statistically different, with a P value higher than 0.05 for both the metal targets (Table 1). These results confirmed that the Cu and Zn leaching from PCBs were due to the concurrent effects of citric acid and oxidant agent and excluded the possible effect of glucose or other organic acids (such as oxalic or gluconic acid) produced by *A. niger*.

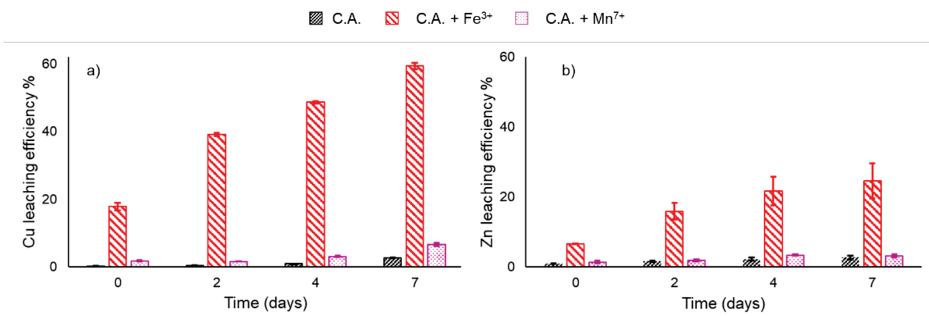

Figure 4. Cu (**a**) and Zn (**b**) leaching efficiency in the chemical control carried out with citric acid (C.A.) and oxidant agents (Fe3$^+$ or Mn7$^+$).

Table 1. The variance analysis comparing the chemical controls with the respective bioleaching experiments.

Treatment	Statistical Analysis (ANOVA)						
	df	Cu			Zn		
		MS	F	P	MS	F	P
C.A.	1	2.98	3.74	0.19	2.06	50.75	0.05
C.A.+Fe^{3+}	1	5.74	0.46	0.57	140.6	2.98	0.23
C.A.+Mn^{7+}	1	0.58	0.33	0.62	1.48	8.74	0.10

3.3. Citric Acid Production Using Alternative Carbon Sources

When food wastes (olive wastewater or milk whey) were used for the fungal growth, only 0.13 ± 0.01 g/L of citric acid was produced (Figure 5). The main problems were the toxic effect of phenols on fungal metabolism in the case of olive wastewater [55–57] and the low availability of lactose as a carbon source for fungal metabolism in the milk whey experiment [58–62]. The additional pretreatment by ozonation allowed reducing the concentration of phenols and decomposing lactose in a more available saccharide such as glucose, galactose, or fructose. After the pretreatment step, *A. niger* produced around 6.1 ± 0.1 and 13.7 ± 4.4 g/L of citric acid after 14 fermentation days with olive wastewater and milk whey, respectively. These quantities were enough to complete the leaching of the two metal targets. The decrease of the final COD concentration in both food wastes simplified the final sludge management.

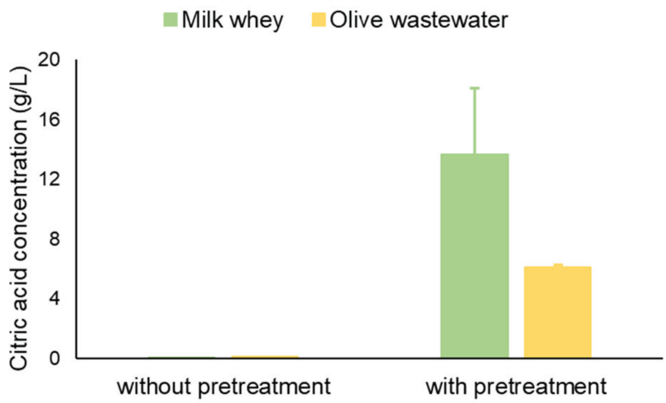

Figure 5. Citric acid produced by *A. niger* using agricultural and food wastes without and with pretreatment with ozonation after 14 days of fermentation.

4. Discussion and Conclusions

This work proposed a bioleaching process for metal extraction from end-of-life PCBs with *A. niger*. The results prove the possibility to increase the treated PCB amount from 0.5% to 2.5% *w/v* without Cu efficiency decrease [10,20]. The relevance of the proposed approach is confirmed by two main reasons: (i) Cu is the main metal of interest in PCBs, after precious metals (Au and Pd). The economic sustainability of its extraction from these scraps is also connected to its high concentration [4,7,63]. (ii) Cu is the main interferent in Au leaching; therefore, its previous extraction allows for a significant increase of both efficiency and purity in the Au recovery [32,33,64]. The present paper represents an example of success in the implementation of circular economy principles described by the New European Circular Economy Action Plan [65]. Indeed, PCBs are included within the list of key products in the documents (electronics and ICT). Furthermore, the biotechnological implementation allows the substitution of hazardous chemicals to protect citizens and the environment. The chance to give value to the waste (both PCBs and food waste for the citric acid production) pushes the market towards the creation of a secondary raw materials market, while avoiding export to non-European countries, in agreement with the modern circular policies. More comprehensively, the biotechnological approach using the *A. niger* strain allowed the exploitation of end-of-life PCBs at a low temperature, reducing the consumption of chemical agents. High efficiencies, around 60% and 40% for Cu and Zn, respectively, were achieved at the best selected conditions: addition of PCBs and Fe^{3+} (oxidant agent) 14 days after the start of fermentation (when *A. niger* reached the exponential growth phase and produced the maximum amount of citric acid (around 15 g/L)), 30 °C, 7 days leaching time, and 2.5% (*w/v*) PCB concentration. A further recovery process allows for the new metal's placement on the market, while avoiding the depletion of raw materials. Moreover, the environmental sustainability of the treatment was enhanced by the use of food wastes (milk whey and olive wastewater) for *A. niger* metabolism and was able to replace the glucose from primary sources, solving the criticalities connected to their management.

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sustainability

Article

Environmental Sustainability Analysis of Case Studies of Agriculture Residue Exploitation

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Abstract: The agriculture sector produces significant amounts of organic residues and the choice of the management strategy of these flows affects the environmental sustainability of the sector. The scientific literature is rich with innovative processes for the production of bio-based products (BBP) from agriculture residues, aimed at the implementation of circular economy principles. Based on literature data, the present paper performed a life cycle assessment and assessed the environmental sustainability of five processes for the exploitation of rice and wheat straw, tomato pomace, and orange peel. The analysis identified as significant issues the high energy demand and the use of high impact organic solvent. The comparison of BBP with conventional products showed higher environmental loads for the innovative processes that used organic residues (except for rice straw case). The obtained results do not want to discourage the circular strategy in the agriculture sector, but rather to draw the attention of all stakeholders to the environmental sustainability aspects, focusing on the necessity to decrease the electricity demand and identify ecological agents to use in BBP manufacturing, in agreement with the most recent European policies.

Keywords: circular economy; agriculture residue; environmental sustainability; life cycle assessment; bio-based product

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1. Introduction

1.1. State of the Art of Exploitation of Agriculture Residues

The agricultural production is genuinely diverse; nevertheless, it focuses on some central species fundamental for human diet, such as cereals, but also fruits and vegetables, whose quantities exceed billions of tons of biomass produced [1]. Italian agriculture has a significant role in Europe, being the 3rd country based on its production value in 2019 [2]. From the ISTAT database, it appears to be dominated by fodder plants, but cereals are another important role in every regional production; besides these main species, horticulture and fruit growing have another important role to play [3]. Due to the world population growth in the current century, food demand has increased worldwide and consequently the residues that food production generates too [4]. This biomass can reach huge quantities and sometimes its disposal might create environmental or health issues. For this reason, a further exploitation can be pursued to reduce these negative effects and enhance the underused potential; in this context, the bio-based products (BBP) can be a viable option [5]. In the scientific literature, several studies have been conducted about agricultural residues and byproducts exploitation. As shown in Table 1, many studies propose solutions for the exploitation of residues from species actually produced in Italy (but not only), i.e., cereals to horticultural species, but also fruits and fodder plants. As reported in the literature, the BBP manufacturing can start from both residual biomass, collected during harvesting stage, and industrial processes. The BBP from agriculture residues can be classified on the basis of the levels of residue manipulation. The first level of manipulation is the lowest (mainly mechanical, physical treatments, and mixing with other components), e.g., composite panels used in the building sector made from sunflower or maize lignocellulosic fibers [6,7]. A greater manipulation level allows the extraction of molecules used in their unaltered state, such as antioxidants and vitamins [8,9]. A third level of transformation consists of more complex processes, creating nanoparticles or functional polymers [10,11]. As an alternative, they can be categorized as chemicals and composites. Acids, enzymes, and coloring substances are chemicals used in pharmaceutical and textile industries, as well as food and biomedical sectors [12]. Among these molecules, there are also the functional ingredients that improve or provide more value to other products of food and cosmetic industries [13]. Examples of these substances are vitamins, fibers, antioxidants, and pigments derived from fruits and vegetables peels [8,9]. On the other hand, composite materials are made of two main elements, a matrix and a filler [14]. Among composite materials, polymers, e.g., hydrogel [15] or plastic films [5], have great importance and they can have several structures, e.g., adsorbent polymers for metal particles [16] or packaging materials. This second type of products includes the smart polymers that can react to some parameter variations to point out the initial deterioration, preventing food loss [17]. Moreover, nanoparticles (NPs) have gained great attraction due to their submicronic dimensions that make them more performing than macro and micro composites for nanocomposites production [14]. In this regard, lignin molecule is used as capping and reducing agent on the surface of silver nanoparticles. Possible applications can be in the textile industry and in biomedical and electronic fields [18,19].

Several articles carried out a comparison between traditional products on the market (produced by conventional manufacturing chain, from raw materials different from byproducts) and bio-based alternatives from organic residues, identifying as the most common benefit the use of low value residual biomass available in huge quantities, for example wheat, rice, and maize [16,20–24]. A common goal of the processes presented by the scientific literature about organic residue exploitation is the green production, meaning low energy consumption and nontoxic agent applications [15,19,23,25]. To complete the current overview about BBP, mainly in an Italian context, the SPRING cluster deserves to be mentioned. It is an Italian cluster that involves bio-refineries and innovation stakeholder with the common goal of enhancing the circular and sustainable economy in the green chemistry sector [26]. Despite the several advantages of BBP manufacturing, the use of organic byproducts shows some relevant challenges. The first one is due to the residue availability, concentrated in a short time span [7], which makes the stocking methods essential [9]. There are also mechanical-physical observations to do about these materials. In this regard, the advantage of the use of bio-based polymers, mainly lignocellulosic materials, is their performance, also as far as it concerns the flammability behavior [7,27]. Nevertheless, they show some disadvantages as the scarce mechanical properties that can be improved by mixing different polymers [11,28]. Furthermore, the literature underlines the necessity to combine studies of BBP production with the analysis of the specific aspects of these products; for example, for human health applications, by clinical tests of the real physiological action [8,18]. Last but definitely not least, the environmental performance of manufacturing processes should be assessed, supported by tools able to implement a life cycle approach.

Table 1. Selected exploitation processes for the use of agricultural residues.

Bio-Based Product	Exploitation Process	Reference
	Rice byproducts	
Composite panel filter	Chopping; mixing with Lignin bioplastic Arboform®; extrusion; injection molding	[27]
Ceramic material	Combustion; calcination; pressing; sintering	[29]
Breakfast bar	Mixing with passion fruit peel and whey; extrusion	[30]
Rice husk broth for polymer production	Pulverizing; acid hydrolysis and steam treatment; neutralization with NaOH; dilution	[24]
	Wheat byproducts	
Filler in polypropylene-based composites	Milling; mixing with polypropylene and additive; drying; extrusion; granulation; drying; injection molding	[31]
Li-Ag NPs	Mechanical pre-treatment; alkali extraction; purification; mixing with $AgNO_3$	[18]
Hydrogel	Milling; treatment with sodium monochloroacetate in isopropanol/NaOH; crosslinking; crushing; sieving; water suspension; washing; drying	[15]
Graphene layers	Mechanical pre-treatment; hydrothermal treatment; pyrolysis; graphitization	[23]
	Corn byproducts	
Adsorbent powder	Washing; cutting; drying; crushing; sieving	[21]
Adsorbent spongy aerogel	Mechanical pre-treatment; stirring in NaOH solution; HCl addition; washing; mixing with filter paper; freezing; freeze-drying; silanization with methyltrimethoxysilane	[22]
	Tomato by-products	
Vanillin, syringaldehyde	Milling; suspension in NaOH solution; heating under microwave radiation; vacuum filtration; acidification with HCl; extraction with ethyl acetate	[20]
Polyester film	Drying; crushing; dewaxing with hexane and methanol; drying; hydrolysis; fraction separation; melt-polycondensation	[5]
	Grape byproducts	
Ag NPs	Mechanical pre-treatment; extraction; centrifugation; mixing with silver nitrate; centrifugation	[32]
Indicator in intelligent film	Freeze-drying; milling; sieving; mixing with k-carrageenan, sorbitol, distilled water, hydroxypropyl methylcellulose; casting; drying	[25]
	Sunflower byproducts	
Particleboards	Grinding; sieving; mixing with synthetic binder; thermopressing	[7]
Reinforcement for thermoplastic material	Steaming; drying; extrusion with polypropylene and coupling agent; granulation; drying; compression molding	[6]
	Orange byproducts	
Functional ingredient in food products	Washing; sanitization in sodium hypochlorite solution; dehydration; grounding; sieving	[33]
Adsorbent polymer	Mechanical pre-treatment; crosslinking; polymerization; extraction; hydrolysis; post-treatment	[16]

Table 1. *Cont.*

Bio-Based Product	Exploitation Process	Reference
	Other agriculture byproducts	
Active polymeric film from potato peel	Mechanical pre-treatment; water suspension; glycerol addition; stirring; bacterial cellulose addition; homogenization; stirring; degasification by ultrasound; pouring in petri plates; drying	[28]
Filler in polyhydroxyalkanoates composites from peas fibers	Drying; milling; mixing with poly(3-hydroxybutyrate-co-3-hydroxyvalerate), acetyltributylcitrate and $CaCO_3$; extrusion; injection molding	[34]
Cellulose nanocrystals for the preparation of agar-based bio-nanocomposites films from onion peel	Mechanical pre-treatment; bleaching with sodium chlorite solution; boiling; washing; treatment with NaOH; treatment with acetic acid; washing; drying; acid hydrolysis with sulfuric acid; centrifugation; sonication; freeze-drying	[35]
Film from prickly pear peels	Mechanical pressing; ethanol addition; drying; dispersion in water; glycerol addition; stirring; casting; drying	[11]
Polyphenols, flavonoids, anthocyanins, vitamin C from peach peel, seeds, and pulp	Dispersion in ethanol; mixing; extraction (ultrasound/microwave)	[9]
Functional ingredient in food products from beet leaves	Cutting; extraction in ethanol; centrifugation; drying; resuspension in water	[36]
Reinforcement for thermoplastic material from bagasse fiber	Steaming; drying; extrusion with polypropylene and coupling agent; granulation; drying; compression molding	[6]
Polyurethane foam from rice, oilseed rape and wheat straw and corn stover	Drying; liquefaction; washing with acetone; rotary evaporation; drying; polyol neutralization with NaOH; mixing with reagents	[10]
Functional ingredient in food products from cauliflower and celery leaves and stem, onion peel, carrot bottom and tips	Extraction in boiling water; hand-squeezing; homogenization	[8]
CuO NPs from cauliflower waste, potatoes and peas peels	Mechanical pre-treatment; water-dispersion; shaking; mixing with solutions of $CuCl_2 \cdot 2H_2O$ under shaking; washing; drying; sintering	[19]

1.2. The GRASCIARI RIUNITI Project

The present paper is part of a preliminary analysis of the environmental sustainability within the GRASCIARI RIUNITI project (within the European plan to support the Regional development FEASR-PSR MARCHE 2014–2020). Several farms on the Marche territory have identified a relevant problem due to the management of the organic residue from their agriculture activity. This problem is mainly due to the growing specialization of the crops, which has ensured high production levels but it has changed the way of considering the agriculture residues: from a biomass resource of the past to a waste to dispose of the present. This practice has disrupted the balance of agriculture in many Italian regions. The founded project, which combines local farms and research partners, has the ambition to create a virtuous management system of waste and byproduct, suitable for a real scale implementation. With this aim many possibilities of agriculture residue exploitation will be considered (e.g., production of BB materials, active principles with specific action, fertilizers, biostimulants, energy recovery) in order to combine the best options for the most sustainable result. Starting from the byproduct criticality, really highlighted by the local farms, the present manuscript analyzed many papers from the scientific literature addressed to the BBP production (Table 1) and it selected five case studies (focused on the exploitation of residues of the main Italian agricultural productions) for an environmental sustainability analysis. The research did not have the presumption to find a single answer but to critically observe some possibilities of agriculture residue exploitation, to verify the effective implementation of the circular economy pillars. With this aim, the environmental sustainability analysis was carried out by a life cycle assessment (LCA) approach.

2. Materials and Methods

2.1. Methods and Software

The quantification of the environmental impact represents an essential step for the development of processes for agriculture residue management, consistent with the circular economy principles [37]. Therefore, the present paper assesses five exploitation processes of four different types of agriculture residue, from Table 1: rice and wheat straw, tomato pomace, and orange peel. These species were included among the most common of the Italian agriculture with the consequent production of huge quantities of byproducts. Therefore, they have been considered relevant for the national scenario. The analysis, according to the attributional LCA methodology, has been performed in agreement with the LCA ISO standard 14040 and 14044:2006 [38,39]. The assessment aims at answering at two main research questions, inspired by [40]:

- What are the environmental hotspots in the considered exploitation processes of agriculture residues? What is the environmental impact of these innovative processes?
- What is the environmental impact of these processes compared with the most common manufacture of comparable products (using conventional raw materials)?

The system boundaries considered for the present paper focused on the byproduct exploitation (from gate to gate), starting with the produced agricultural residue, excluding the use phase and the end of life, because they are considered equal between the conventional and the biobased product. The environmental burden of byproduct is considered 0, since it has been assumed its simple use, in animal husbandry field, in the case of avoided use in BBP [41–43]. Furthermore, the use of the zero-burden assumption for agricultural residues is common for attributional-LCA studies [44]. All LCA steps have been realized, including the optional normalization and weighing, to assess the most affected impact categories and the most critical steps of each process. The software used for data collection is thinkstep Gabi software 9.5, combined with the Database for Life Cycle Engineering (compilation 7.3.3.153; DB version 6.115). The method selected for the analysis is EF 3.0, including all the environmental categories, recommended models at midpoint, together with their indicators, units and sources [45,46]. The functional unit selected for the process analysis is 1 kg of agricultural residue to produce selected bio-based products (with emerging technologies). To answer to the second research question, the functional unit is a specific amount (reported in Figures 1–4) of bio-based products, resulting from the treatment of 1 kg of agricultural residue, in order to facilitate a comparison with a conventional production process (baseline scenario). The processes considered for the present assessment were developed at lab scale (maximum TRL4). The literature reports that in a higher technology development stage environmental and economic impacts are usually lower than a lab scale [47]. Therefore, some sensible assumptions are made to realize this analysis, hypothesizing the further scale-up:

- The electricity consumption reported within the datasheet of real industrial machineries is considered to calculate the energy environmental load of mechanical-physical steps (e.g., grinding, sieving, mixing, heating); the further implementation of a renewable energy production system by a photovoltaic panel system is considered as an alternative to supply the energy to the machineries [47]. This possibility is not considered for the traditional processes (from raw materials) since it is more likely that a new technology invests in a renewable technology.
- The recirculation of 90% of organic solvents for extraction and washing treatments is applied. This assumption, consistent with the real-scale conditions, makes the processes more efficient and environmentally sustainable, thanks to both the reduction of raw material consumptions and waste flow [47,48].
- The conditions selected for the washing operations have been the residue and the washing solution ratio: 1:2 ratio and the time: 1 h, if not specified elsewhere.
- Considering the low electricity demand, compared to the other process steps (<0.002 kWh/kg residue), the filtration energy demand is considered negligible [49].

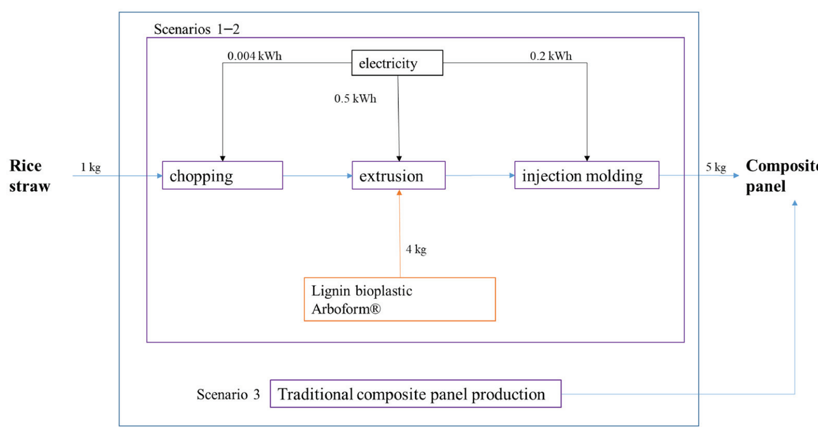

Figure 1. System boundaries and mass and energy balance of rice straw exploitation (scenario 1) and traditional process (scenario 3); scenario 2 includes the same conditions of scenario 1 with electricity from renewable energy. Functional unit: 1 kg of organic residue.

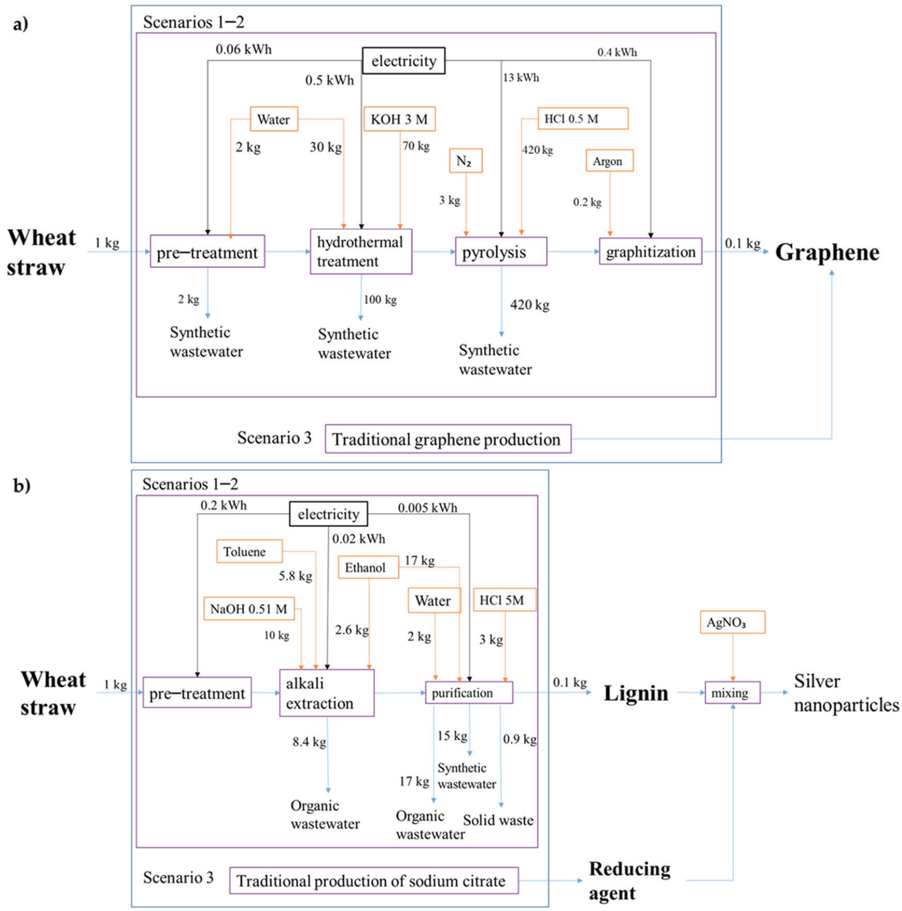

Figure 2. System boundaries and mass and energy balance of two wheat straw exploitation processes as graphene ((**a**), scenario 1) and reducing agent ((**b**), scenario 1) and traditional processes (scenarios 3); in both (**a**) and (**b**) options, scenarios 2 include the same conditions of scenarios 1 with electricity from renewable energy. Functional unit: 1 kg of organic residue.

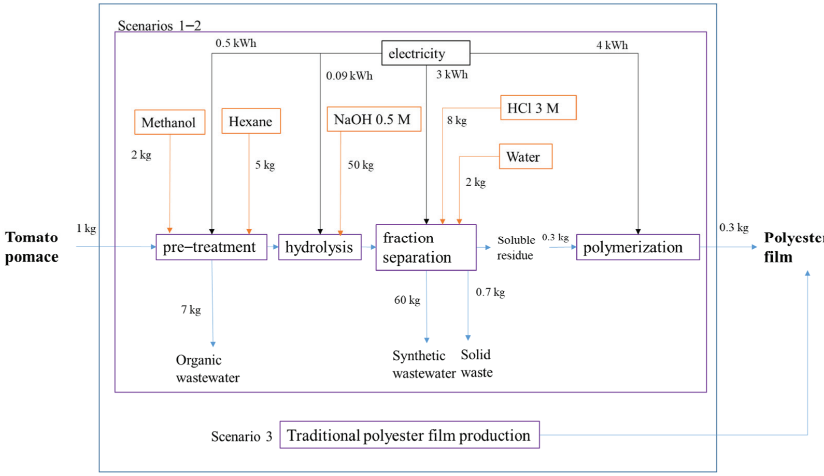

Figure 3. System boundaries and mass and energy balance of tomato pomace exploitation (scenario 1) and traditional process (scenario 3); scenario 2 includes the same conditions of scenario 1 with electricity from renewable energy. Functional unit: 1 kg of organic residue.

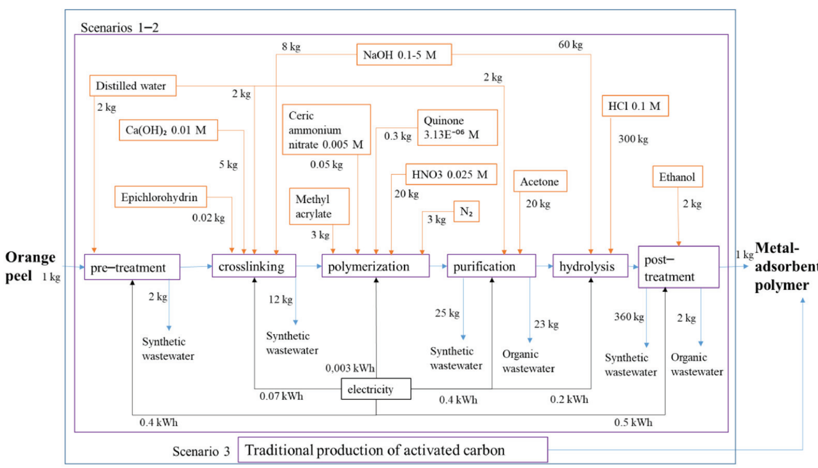

Figure 4. System boundaries and mass and energy balance of orange peel exploitation (scenario 1) and traditional process (scenario 3); scenario 2 includes the same conditions of scenario 1 with electricity from renewable energy. Functional unit: 1 kg of organic residue.

Further assumptions, specific for each process, are reported in the supporting materials (Table S1).

2.2. Exploitation Processes

In this section, the five processes (selected among the options in Table 1) are described and showed through mass and energy balances flow charts. The choice of these processes has been determined by the will of the authors to prove the possible use of BBP in a wide range of application fields (e.g., building field of the composite panel and the medical sector of silver nanoparticles).

Currently, rice straw is separated from rice after harvesting and threshing and it is used in animal husbandry, as bedding [41]. As an alternative, the exploitation process in Figure 1 is realized through cutting the residue, mixing with Lignin bioplastic Arboform®, extrusion and injection molding, obtaining 5 kg of composite panel for interior design as final product [27]. On the other hand, the manufacturing of a traditional panel involves wood and polypropylene, by a process comparable to the innovative one [50].

As well as rice straw, wheat straw is produced after harvesting and threshing and it is used in animal husbandry, as bedding [42]. Two processes have been considered as alternative enhancements of this residue and they both represent innovative solutions in electronics and biomedicine, respectively: graphene (Figure 2a) and lignin as reducing agent for silver nanoparticles (Figure 2b). More in detail, the graphene is produced through hydrothermal treatment, pyrolysis and graphitization [23]. Lignin, as reducing agent is extracted from wheat straw, purified, and mixed with silver nitrate [18,51]. There are several techniques currently used for the graphene and lignin productions. The present study considers, as traditional scenario, the electrochemical exfoliation of graphite, which produces graphene monolayer [52] and the production of sodium citrate, as reducing agent [53,54]. In the reducing agent case, system boundaries exclude the silver nitrate addition for the nanoparticles production, since it is a common step in both innovative and traditional scenarios and does not affect the comparison results.

Tomato pomace is a byproduct of the transformation industry and it is currently used in animal feed composition [43]. In the study taken into account (Figure 3), this residue is exploited through the extraction of fatty acids that are used to produce a polyester polymer, after hydrolysis and fraction separation. The product shows many promising qualities, it is insoluble, nontoxic, biodegradable, and waterproof, which are optimal features resulting from the chemical composition of the initial biomass matrix [5]. The comparison has been carried out with a traditional polyester production described in the Gabi database [55].

Orange peel is a byproduct of the juice industry [16] and it is currently used as animal feed, as some of the previous agriculture scraps analyzed [43]. In the innovative scenario (Figure 4), this residue undergoes several steps: it is cut into small pieces, washed and dried, crushed and sieved during the pre-treatment. Thereafter, it is crosslinked with epichlorohydrine [16,56], a crosslinking agent that, owing to covalent bonds with the polymer, makes it more stable in acid conditions improving its adsorbing capacity [57]. The polymerization is realized with methyl acrylate and the following steps aim at the product purification. The process produces 1 kg of polymer characterized by a high adsorbent capacity, useful in wastewater treatment. This purification mechanism can be achieved with different techniques, mainly with activated carbons [16]. This material is selected for the comparison with the innovative proposed adsorbent; in detail, the manufacture of activated carbons includes a chemical activation with potassium hydroxide and pyrolysis of biomass [58].

3. Results

3.1. Classification and Characterization

The step of the analysis including classification and characterization steps has been performed (by thinkstep Gabi software 9.2.1, Database for Life Cycle Engineering, Sphera, Chicago, IL, USA) with the aim to identify both the strengths and weaknesses of the considered processes. The total results for the considered impact categories (referred to the functional unit) are reported in Table 2; the detail of each process is reported in the supporting materials.

Table 2. Results of classification and characterization. Functional unit: 1 kg of organic residue.

Environmental Impact Category	Resulting Bio-Based Products (BBP)				
	Composite Panel	Graphene	Lignin	Polyester Film	Metal-Adsorbent Polymer
Acidification terrestrial and freshwater (mole of H^+ eq.)	1.66×10^{-2}	1.32×10^{-2}	1.02×10^{-2}	1.11×10^{-2}	2.85×10^{-2}
Cancer human health effects (CTUh)	9.81×10^{-10}	1.92×10^{-9}	1.66×10^{-9}	1.37×10^{-9}	3.93×10^{-9}
Climate change (kg CO_2 eq.)	3.64	7.91	6.64	6.20	$1.26 \times 10^{+1}$
Ecotoxicity freshwater (CTUe)	$2.87 \times 10^{+1}$	$7.10 \times 10^{+1}$	$5.98 \times 10^{+1}$	$4.88 \times 10^{+1}$	$1.90 \times 10^{+2}$
Eutrophication freshwater (kg P eq.)	1.33×10^{-5}	8.50×10^{-5}	6.06×10^{-5}	7.28×10^{-5}	2.95×10^{-4}
Eutrophication marine (kg N eq.)	2.37×10^{-3}	3.97×10^{-3}	2.74×10^{-3}	3.20×10^{-3}	7.60×10^{-3}
Eutrophication terrestrial (mole of N eq.)	2.55×10^{-2}	4.06×10^{-2}	2.74×10^{-2}	3.18×10^{-2}	7.17×10^{-2}
Ionizing radiation-human health (kBq u235 eq.)	1.40×10^{-1}	1.04	1.13×10^{-1}	5.96×10^{-1}	1.41
Land use (Pt)	6.25	$5.15 \times 10^{+1}$	3.85	$2.73 \times 10^{+1}$	$1.69 \times 10^{+1}$
Non-cancer human health effects (CTUh)	7.20×10^{-8}	7.43×10^{-8}	8.41×10^{-8}	6.76×10^{-8}	2.10×10^{-7}
Ozone depletion (Kg CFC-11 eq.)	2.48×10^{-14}	2.46×10^{-13}	8.73×10^{-13}	1.29×10^{-13}	1.01×10^{-9}
Photochemical ozone formation-human health (kg NMVOC eq.)	1.05×10^{-2}	1.04×10^{-2}	1.01×10^{-2}	8.64×10^{-3}	2.52×10^{-2}
Resource use, energy carriers (MJ)	$1.75 \times 10^{+2}$	$1.13 \times 10^{+2}$	$1.66 \times 10^{+2}$	$1.17 \times 10^{+2}$	$3.47 \times 10^{+2}$
Resource use, mineral and metals (kg Sb eq.)	5.89×10^{-5}	3.07×10^{-6}	5.64×10^{-7}	1.66×10^{-6}	1.63×10^{-5}
Respiratory inorganics (disease incidences)	1.33×10^{-7}	1.30×10^{-7}	9.38×10^{-8}	1.11×10^{-7}	2.44×10^{-7}
Water scarcity (m^3 world equiv.)	1.12	2.26	1.16	1.25	2.22

3.1.1. From Rice Straw to Composite Panel

Figure S1 in Supplementary Materials shows the results of classification and characterization steps of LCA carried out on the rice straw treatment for the manufacturing of the composite panel. Overall, it can be observed that the lignin bioplastic Arboform causes the most relevant impact, irrespective of the impact category with a minimum contribution of 55%, which reaches values higher than 95% of the total results. This result is explained by the energy demand and the extraction phase included within the production process of lignin bioplastic Arboform [59,60]. On the other hand, the extrusion step has a non-negligible impact on ionizing radiation-human health effect, land use, and ozone depletion categories due to its high-energy demand. The effect of electricity consumption on the land use category can be justified by the electricity grid mix considered for the analysis (supplied by Gabi database) composed of energy from: 44% of natural gas, 15% hydroelectric, and 12% hard coal (and other lower contributions from additional resources). Instead, the chopping step and has no substantial influence, with a contribution lower than 1% overall, thanks to the low energy demand.

3.1.2. From Wheat Straw to Graphene and Nanoparticles

Considering the availability of two processes for the exploitation of wheat straw, a double result is shown in Supplementary Materials (Figure S2) the contribution of every step on the environmental load of each treatment and the comparison between the two options in all the impact categories. The results show that graphene production has a higher impact than lignin production for most of categories. The pyrolysis step explains this result, due to the energy demand to reach high temperature, around 800 °C for three hours. The effect of the pyrolysis operative conditions is mainly highlighted in the categories of ozone depletion and water scarcity with a contribution of pyrolysis phase around 87% for each of them (Figure S2 (m) and (r)). On the other hand, the pre-treatment stage results as not significant, since its share does not exceed 2% in any category. Even if it is the least influencing process, the lignin production shows as main critical point the purification step. This stage represents the most significant share in most of the categories, affecting by 67% the whole enhancement process and the reason can be identified in the ethanol use. In addition, alkali extraction has an impact due to the use of toluene. This organic compounds use makes the graphene production the best choice mainly in the categories connected to the human health aspects in Supplementary Materials (Figure S2 (l) and (n)). The environmental credit (the negative value) achieved in the water scarcity category (Figure S2 (r)) is obtained by the treated wastewater that has been discharged in the environment.

3.1.3. From Tomato Pomace to Polyester

The results of the tomato pomace exploitation for the polyester film production are presented in Supplementary Materials (Figure S3). The impact of the different steps depends on the impact category; therefore, the further normalization and weighting steps are essential to identify the significant issues of the process. The fraction separation step is the most influencing phase because of the 72 h-vacuum thermic treatment, whose impact is higher than 37%. However, in the water scarcity category (Figure S3 (r)), the fraction separation step has a negative share, an environmental credit derived from the water recovery from the wastewater treatment. In the same category, the most significant step is the hydrolysis due to the high request of water. Overall, pre-treatment and polymerization phases are not negligible with variable contribution to the different categories, between 3% and 48% and between 9% and 40%, respectively. The reasons are the energy demand in the polymer synthesis and the use of organic solvents (hexane and methanol) in the pre-treatment. This information suggests the relevance of the organic agents recirculation to enhance the environmental sustainability of the process.

3.1.4. From Orange Peel to Metal-Adsorbent Polymer

As concern the orange peel exploitation for metal-adsorbent polymer manufacturing, the highest environmental load of polymerization is shown in Supplementary Materisls (Figure S4). The main reason of this impact, starting from 35% up, is the use of methyl acrylate that is an organic compound, essential for the reaction. In agreement to what has been observed in the tomato pomace exploitation process, the hydrolysis phase causes the main contribution (85%) in the water scarcity category (Figure S4 (r)). In addition, the wastewater treatment included in the post-treatment phase produces an environmental credit in the water scarcity category, even though this step has the highest contribution in eutrophication freshwater category. On the other hand, pre-treatment is a negligible phase in almost each category, with a low contribution, steady under 1%, due to the low energy and water consumption.

3.2. Normalization and Weighing

The classification and characterization steps showed relevant information to identify the most critical steps in each process. Nevertheless, the normalization and weighting phases were necessary to assess the whole magnitude of each phase of the treatments and to estimate the environmental performance index (EPI), able to include all the impact categories. In agreement with the selected method, this value is expressed as person equivalent (p.e.), i.e., the number of people (average citizens) that generates the same effect in one year [61].

Overall, Figure 5 shows that the most affected categories in the five processes are resource use-energy carriers (in dark blue), ionizing radiation-human health (in yellow) (both connected to energy issue [62]) and climate change (in plum). More in detail, the effect on ionizing radiation-human health is due to the radionuclides (potentially toxic for humans) resulting from both the nuclear energy production, and the mineral oil and gas extraction, used as energy carriers [63,64]. Moreover, greenhouse gas emissions (e.g., CO_2, CH_4, and more) are the main drivers of climate change, whose biggest contribution stems from energy and industrial activities [65]. From these observations, it is evident that the main criticalities in the innovative processes are the huge energy demand (e.g., pyrolysis in graphene production) and the organic solvents use (e.g., methyl acrylate in orange peel exploitation and ethanol in wheat straw enhancement as lignin). The further detail of impact category loads for all the assessed scenarios is reported in Supplementary Material (Table S2).

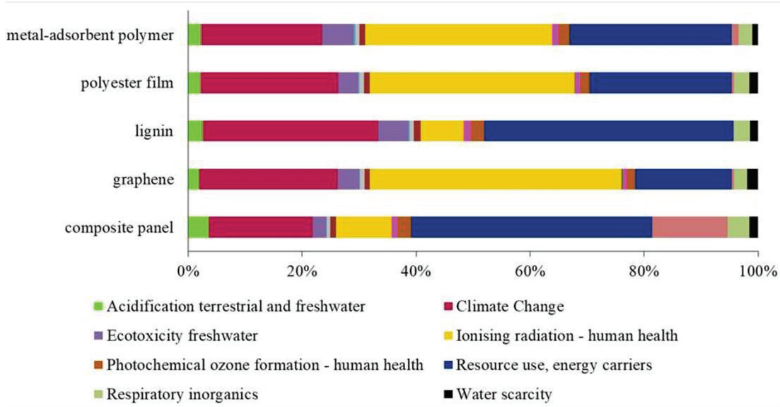

Figure 5. Normalization and weighing graphic of the five exploitation processes. Functional unit: 1 kg of organic residue. The impact categories mentioned in the legend are the most relevant only.

More in detail, the assessed EPI for rice straw exploitation for the production of the composite panel is 0.05 person equivalent. Even though the resource use-energy carrier is the most affected category, 31% of the whole impact is equally distributed between climate change and resource use-minerals and metals categories. The most critical step is Lignin bioplastic Arboform® production that, coherently with the characterization phase, creates the biggest impact on resource use-minerals and metals. The normalization and weighting phases confirm the exploitation of wheat straw for lignin production as the best environmental performance choice, if compared to graphene production. Indeed, the EPI resulting from the assessment of the second process is two times lower than the first one. If graphene production has its biggest impact on ionizing radiation-human health, lignin production largely influences resource use-energy carriers. Particularly, pyrolysis weighs 71% on the graphene production process; moreover, the category ionizing radiation-human health is the main affected, as well as it happens in other stages of the process. Instead, during lignin production process the most influencing step is purification; in this case, resource use-energy carriers is the most critical category, even though there is a significant impact to climate change category too. The tomato pomace exploitation has an environmental performance index of 0.06 person equivalent and the ionizing radiation-human health category is the most affected category. The most important step is hydrolysis that constitutes 31% of the total process impact; the three remaining steps of the process have a significant impact as well and they affect ionizing radiation-human health and resource use-energy carriers more than any other categories. Finally, the orange peel EPI is 0.2 p.e. and the process has the highest effect on ionizing radiation-human health category, as shown in Figure 5. Similarly, to the characterization phase, the most significant step is polymerization, with a contribution of 51% compared to the others and it generates its biggest impact on ionizing radiation-human health and resource use-energy carriers categories.

3.3. Comparison with Traditional Production Processes

In this section, the results of the comparison between the innovative methods based on agricultural residues and traditional methods are shown, considering the normalization phase only and the functional unit equal to the quantity of final product generated by each process, with an initial residue biomass of 1 kg.

The composite panel produced through the enhancement of rice straw is compared in Figure 6 with a traditional composite panel, made of wood and polypropylene. It is evident that the innovative option allows a relevant decrease of the environmental load (from 0.07 to 0.05 p.e.) thanks to the non-use of polypropylene that is necessary in the traditional process. In the same figure, the production of bio-based composite panel with renewable energy is shown and its impact value is comparable to the EPI of the bio-based composite panel made with mixed energy, since the electricity production is not a critical issue.

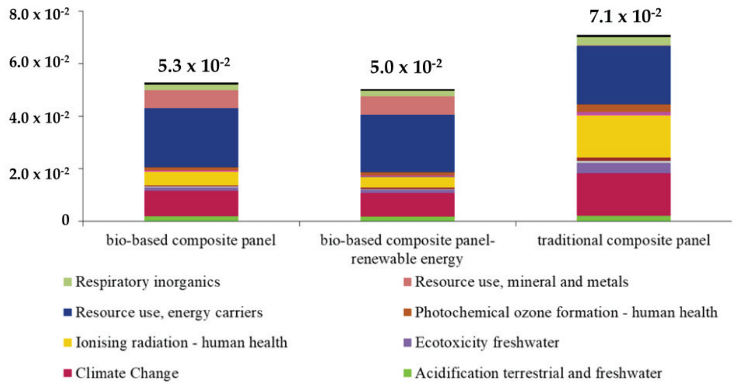

Figure 6. Normalization and weighing graphics of three different composite panel production scenarios, expressed as person equivalent (p.e.). The impact categories mentioned in the legend are the most relevant only. Functional unit: 5 kg of product.

The wheat straw as graphene monolayers is compared to electrochemical exfoliation of graphite [52], obtaining the results in Figure 7. In this case, the residue exploitation does not show advantages for the environment, if compared to the traditional graphene manufacturing. This difference is due to the higher energy demand of the bio-based graphene production. This aspect is confirmed by the possibility of green energy use, which reduces EPI of about 50%, even though it still has a higher impact than traditional graphene.

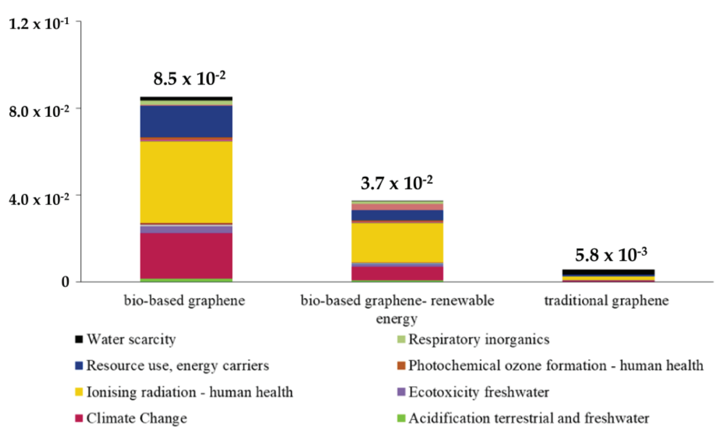

Figure 7. Normalization and weighing graphics of three different graphene production scenarios, expressed as p.e. The impact categories mentioned in the legend are the most relevant only. Functional unit: 0.1 kg of product.

In the second exploitation option, lignin production is compared to sodium citrate production [53,54], which is a reducing agent as well. The comparison between these two processes is visible in Figure 8 with a resulting EPI five times higher than the traditional choice: lignin production has a higher value, because of the use of organic agents, missing in the sodium citrate production. In the same graphic, it can be observed the impact of the production of lignin using renewable energy. The index is comparable to that of lignin made with mixed energy, since the electricity production is not a critical issue of this process.

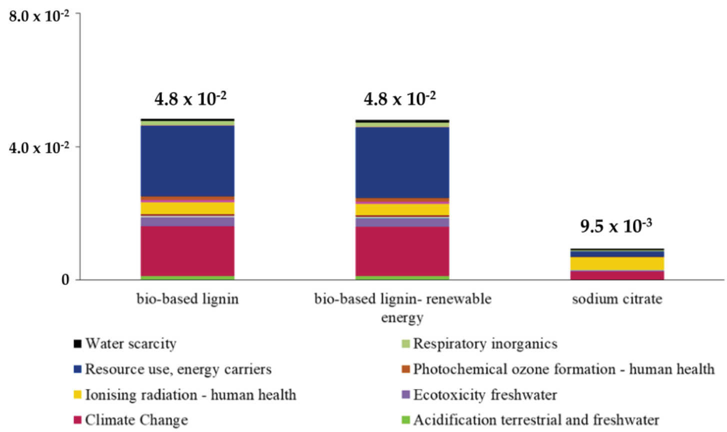

Figure 8. Normalization and weighing graphics of three different reducing agents production scenarios, expressed as p.e. The impact categories mentioned in the legend are the most relevant only. Functional unit: 0.1 kg of product.

Tomato pomace is used to produce a polyester film. Therefore, the comparison is made with traditional polyester [55]. As shown in Figure 9, innovative polyester film has a bigger impact and its EPI is one order of magnitude higher than classic polyester film. Specifically, both the use of caustic soda and the energy demand are the penalizing factors of the bio-based polyester film production, making it more disadvantageous compared to current production methods. In order to reduce this impact, the alternative of bio-based polyester film made with renewable energy is analyzed and it actually has a smaller value than bio-based polyester film, but still higher than traditional polyester.

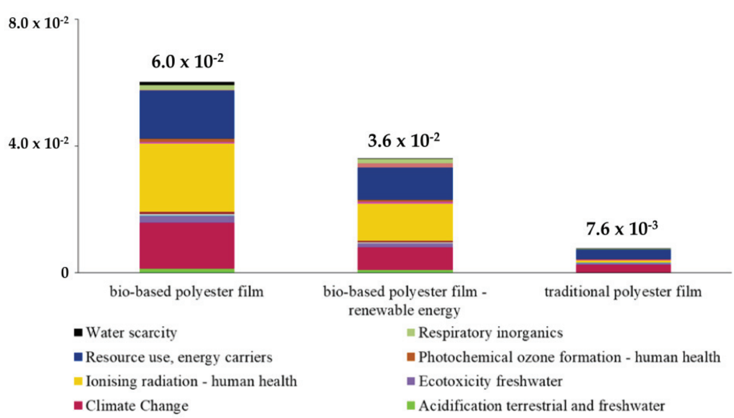

Figure 9. Normalization and weighing graphics of three different polyester production scenarios, expressed as p.e. The impact categories mentioned in the legend are the most relevant only. Functional unit: 0.3 kg of product.

From orange peel, a metal-adsorbent polymer is produced, whose equivalent on the market is activated carbon [58] (Figure 10). The adsorbent polymer has an EPI almost three times higher than the activated carbon production due to the use of organic solvents in the polymer production. The bio-based polymer made with green energy has a comparable impact to the bio-based polymer made with mixed energy: in fact, as well as for the wheat straw exploitation as lignin, the impact of the bio-based alternative is generated by the solvents use and the impact is not significantly reduced by changing the energy source.

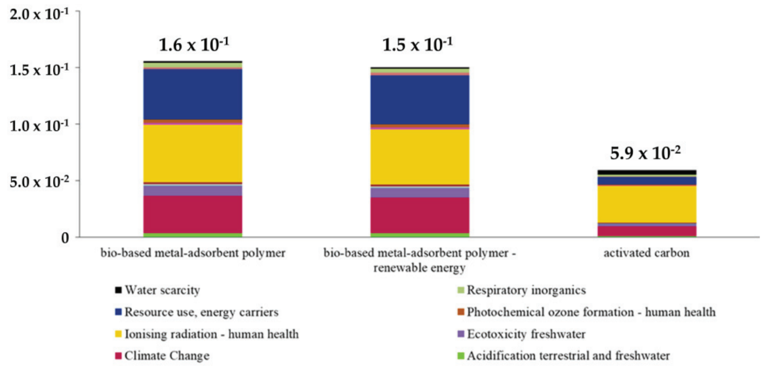

Figure 10. Normalization and weighing graphics of three different metal-adsorbents production scenarios, expressed as p.e. The impact categories mentioned in the legend are the most relevant only. Functional unit: 1 kg of product.

This comparison with the traditional methods shows that the bio-based alternative is more impacting than traditional processes; this result is mainly due to relatively high-energy demand and organic solvents use (as proved by the energy and raw material balances in Figures 2–4). Therefore, even though bio-based products are accessible and desirable alternatives, experimentation must proceed further to make these processes as beneficial as actual production methods.

4. Discussion and Limitation of the Study

The present study implemented an environmental sustainability assessment of innovative processes for the use of common Italian byproducts from agriculture sector. The assessed case studies were extracted from the scientific literature, implemented at lab-scale. Nevertheless, they were considered interesting for their proposal to use organic residues in a wide range of application fields. The data used for the implementation of the analysis can be considered of good quality since they were extracted from an international peer-reviewed journal. The additional assumptions implemented for the hypothesis of upscaling followed the literature methods. Comparable observations are carried out for the traditional products. The possibility to use data from wood handbook (for composite panel from rice straw) and from the average value of the Gabi database (for polyester film from tomato pomace) ensured high levels of representativity.

The present assessment shows some limitations:

- Zero burden approach for agricultural residues was used, effects of redirection of residue from today's application is not included.
- The effect of using other impact assessment methods or normalization sets was not evaluated. Nevertheless, the authors selected the updated method EF 3.0 (recommended by European Commission), which ensured the result validity.

5. Conclusions

The circular economy represents one of the main pillars that drive the choices of countries, all over the world, towards a sustainable development. As confirmed by the detailed study of the scientific literature and the GRASCIARI RIUNITI project, the development of circular strategies within the agriculture field is a primary concern. Nevertheless, this analysis proved that there is still a necessity to evaluate the proposed solutions combining technical/experimental aspects with environmental sustainability issues. More in detail, the LCA of five case studies highlighted some significant issues due to both the significant energy demand and the high impact organic solvents, despite the reduced organic agent demand assumed for the upscaling. The obtained results had not the target to discourage the development of alternatives for the agriculture residue enhancement, but rather to draw the attention to the environmental sustainability aspects. Indeed, an effective implementation of circular economy strategy should have a holistic view, able to consider the effect of the technologies in different environmental categories (as well as in social and economic spheres). In this regard, many aspects play an essential role (as also discussed in the European circular economy action plan and the European Green Deal), as the avoided use of toxic (for both human and environmental health) agents and the low energy demand. Overall, the implemented LCA proved the significant effect of the renewable energy transition and the current necessity to identify ecological agents for an effective environmentally sustainable production of BBP.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13073990/s1, Figure S1: Classification and characterization graphics of rice straw exploitation process. Functional unit: 1 kg of organic residue, Figure S2: Classification and characterization graphics of two wheat straw exploitation processes. Functional unit: 1 kg of organic residue, Figure S3: Classification and characterization graphics of tomato pomace exploitation process. Functional unit: 1 kg of organic residue, Figure S4: Classification and characterization graphics of orange peel exploitation process. Functional unit: 1 kg of organic residue, Table S1: Specific assumptions: comparable raw materials chosen to substitute the raw materials missing in the database, Table S2: Weight of each impact category on the normalization and weighing results. Functional unit: 1 kg of organic residue. References [66–76] are cited in the Supplementary Materials.

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