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Core Elements Affecting the Circularity of Materials

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Abstract: The authors have revised the circularity of materials, which is essential to stimulate circular activity processes. The theoretical part starts with the revision of material circularity under linear and circular models, and answers to the question of how to use modern technologies to ensure the sustainable use of natural resources. Later on, the authors describe the material circularity in the concept of close-loop and open-loop production. Further on, the authors examine the recycling of different waste categories as an essential element necessary for the circularity, give the results of reviewing various sectors and present key elements affecting material circularity. The authors revised the set of variables and formed a correlation matrix and used a dynamic regression model to identify the circular material use rate. The authors suggested a three-level methodology that provided a dynamic regression model that could be applied for forecasting the size of circular material use rate in European Union countries. The empirical research results show that the key elements affecting the circularity of materials are private investments dedicated for recycling, the recycling of electronic waste and other municipal waste.

Keywords: circularity of materials; recycling; regression model; key elements

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1. Introduction

Global consumption of fossil fuels, metals, minerals, and biomass is projected to increase over the upcoming few decades and by 2050. The annual waste generation will increase by as much as 70%. The extraction and processing of resources account for half of all CO_2 emissions, the loss of biodiversity is more than 90%, including water scarcity [1]. To tackle harmful natural processes, the European Green Initiative has announced a co-ordinated strategy for the improvement of climate, the efficient use of resources, and the competitiveness of economy [2]. The strengthening of the role of circularity will ensure the competitiveness of the EU until 2050 focusing on economic growth by the reuse of resources.

The circularity of materials is essential for sustainable development as it helps save resources and minimize the negative environmental impact [3]. The literature review shows that the circular loop is the main key element talking about the recycling of material. The other important condition impacting the circularity of materials is the product's design, allowing reuse of the material in the construction of other products later on or the extension of the product's lifetime. Not all materials are recyclable; many of them cannot be recycled. Many of the materials recycled today are being reduced, and recycling some materials requires more energy than new production [4].

Increased economic activity and consumption of raw materials have led to the dependence of many countries in the world, including the European Union (EU), on imports of materials and energy [5]. An additional consequence of increased human consumption is the significant jump in the amount of waste gathered, which is also an opportunity to solve the problem of materials (and partly energy) shortages [6,7].

The review of papers placed under Google Scholar shows that researchers rarely discuss the theme of material circularity under the literature on recycling. The literature review provided under Table 1 shows that only 0.3 per cent of the above papers give investigations in the research area. Of course, the attention to the topic was growing in the recent 2021–2022 years.

Table 1. Literature review.

			Theme of Material Circularity
Year	Literature on Recycling	Literature on Material Circularity	Under the Literature of Recycling
2016–2020	16,000	24	0.15%
2021–2022	7040	45	0.64%
Total	23,040	69	0.30%

Source: Constructed by authors, according to publications present in Google Scholar.

The objective of this paper is to theoretically revise and empirically identify possibilities allowing the increase of the circularity of material.

This paper consists of a literature review where main elements necessary for the circularity are revised, the concept of material circularity is presented, and recycling as the option for circularity is overviewed. Later, the empirical part is provided, which consists of the three-level methodology highlighting the circularity and the correlation matrix of variables, allowing to identify ones that could be used to construct regression equations to forecast the circular material use rate. Finally, discussions and conclusions are presented.

2. The Evidence of Material Circularity in Linear and Circular Models

According to a United Nations report [8], the population is projected to grow: by 2030 it will increase to 8.6 billion, then by 2050 it will increase to 9.8 billion, and by 2100, there will be 11.2 billion people on the planet. With an annual contribution of around 83 million people to the world's population, the population growth trend is expected to continue, even if the birth rate continues to fall [9].

The essence of a linear model is summarized as "take—make—dispose of" [10–13]: take the necessary resources, sell goods and make a profit and dispose of everything you do not need—including a product according to its life-cycle nearing its end. A traditional linear economy model is not sustainable; it is based on product development, consumption, and disposal. This model further reduces limited resources and generates large amounts of waste and emissions [14]. Rodríguez et al. (2020) emphasize that such linear model of production and usage depletes natural resources and generates waste, but the environment does not have unlimited capacity to absorb waste and pollution. According to Di Maio and Rem (2015), it is necessary to rethink the use of materials according this model because, by following modern technology, not all stocks of basic materials seem to be sufficient in maintaining the contemporary life quality.

Authors [15–18] note the need to build a sustainable society transforming the current linear "take-make-dispose" economy into a waste-free community. It is, therefore, necessary to move to a model that will ensure material circularity.

Elisha (2020) has carried out a study on increasing the sustainability of the market by moving away from over-consumption and resource use in traditional take-do-throw practice (linear model) to use (circular model) practices.

According to the authors [17,19–21], in the transition from one model to another, products should be developed according to the definition of circular business modeling, and traditional business modeling processes should identify the necessary changes in existing product design practices.

According to Oghazi and Mostaghel (2018) and Michelini et al., 2017, the adoption of circular business models is associated with product design that must meet life prolongation and multiple-use conditions ensuring material circularity. Zucchella and Previtali (2019), Lieder and Rashid (2016), and Bocken et al. (2016) note that the new products are more robust, more adaptable, and have a more comprehensive range of properties and are specially designed to be extendable, recyclable and remanufacturable.

The potential for material savings from the European industry's shift to a more resource-efficient model is estimated to be EUR 500 billion a year [22–25]. The strategic benefits [11,26,27] of the circular model approach are reduced by the risk of price volatility and supply disruptions, the potential of new technologies (to improve the productivity of resources, the substitution of materials, the management of waste, including recycling activities), direct and reverse supply chain and operations optimization cycles and business modelling. The reverse operations are quite important for recycling activity, supporting materials' circularity.

In their work, the authors Bocken et al. (2016), Stahel (1994), and Stahel (2010) distinguish and describe three resource cycles: closing the resource loop, slowing the resource loop, and narrowing the resource loop. A 'closed-loop system' distinguishes between two fundamentally different types of cycle: (1) reuse of products, and (2) recycle of materials [17,28,29]. Reusing products means recovery of the extension of the items' period through the designing of durable goods. To expand the existing one, the lifetime of products, including the reuse of products, repair, renewal, technical upgrading, and service loops are introduced. The reuse of goods and the life extension of products has several relationships with time, and the result has slowed the flows of materials from manufacturing to recycling.

According to Morseletto (2020), recycling is the treatment of materials to a different quality of material: high quality, which is the same as it was before processing, or lower quality. Worrell and Reuter (2014) note that the recycling of discarded materials/products results in materials that are called secondary materials. Recycled materials can also be recycled, a process in which materials are transformed into materials of higher quality and uniform/increased functionality, or vice versa when the quality of a product is reduced. Recycling should be the most appropriate solution to prolong product life and improve value and quality, but not all products can be recycled, and recycling is not possible in all cases [30–32].

The second cycle involves the recycling of materials, which means loops between waste after recovery and closure of production. According to the authors [13,21,33,34], these two key strategies focus on three resource cycles:

(1) Closing of resource loops: A circularity of materials occurs when processing closes the loop between use and production.
(2) Slowing stock loops: t. y. service loops adapt the design of services and products and extend the life of products when goods are repaired or recycled, thus slowing down resource flow. These several approaches differ from the last one aiming to reduce the flows of materials.
(3) Minimization of resource flows (or the increase of the efficiency of resources) per product loop aims to increase material productivity, improve asset utilization and use fewer materials.

To increase the use of products, products are recycled, secondary materials are used, and the reuse, repair, refurbishment, and production of products ensure several life cycles, thus closing material loops [35–37]. It increases the product's longevity, prolongs its service life, and exploits the possibilities of reuse and repair, thus extending the material cycle. Narrowing the loops of materials involves a variety of efforts to achieve resource efficiency by increasing the productivity of materials throughout the product value chain and expanding the sharing and service economy [38–40]. These characteristics are presented in Table 2 below.

Table 2. Key characteristics of circular models.

	Closing the Resource Loop	**Slowing the Resource Loop**	**Narrowing the Resource Loop**
Features	Recycling; Product repairing and remanufacturing	Product life extension; Product reuse and repair	Increased material productivity; Improved asset utilization; Individual behavior changes
Main effects	Decreased demand for primary materials; Increased use of secondary materials	Decreased demand for primary materials; Better quality and durability of materials in goods	Decreased demand for primary materials; Expanded sharing
Solution examples	Subsidies for the retrieval of secondary materials through recycling	Extended producer responsibility; Implemented product design standards	Implemented resource efficiency standards

In Table 2, the authors have presented the slowing, closing, and narrowing of loops oriented to the circularity of materials, distinguishing features and main effects, and provide solution examples.

3. Material Circularity under the Concepts of Closed and Open Loops

By applying the principles of material circularity [11,41,42], it is expected that by 2030 0.5% of EU-wide GDP could increase EU GDP and create around 700,000 new jobs. Closed-loop models can increase the profitability of EU producers and protect them from fluctuations in resource prices, as, on average, about 40% of their materials are spent in the EU [43,44].

The current circular package [45] introduces a new phase: covering the whole life cycle of a substance/product, from its production processes, the use of products, the management of waste, its disposal as required, to the recovery of materials. This stage is described as the concept of a life cycle "closure cycle" [46–48]. The advantage of the "closing the loop" stage is that resources, materials, and products circulate in the product life cycle from production to end-of-life, thus enabling them to retain their material value, energy, and economic value in the economy for as long as possible [49].

The circularity and the concepts of closed-loop production have some features in common. It is widely accepted that both ideas cover reverse material flows through return systems, recycling, repair, reclamation, recycling, and reuse [17,33]. The circularity, meanwhile, is defined through economic growth, the promotion of renewable energy, and the concepts of 'recovery' and replenishment. It should be noted that the concept of a closed-loop can also be understood through material circularity, as a broader concept of loop closure is compatible with the implementation of eco-design [34,50].

'Closed-loop' recycling is when secondary materials are recycled back into original products, and 'open-loop' recycling is when secondary materials are employed to make new things different from previous products [35].

In Figure 1, the traditional linear model "take—make—dispose of" with more detailed steps and the closed-loop model, which include the circularity of material, are presented.

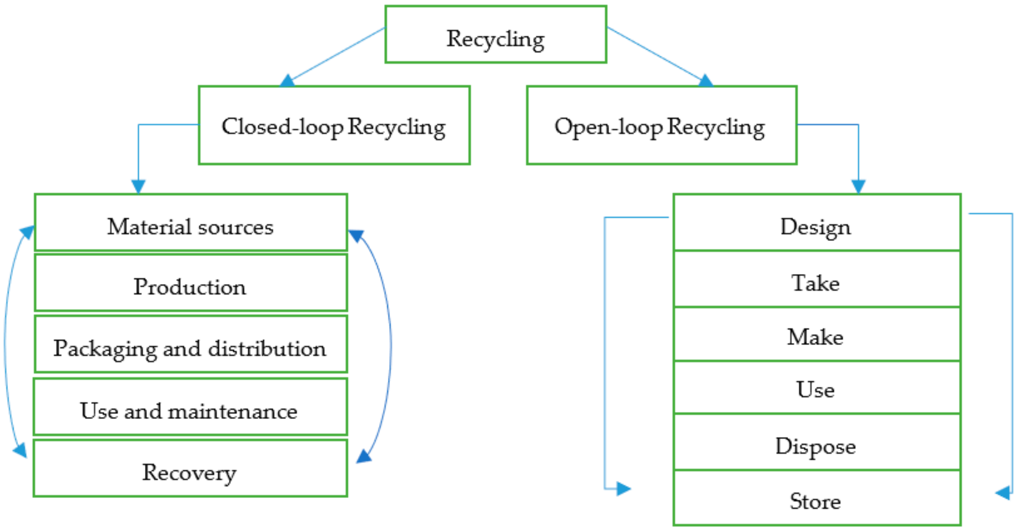

Figure 1. 'Closed-loop' and 'open-loop' recycling.

When recycling occurs in the same closed or another available product system, we are talking about closed-loop or open-cycle recycling; different aspects have to be taken into consideration [51,52]. Closed-loop recycling is when a secondary product is returned to a previous process in the same system, where it directly replaces the direct manufacturing costs of the same materials [53,54]. Open-cycle recycling occurs when at least some secondary goods are used in various systems [53,54]. According to the statements mentioned above, to achieve the objectives, priority should be given to closed-loop solutions over open-loop solutions, as transport and collection in third countries are skipped, and the manufacturing process can process recycled raw materials with no additional energy. However, Geyer et al. (2016) and Haupt et al. (2017) note that recycling is the preferred activity for material circularity. The authors also mentioned that 'closed-loop' recycling is not necessarily better than 'open-loop' recycling [49,55–57]. The possibility of reducing environmental impact is a better principle for setting material circularity targets [55,56]. According to this principle, goals have to be explicitly defined for different products/materials/industries.

4. Recycling Activity Is Preferred for Material Circularity

A system that follows ten strategies for circular activity (i.e., recover, recycling, repurpose, remanufacture, refurbish, repair, reuse, reduce, rethink, refuse) is used. According to Lingaitienė and Burinskienė (2021), three blocks of general circular activity strategies are distinguished. R0 refuse, R1 rethink, and R2 reduce are included in the products' more innovative use and production. Product life extensions include R3 reuse, R4 repair, R5 refurbish, R6 remanufacture, and R7 repurpose. Applicable materials include R8 recycle and R9 recover [57–60]. In this paper, we will examine several of them.

The problem of dependence on material imports can be alleviated to some extension by involving activity of recovering materials from waste [61]. EU waste policy focuses on reducing waste management's health and environmental impact and improving efficiency of resources. The hierarchy of waste, which states recycling as the preferred recovery option for waste, aims to extract more materials.

The recyclability and quantification of the various types of waste are highly dependent on the recyclability of technical goods and an understanding of how the result, which we will call 'recycled,' is to be defined [62,63]. In some cases, the amount of separately collected recyclable materials is considered 'recycled'. These different methods make the comparison of recycling rates not easy and even meaningless, as any step in the waste/recyclable recycling chain from collection to the efficient substitution of raw materials causes losses in quantity and thus reduces circularity rates in practice [64]. For example, due to the same recycling situation associated with waste streams, the recycling rate could range from 40% to 80%, depending on different reporting rules for recycling rates.

When waste is recycled, secondary resources gathered from materials that might be similar to waste cease to be waste (the end of waste—abbreviation EoW) and otherwise, they are included into commodity [65,66]. The transition from waste to commodity could enter into process in which the secondary materials become waste. Another possibility is that the EoW state is reached before a specific function using the appropriate secondary resources. In this situation, the secondary substance must meet precise EoW quality specifications, the marketing criteria for chemicals applicable to any other primary importance [67].

Facilitating and promoting recycling through the reduction of natural resources, the removal of waste going into disposal, and seeking high level environment protection are objectives of defining EoW criteria and retrieving materials from specific waste streams that can be traded freely on the open market scope [65,68]. Many factors can be revised when determining waste cases to end as waste or become product when it is challenging to recycle certain wastes. Particular specified wastes end up being waste after recovery (including recycling) and meet specific criteria under the following conditions: 1. the substitute product is generally used for specific purposes; 2. the market is available for a particular material; 3. the material complies with technical requirements, and 4. the use of the material has no negative effect. EoW status is classified as waste when it meets all four criteria [69,70].

Recycling of waste helps to meet high rates of material circularity by recovering the material using various approaches, including the implementation of innovative ways.

5. Elements Affecting Circularity

The take-it-or-throw-out linear model does not incentivize manufacturers to make their products more circular, even though up to 80 percent of a products' environmental effect is determined during its design phase. Many products break down quickly, are for single use only, and are not easy to reuse, repair, or recycle. At the same time, the single market sets product sustainability standards and influences the design of products and the management of the value chain world-wide.

The authors [17,18,20,22,24,37,71] point out that companies which adopt to ring economy (CE) at the strategic company level should think about designing products and modelling business activities.

The circular activity seeks sustainable leadership that will gradually become the norm to use resources efficiently, reduce waste and make products climate-neutral. The following are principles of sustainability for leadership in the circular activity [11,41,42,72]:

- product sustainability, reuse, improvement and repair, removal of hazardous chemicals from products, energy and resource efficiency;
- increasing the number of processed products, ensuring their operation and safety;
- creating conditions for re-production and quality processing;
- reducing carbon footprints in the environment;
- restriction of single-time use products and prevention of premature aging;
- introduction of a ban on the destruction of unsold durable goods;
- maintaining the ownership or responsibility of manufacturers for the operation of the product throughout its life cycle;
- product digitization, involving such solutions as digital passports, marking, and watermarks.

According to Velenturf and Purnell (2021), in a circular activity, resource use is improved by minimizing the extraction of natural resources, maximizing waste prevention, and optimizing the social, environmental, material-focusing, and economical values throughout the lifecycles of materials, components, and products.

The circular activity relied heavily on the 3R Principles: Reduce, Reuse and Recycle [58,72,73]. Using 3R principles, we aim to optimize production to use fewer natural resources and reduce pollution, emissions and waste.

Following to Ciulli et al. (2020), the recovery of waste depends on establishing links in the operations so that operators with products at risk of becoming waste can pass it on to those who could use it as raw material or for their consumption. However, this use of waste is often influenced by the lack of communication between waste generators and potential recipients, i.e., "circularity holes" [74–76].

In Table 2, the authors singled out the effects of different types of waste on the circular activity. The indicator defining circularity in the municipal solid waste category is energy recovery from municipal solid waste (MSW). This recycling process has several important aspects, such as a positive environmental impact, as it saves primary energy from fossil fuels and the benefits of the power itself from recycled municipal solid waste.

Waste of electrical and electronic equipment (WEEE or e-waste) requires strategic planning based on the principles of circular activity to return e-waste to new production cycles. This method implies measures that allow the anthropogenic system to re-import waste into new natural or technological processes, creating environmental, social, and economic benefits [13].

Inorganic wastes such as plastics, metals, glass, rubber and textiles cannot decompose and be reused in nature. Most household and commercial waste is collected by garbage trucks and taken to a landfill or a waste recycling plant, where all collected waste is sorted, treated and processed into a semi-finished or finished product.

Organic waste is organic and biodegradable and can be decomposed; food waste collected from households and catering establishments, vegetable market waste, yard waste, grass, plant, and animal waste. Such waste can be composted, naturally converted into a stable product, compost-rich in essential nutrients. Compost is a popular organic fertilizer that is a much cheaper alternative to conventional but expensive inorganic fertilizers.

In the above stated Table 3, the authors revised the types of waste dedicated to circular activity that were used by other authors for their research, emphasizing that reuse and recycling are two of the most critical strategies for the practical application of the circular action (CE) and for assessing the efficiency of waste management in different types of waste.

Table 3. Types of Wastes affecting circularity.

Type of Waste	Effect of Waste	Authors
Municipal waste	The effect is defined via interactions with municipal waste management to use waste for energy, improvement of urban environment	[3,77–94]
E-waste or WEEE (waste electrical and electronic equipment)	E-waste is a hazardous for human health and environment. Circularity reduces harmful effects of e-waste	[3,90,91,95–100]
Inorganic waste (paper/cardboard, plastic, metal, glass rubber, leather, textile)	Minimizes inorganic waste which issues inorganic pollution, greenhouse effect and other environmental pollutions	[1,11,19,86,94,101–107]
Organic waste (food, wood, agricultural)	Effect is positive and associated with the additional organic load supplied for composting	[1,11,12,19,29,84–87,89,91–95,108]

In Table 4, the authors have identified three dominant groups that influence the circular activity regarding product design, environmental friendliness, and commercial products components. In each group, characteristic subgroups are recognized and mentioned by different authors in the scientific literature.

Table 4. Elements affecting circularity.

Group	Effect of Elements' Group on Material Circularity	Elements Affecting Circularity	Authors
Designing	Ensures product and packaging integrity and longevity	Eco-designing	[71,79,81,103,104,108–114]
		Product designing	[71,72,79,99,101,103,108,109,112,113,115–120]
		Designing for environment	[109,110,114,121]
		Green product designing	[110,121,122]
		Designing for product integrity	[71,112]
		Designing for sustainability	[79,99,108–111,113,116,120,121]
		Closed-loop sustainable product design	[72,108,118]
		Designing for multiple use cycle	[113]
		Circularity supporting designing	[71,72,101,103,109,112,113,116–118,123]
		Designing driven innovation	[101,108,118]
		Future proof designing	[112]
		Designing for disassembly	[112,118]
		Designing for maintenance	[103,108,112,116]
		Designing for durability	[103,108,112,116,117]
		Packaging designing	[110,118,119,121]
		Product-service system designing (PSS)	[109,112,123]
		Designing for recovery	[103,113,116]
		Designing for remake and recycling	[103,108,112,115,116,124]
Environmentally friendly	Ensures innovations and approaches have a positive effect on environment	Eco-industrial approach	[80,81,83,99,120,124–126]
		Industrial and territorial ecology approach	[81,99,104,120,124,125,127,128]
		Sustainable circular activity	[80,82,83,111,120,124–127,129]
		Zero waste orientation	[1,95,99,101–106]
		Green (circular) economy focus	[99,130]

Table 4. *Cont.*

Group	Effect of Elements' Group on Material Circularity	Elements Affecting Circularity	Authors
Environmentally friendly	Ensures innovations and approaches have a positive effect on environment	Green supply chain management	[104,114,122,125,126,128,129]
		Eco-innovation approach	[83,104,110,114,126–130]
		Environmental innovation implementation	[80,82,126,128]
		Sustainable innovation implementation	[114,126,128,131]
		Green innovation implementation	[104,114,122,127–129]
Ecological economic	Ensures investments and recycling	Circular activity system/model application	[71,79–83,103,110–112,115,118,125]
		Private investment	[80,132–137]
		Circular business model	[103,108,109,112,113,116,123–126,128,131]
		Resource/responsible consumption	[80–83,99,104,108,114,120,122,125,126,128,130,131]
		Extending the duration of use/prolonging product life cycle	[71,103,108,109,112,116,128,130]
		Processing industry	[115,138–140]
		Recycling	[71,79–83,99,103,104,108,110,112,115,117,118,124,128–130,139]
		Renewable energy/resources/materials	[71,79–83,99,103,108,114–116,118,122,128,129,139,140]

In Table 4, the main groups are divided into subgroups. It is noteworthy that more and more research is proving that the field of designing is the most important in moving a circular activity forward. By researching key elements, the authors leave out the recycling of municipal waste element.

The designing offers functional systems, tools, and strategies to implement circular design principles. For example, a design that looks to the future slows down the flow of products and ensures that products are used for longer. Following den Hollander et al. (2017), the basic concepts oriented to circular product designing include several fundamental principles of products' integrity and designing for recycling means that the product will not become obsolete and will be able to recover the highest value. He also describes many design strategies when creating longevity: designed maintenance and refurbishment and planned refurbishment and repair.

In the interests of sustainable environmental and economic development, the circular activity is proposed as a way of economic growth. In Table 4, the authors have classified the literature according to the focus topics. The concept of an environmentally friendly one is loosely based on a set of fragmented ideas derived from some disciplines, including new fields and semi-scientific concepts. These sources include, for example, eco-industrial, industrial and territorial ecology, sustainable circular activity, green (circular) economy focus, green value chain management, implementation of eco-innovation, environmental innovation, green innovation and other directions.

In Table 4, the authors have identified three components that embed the circular activity: design, ecology and economics. Economics in the context of the circular movement has to be talked about from the ecological view, so the researchers also presented subgroups of the ecological economy in the table. The environmental economy is a new field that has been separated from the area of the ecological economy and is treated as a new field. The authors note the importance of private companies investing in reuse projects and the importance of reusable management of ownership and business modeling. The unique role of private investment in developing and managing the waste system, which has a positive impact on climate change, is emphasized.

To achieve climate-neutral effects and long-term competitiveness, it should be noted that turnover is an important part of a more comprehensive industrial transformation. It significantly saves materials in value chains and manufacturing processes, creating added value and opening economic possibilities. The challenge of sustainability posed by key value chains calls for urgent, comprehensive, and coordinated action to respond to climate emergencies.

The authors analyzed the effect of crucial product consumption on waste: electronics and ICT, batteries vehicles, packaging materials, plastics, textiles, construction outputs, food, water and nutrients. Table 5 briefly describes the environmental impact and consumption amounts of these products.

Table 5. The effect of product consumption by waste category.

Category	Essential Description	Authors
Electronics and ICT	The current annual growth rate of electrical and electronic equipment is the fastest growing waste stream in the EU, at 2%, and less than 40% of electronic waste is recycled. The value is lost if fully or partially functional products are discarded because they cannot be repaired.	[56,141–150]
Batteries and vehicle	The increase of battery circulation in the transport sector is the key to future mobility	[56,144,145,149–151]
Packaging	Packaging waste in 2017 in Europe reached a record 173 kg per capita. To reap the economic benefits of packaging, by 2030 the aim is for all packaging on the EU market to be reused or recycled.	[56,144–146]
Plastics	Trends show that plastic waste will double over the next 20 years, leading to a global response to plastic pollution through the initiatives in the circular activity strategy.	[56,96,144,145,148]
Textiles	Only less than 1% of all textiles worldwide are recycled into new textiles. Given the complexity of the textile value chain, the aim is to strengthen industrial competitiveness and innovation, promote the EU market for sustainable and circular textiles, the market for textile reuse, and develop new business models.	[56,96,145,152–155]
Construction and buildings	More than 35% of all waste in the EU is generated in the construction sector. A total of 5–12% of total EU GHG emissions come from extraction, construction products, building construction, and renovation materials.	[56,144,145,151]
Food, water and nutrients	The circular activity can significantly reduce the negative environmental impact of extraction and exploitation of natural resources.	[56,144,148,154]

Despite efforts, waste is not declining, generating EUR 2.5 billion a year from all economic activity in the EU. The amount measures in tons, or 5 tons per capita per year. Much effort will be needed to decouple waste generation from economic growth throughout the value chain in every living place.

6. Materials

The circularity of materials involves production and recycling operations. In pursuit of sustainable development, this study aimed to identify critical practical actions in decision-making.

Various stakeholders take decisions:

- Manufacturers who select which materials to use in commodities and to what extent, what production methods should be used;
- Consumers who use sorting and product reuse practices;
- Waste collection service providers sort the waste and identify circular materials.

The authors of this paper constructed the methodology from three levels highlighting the materials' circularity (see Table 6).

Table 6. Three-level methodology highlighting the circularity of materials.

Level of Analysis	Relationship to the Circularity of Materials	Description of the Circularity of Materials	Application of Methods	Link with Sustainability Approach
1st level Use of circular materials	The physical system supports the production and the increase of the circularity of materials.	Choice of methods is followed to prolong the shelf life of substances.	Review of literature; Investigations.	Such a solution helps to reduce the negative effect towards environment.
2nd level Effect of private investments	The private investments are used to support the circularity.	Involvement of private investments is required to support the development of circularity.	Panel data analysis; Regression analysis.	Investments supporting sustainability.
3rd level Evidence in waste	The physical system supports circularity via waste collection.	We are sorting during the collection of waste.	Panel data analysis; Regression analysis; Comparison.	Allows to return for reuse and to save natural resources

Table 6 presents a summary focusing on the increase of the circularity of materials indicated by the above presented methodology, providing relationships, their description and application of methods identified for each level separately.

For the empirical research, we use following indicators:

(1) Trade-in recyclable raw materials;
(2) Patents focusing on recycling and secondary raw materials;
(3) Private investments, jobs, and gross value added related to circular activity sectors;
(4) The recycling rate of e-waste;
(5) The recycling rate of municipal waste;
(6) Other recycling and general waste generation indicators.

7. Methods

Eurostat (2021) data for the years 2000–2019 were obtained from 32 European countries (27 countries of the European Union, islands, Norway, the United Kingdom, Serbia, and Turkey). There was a total of 6642 datasets with values.

In the paper, the authors refined the collected data, by using it with a formed matrix of correlation coefficients, and further on used only those elements with a probability of less than 0.1 for the regression model (Table 7). The study's novelty is defined as the authors developed a dynamic regression model analyzing effects in different years t and t-n. The authors used the approach suggested by Petris et al. (2009) [155–157].

Table 7. Correlation matrix for the variables which are transformed into dlog.

Indicators	Abbreviation	Statistical Indicators	Circular Material Use Rate
Patents related to recycling and secondary raw materials	DLOG(PATNTS)	Corr. Coefficient	−0.174
		Probability	0.282
	DLOG(PATNTS(-1))	Corr. Coefficient	−0.085
		Probability	0.601
Private investment, jobs, and gross value added related to economy sectors	DLOG(PRINV_CIRC)	Corr. Coefficient	−0.057
		Probability	0.725
	DLOG(PRINV_CIRC(-1))	Corr. Coefficient	−0.279
		Probability	0.081
Recycling of biowaste	DLOG(REC_BIOW)	Corr. Coefficient	−0.072
		Probability	0.659
Recycling rate of e-waste	DLOG(REC_EW(-1))	Corr. Coefficient	−0.474
		Probability	0.002
Recycling rate of municipal waste	DLOG(REC_MU)	Corr. Coefficient	0.021
		Probability	0.897
	DLOG(REC_MU(-1))	Corr. Coefficient	−0.034
		Probability	0.834
	DLOG(REC_MU(-2))	Corr. Coefficient	−0.371
		Probability	0.019
The recycling rate of packaging waste by type of packaging	DLOG(REC_PCW)	Corr. Coefficient	0.130
		Probability	0.424
	DLOG(REC_PCW(-1))	Corr. Coefficient	0.110
		Probability	0.500
Recovery rate of construction and demolition waste	DLOG(RECOV_CNSTR)	Corr. Coefficient	−0.213
		Probability	0.186
	DLOG(RECOV_ CNSTR(-2))	Corr. Coefficient	0.042
		Probability	0.799
Trade-in recyclable raw material	DLOG(TRD_REC(-1))	Probability	−0.039
		Corr. Coefficient	0.809
Generation of municipal waste per capita	DLOG(MUNW)	Probability	0.024
		Corr. Coefficient	0.884
	DLOG(MUNW(-1))	Probability	−0.94
		Corr. Coefficient	0.565

The methodology has some steps:

1. Transforming the time series to help determine the dependent variable;
2. The dynamic relationships with the regressors is defined;
3. The model is constructed and validated by using Durbin-Watson statistics.

The authors formed a dynamic regression model to estimate the circular material use rate size.

The authors identified the regressors in constructing mathematical equations. The mentioned equation is placed below (1):

$$circ_t = \beta_0 + \beta_1\, prinv\_circ_{(t-n)} + \beta_2\, rec\_ew_{(t-n)} + \beta_3\, rec\_mu_{(t-n)} + u_t \quad (1)$$

where:

$circ_t$—dlog of circular material use rate in year t, measures in percentage the share of material recycled and fed back into reuse;

β_0—intercept in the equation;

$prinv\_circ_{(t-n)}$—dlog of private investments, jobs, and gross value added related to economic sectors;

$rec\_ew_{(t-n)}$—dlog of recycling rate of electrical and electronic waste, in year t−n;

$rec\_mu_{(t-n)}$—dlog of recycling rate of the municipal waste, in year t−n, the tonnage recycled from municipal waste divided by the total municipal waste arising;

u_t—random error of regression model;

$\beta_{1,2,3}$—the influence of regressors on the circularity of materials processing reflected the coefficients of elasticity.

8. Results

The results of the correlation investigations are presented in the table below by providing correlation coefficient and probability for each pair of variables.

Table 7 presents the results of the correlation investigations performed for the study, noting the strength of the correlation between the core elements provided in above mentioned table. The constructed table demonstrates the relationship between the circular material use rate and other indicators. Table 7 shows that the circular material use rate has links with two recycling rate indicators (specifying municipal waste in the second year and electrical and electronic waste in the third year) and private investments indicated in the previous year.

The results demonstrate that the residuals of the formed equation spread by following normal distribution (Figure 2). The statistics provided with the Figure 2 show that the mean is approaching zero.

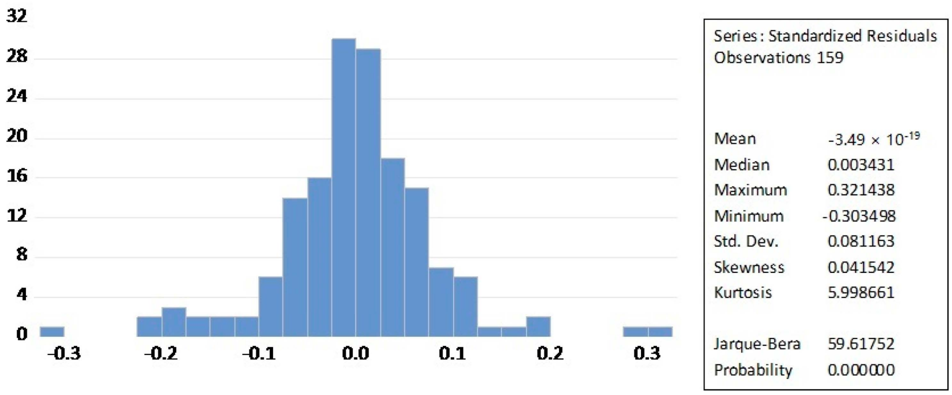

Figure 2. Equation residuals spread.

Figure 2 presents that the average of residuals approximates zero.

The forecasting of volumes generated due to the circularity of materials is shown in Figure 3 under the curve fitted. In Figure 3, the curve represents actual values of circular material use. The third curve dedicated to residuals shows the same results as in Figure 2 that the residuals of the equation are approximate to zero.

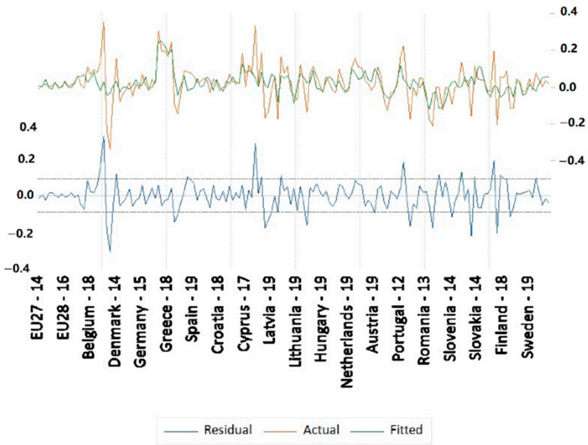

Figure 3. Forecasting the recycled biowaste level by the European Union countries.

The equation of the dynamic regression model is placed below (2). The authors identified coefficients of the equation and standard error:

$$\underset{}{circ_t} = \underset{(0.009)}{0.03} - \underset{(0.107)}{0.261}\ prinv\_circ_{(t-1)} + \underset{(0.05)}{0.105}\ rec\_ew_{(t-3)} - \underset{(0.048)}{0.115}\ rec\_mu_{(t-2)} \quad (2)$$

Seeking to summarize concrete values for the dynamic regression model (2), the authors used the panel least squares method and reached results that are demonstrated in Table 8, where the Durbin-Watson statistic is 1.76.

Table 8. Formation of coefficients for Equation (2) by using panel least squares revision method.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.030	0.009	3.202	0.002
DLOG(PRINV_CIRC(-1))	−0.261	0.107	−2.435	0.016
DLOG(REC_EW(-3))	0.105	0.050	2.114	0.037
DLOG(REC_MU(-2))	−0.115	0.048	−2.367	0.020
Root MSE	0.081	R-squared		0.332
Mean dependent var	0.022	Adjusted R-squared		0.149
S.D. dependent var	0.099	S.E. of regression		0.092
Akaike info criterion	−1.751	Sum squared resid		1.041
Schwarz criterion	−1.075	Log likelihood		174,187
Hannan-Quinn criter.	−1.476	F-statistic		1.815
Durbin-Watson stat	1.759	Prob(F-statistic)		0.010

The application of the method identifies that the R squared is 0.33. The statistical validity is tested by applying the Lagrange multiplier tests. The tests present the correct statistical validity.

Also, the authors performed Redundant Fixed Effects tests and tested cross-section and period fixed effects (see Table 9).

Table 9. Formation of Equation (2): panel least squares revision method.

Effects Test	Statistic	d.f.	Prob.
Cross-section F	1.565	−24.124	0.060
Cross-section Chi-square	42.081	24	0.013
Period F	0.885	−71.24	0.520
Period Chi-square	7.754	7	0.355
Cross-Section/Period F	1.457	−31.124	0.077
Cross-Section/Period Chi-square	49.395	31	0.019

The probability of the Chow test is lower than 0.05 and shows that the fixed evaluation method is chosen correctly. The constructed equation could be used to forecast the circular material use rate.

The authors constructed a correlation matrix and used a dynamic regression model to determine the use rates of ring materials. The dynamic regression model is presented according to the three-level methodology proposed by the authors. This model can be applied to predict the use of circular materials in European Union countries, which other researchers have not studied.

9. Discussion

The circularity of material management involves various aspects. These activities must focus on product design, consumption, and waste management. In the article, the authors present crucial elements that help improve materials' circularity.

Most of the authors cited in this paper state that waste is not an option. So, the studies should focus on how to improve the quality of the decisions to manage and recover materials over time.

By revising the studies, the authors identified that the recycling of municipal waste element is not highlighted as an important one. The authors extended the study and revised many other elements from municipal waste categories. The study shows which elements had an effect on the circularity of material and identified this effect in terms of years. Where private investments into patents are evident the next year, the effect of recycling municipal waste is evident in two years and the effect of recycling e-waste is seen in three years. Based on these effects, the authors constructed the dynamic regression equation.

For sustainable development, the authors point to the need to create and expand activities, apply approaches, and implement innovations in production, supply chain management, and consumption areas. In addition, sustainable development seeks to address the integrated approach to environmental and ecological aspects that lead to long-term effects.

The development of sustainable activities is crucial for environmental protection. Reducing the overall negative environmental impact of production and consumption helps to reach results in all types of waste streams, especially municipal waste. Therefore, the article discusses sustainable practices such as improving material circularity.

10. Conclusions

The links and interdependencies between the circularity of materials and waste recycling are a new topic that other authors have not addressed so far. The article also discusses the essential elements of material circularity. The authors compiled the literature review to investigate aspects of material circularity and found that many key features could be included in the research.

10.1. Practical Implications

The authors identified aspects of the materials and their recycling possibilities. This article reveals that municipal waste is strongly and directly related to the circular material use rates. Emphasis is also placed on the design of the material, which plays a role in achieving sustainable development. The authors provided a methodology that identifies the points of connection between key elements and material circularity. The second level of the methodology was investigated mathematically to determine the links between private investments and the improvement of material circularity. The third level of the method is dedicated to waste. To recycle waste, reverse supply chain and logistics seem to support the circularity of material and its collection from consumers. The authors identified three levels of analysis. The authors found that the relationship between the components identified above is essential. The study has some practical implications: the results of the study could be used for policy formation, which aims to minimize the negative effect on the environment and allocates funding in the form of subsidies for such activities seeking to stimulate higher material circularity.

10.2. Limitation of Research

The study has some limitations: the authors do not revise the survival of materials; they identify opportunities to increase material circularity use rates and provide a dynamic regression model to forecast this.

10.3. Future Direction of Study

Further research could assess the impact of specific materials and production methods on improving circular material use rates. The study could also be extended to other countries and include a review of their practices. The authors were also able to compare the elements and define which of them could give better results on material circularity.

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