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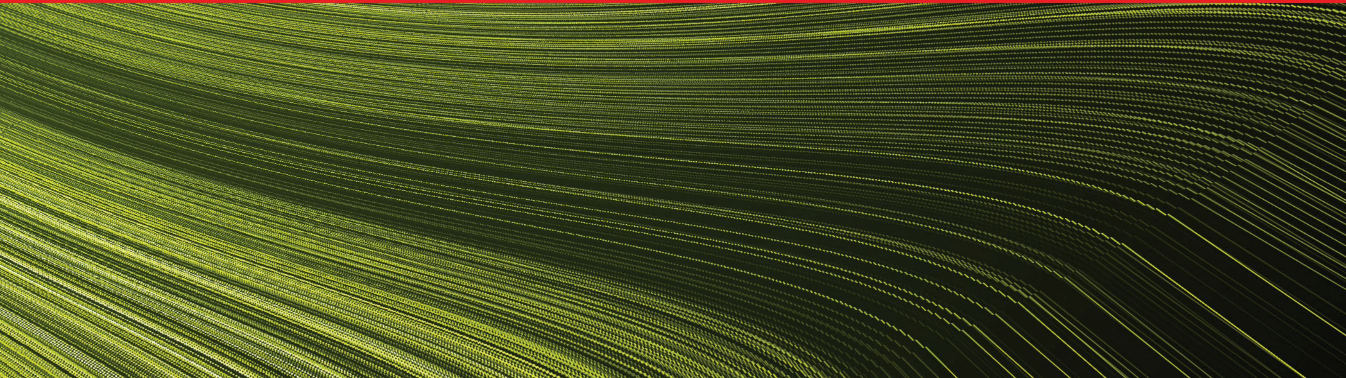
The Circular Economy

Recent Advances in Sustainable Waste Management

Edited by Tao Zhang



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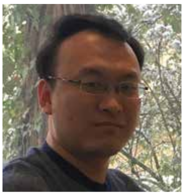
Meet the editor



Dr. Tao Zhang is an Associate Professor and Ph.D. supervisor at the College of Resources and Environmental Sciences, China Agricultural University, China. His academic interests are waste management, wastewater treatment, and utilization of agricultural waste. His H-index is 25 (Scopus) and he has published more than 60 papers in journals including C*hemical Engineering Journal, Water Research, Journal of Hazardous Materials, Green Chemistry*, and *Renewable and Sustainable Energy Reviews*, of which 11 are ESI Highly Cited Papers and 4 ESI Hot Papers. He has more than 20 Chinese patents to his name. He is an awarded Chinese scientist. Among his awards are the Outstanding Young Scientist Award, the China Innovation Award for Industry, the University Research Cooperation of China, the Character Award, and the Invention and Entrepreneurship Award of the China Association of Inventions.

Contents

Preface

In recent years, rapid economic and social development has increased the consumption of natural resources and the generation of solid waste, and the contradiction between economic development and environmental resources has become increasingly complex. The circular economy is a general term for the reduction, reuse and recycling activities carried out in the process of production, distribution, and consumption. It is a new economic development model that provides a new way of thinking to solve the contradiction between resources and the environment, and economic growth. The specific practice of the circular economy started in the late 1980s and early 1990s. In 2016, the United Nations marked a comprehensive stage in its development and practice with the implementation of the Global Sustainable Development Goals (SDGs) for 2030. Many new meaningful and systematic practices were introduced, and the various SDG policy measures provide a reference for China to enhance the level and capacity of its solid waste management through the development of the circular economy. The core of the theory of the circular economy, and the key to the achievement of environmental goals, is to turn waste into resources. The main recycling routes for waste worldwide can be broadly categorized as biological treatment, material recycling, incineration and power generation, and landfill. In order to achieve the goal of sustainable waste development, we must take a number of measures and policies to stimulate and promote development.

1. Strengthen top-level design and continuously promote reduction, recycling, and non-hazardousness

In solid waste management, we should systematically assess the applicability of existing national and local systems, and review the effectiveness of mechanisms, the operability of models, and the compatibility of standards and management policies, in accordance with the Law on the Prevention and Control of Solid Waste Pollution, the Law on the Promotion of Cleaner Production, and the Law on the Promotion of the Circular Economy. The prevention and control of solid waste pollution, in order to establish “waste-free cities”, requires us to gradually promote the transformation from end-of-pipe treatment to front-end ecological design and green manufacturing, systematically and continuously promoting the reduction, resourceful use, and harmless disposal of solid waste.

2. Improve the indicator system and establish an indicator monitoring system

Dynamic monitoring data are needed for key categories of solid waste such as domestic waste, plastic packaging, electronic waste, biomass waste, and construction waste. These can be adjusted dynamically to include relevant indicators that more scientifically and rationally reflect the reduction, resourcefulness, and harmlessness of solid waste, and to achieve tracking and monitoring of solid waste generation, utilization, and disposal. Key data measurement methods based on material flow analysis should be established to monitor typical national and regional resource utilization in terms of input, use, recycling, and emissions. This indicator system can both reflect progress in the reduction, resourcefulness, and non-hazardousness of solid waste, and also be used to forecast future solid waste generation.

The sustainable waste management goals remain a long way off. The key to their achievement lies in the construction of a complete and systematic resource cycle system; only through this approach can we truly be seen to be practicing the implementation of the Sustainable Development Goals.

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Section 1

Introduction

Chapter 1

Introductory Chapter: The Overview of Recent Advances of Sustainable Waste Management

Yingyu Zhang, Yingqi Niu and Tao Zhang

1. Introduction

Circular economy is the abbreviation of closed-loop flow economy [1], which is an economic development model consisting of 'resources-products-renewable resources' and repeated circulation of materials [2]. Its basic characteristics are low exploitation, high utilization and low emission. The basic code of conduct is the '3R' principle: 'reduce,' 'reuse' and 'recycle.' The three principles of circular economy constitute the basic development idea of the circular economy. The principle of reduction belongs to the input-side approach, which refers to the reduction of resource consumption and waste generation in the process of production, distribution and consumption [3]. Its specific requirements are to fully consider saving resources, improving the utilization rate of resources in the production process of unit products and preventing waste generation on the input-side of the production source [4]; while in the production process, through technological transformation, advanced production processes and clean production to reduce the use of raw materials and emissions of pollutants of unit products in the production process [5]. The principle of reuse belongs to the process approach, which means that the waste is directly used as a product or continues to be used as a product after repair, refurbishment and remanufacturing, or all or part of the waste is used as parts of other products. The principle of reuse requires the establishment of a standardized recycling mechanism for waste materials [6]. Recycling led by producers and operators can encourage and guide consumers to return the items they no longer need to the market system and then safely participate in the new economic cycle [1]. The principle of recycling (also called resource utilization) is the input-side approach, which refers to the direct use of waste as a raw material or the recycling of waste. If it cannot be reused as raw material, it should be heat recycled [4]. There are two ways of resource utilization: firstly, primary resource utilization, which means that the waste abandoned by consumers is recycled to form a new product identical to the original; secondly, secondary resource utilization, which means that the waste is transformed into raw materials of other products and then produced into a different type of product [7]. The order of the three principles of circular economy is reduce–reuse–recycle.

The circular economy not only forms a complete structure within its system but also combines the environment and economy in a close and clever way [8]. A circular economy should adapt to the natural ecosystem cycles and utilize these in economic cycles by respecting their reproduction rates (**Figure 1**). In terms of quality, circular

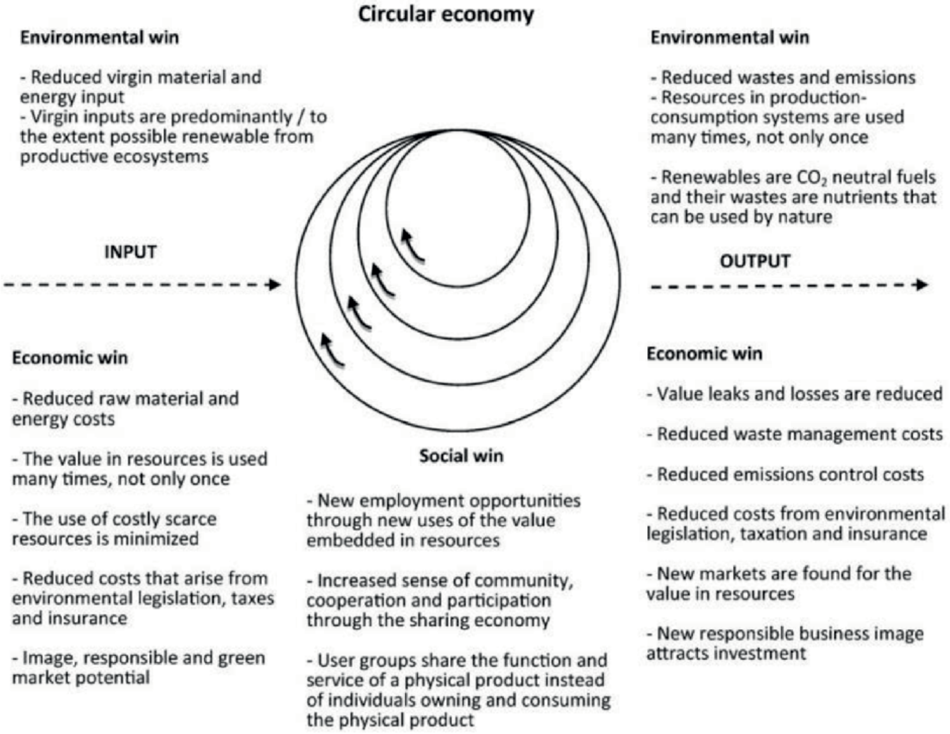

Figure 1.
Circular economy for sustainable development [9].

economy is obviously superior to any single environmental protection measure in both environmental technology and economic technology [10]. At present, the technical means to help the development of a circular economy [6], especially for solid and liquid waste treatment are relatively mature [11, 12]. Many researchers began to focus on the application of laser-induced breakdown spectroscopy [13], as well as the recycling economy method of utilizing the waste after seawater desalination by botanical methods [14]. In the context of carbon neutrality [15], the use of biochar [16, 17] and organic matter [18, 19] is of great concern. Using the idea of circular economy to utilize biochar can not only reduce the waste of resources but also have a beneficial impact on mitigating climate change and improving soil remediation [20, 21].

The circular economy is a major change in the process of economic development, and a new economic form based on the law of energy flow and material circulation of the natural ecosystem, which makes the economic system is integrated into the cycle of the natural ecosystem, and the two promote each other's development [22]. The important idea of a circular economy is to realize sustainable development and establish a production process that realizes comprehensive recycling of resources and waste through clean production [23]. The starting point of the circular economy is to protect the ecological environment [24]. The improvement of scientific and technological innovation is to promote the development of the circular economy while promoting the ecological protection of the environment, and scientific and technological innovation will also bring more green products and create more green consumption methods, which is an important means to protect the environment and promote ecological development [25]. From the principles of circular economy to the methods of using circular economy ideas to the benefits brought by circular economy ideas, this is a closed-loop industry and also the development direction of the new era.

2. Conclusion

Recycling is a critical step in the promotion of the circular economy to translate wastes into new resources and acts as a connection bridging the production and consumption arenas. The motivation behind the development of the circular economy is to mitigate the severe conflicts between economic growth and resource shortages and pollution. We should continue to start from the actual development of the circular economy. According to the 'reduce, reuse, recycle' principle, to promote the construction of circular industrial system, resource recycling industrialization, green consumption and the formation of the whole society's resource recycling system; through demonstration actions, key projects, demonstration cities, demonstration enterprises and parks, the construction of urban mineral demonstration base, improve the efficiency of resource utilization, prevention of environmental pollution at source. Promote green cycle, low-carbon development, ecological civilization, and promote the transformation of economic development.

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References

[1] Morseletto P. Targets for a circular economy. Resources, Conservation and Recycling. 2020;**153**:104553

[2] Schroeder P, Anggraeni K, Weber U. The relevance of circular economy practices to the sustainable development goals. Journal of Industrial Ecology. 2019;**23**(1):77-95

[3] Beccarello M, Di Foggia G. Moving towards a circular economy: Economic impacts of higher material recycling targets. Materials Today: Proceedings. 2018;**5**(1):531-543

[4] Domenech T, Bahn-Walkowiak B. Transition towards a resource efficient circular economy in Europe: Policy lessons from the EU and the member states. Ecological Economics. 2019;**155**:7-19

[5] Mathews JA, Tan H. Circular economy: Lessons from China. Nature. 2016;**531**(7595):440-442

[6] Amato A. The circular economy challenge: Towards a sustainable development. Sustainability. 2022;**14**(6):3458

[7] Ezeudu OB, Agunwamba JC, Ugochukwu UC, et al. Circular economy and frugal innovation: A conceptual nexus. Environmental Science and Pollution Research. 2022;**29**(20):29719-29734

[8] Luttenberger LR. Waste management challenges in transition to circular economy–case of Croatia. Journal of Cleaner Production. 2020;**256**:120495

[9] Stahel WR. The circular economy. Nature. 2016;**531**(7595):435-438

[10] Shaheen SM, Antoniadis V, Shahid M, et al. Sustainable applications of rice feedstock in agro-environmental and construction sectors: A global perspective. Renewable and Sustainable Energy Reviews. 2022;**153**:111791

[11] Wang Y, Zhang T, Westerhoff P, et al. Microwave-assisted digestion and NaOH treatment of waste-activated sludge to recover phosphorus by crystallizing struvite. Environmental Technology. 2017;**38**(10):1211-1222

[12] He X, Zhang T, Ren H, et al. Phosphorus recovery from biogas slurry by ultrasound/H2O2 digestion coupled with HFO/biochar adsorption process. Waste Management. 2017;**60**:219-229

[13] Fadeeva Z, Van Berkel R. Unlocking circular economy for prevention of marine plastic pollution: An exploration of G20 policy and initiatives. Journal of Environmental Management. 2021;**277**:111457

[14] Preisner M, Smol M, Horttanainen M, et al. Indicators for resource recovery monitoring within the circular economy model implementation in the wastewater sector. Journal of Environmental Management. 2022;**304**:114261

[15] Zhang P, Wang H. Do provincial energy policies and energy intensity targets help reduce CO_2 emissions? Evidence from China. Energy. 2022;**245**:123275

[16] Fang C, Zhang T, Li P, et al. Phosphorus recovery from biogas fermentation liquid by Ca–Mg loaded biochar. Journal of Environmental Sciences. 2015;**29**:106-114

[17] He X, Zhang T, Niu Y, et al. Impact of catalytic hydrothermal treatment and Ca/Al-modified hydrochar on lability, sorption, and speciation

of phosphorus in swine manure: Microscopic and spectroscopic investigations. Environmental Pollution. 2022;**299**:118877

[18] Li H, Zhang T, Shaheen SM, et al. Microbial inoculants and struvite improved organic matter humification and stabilized phosphorus during swine manure composting: Multivariate and multiscale investigations. Bioresource Technology. 2022;**351**:126976

[19] Zhang T, Wu X, Shaheen SM, et al. Effects of microorganism-mediated inoculants on humification processes and phosphorus dynamics during the aerobic composting of swine manure. Journal of Hazardous Materials. 2021;**416**:125738

[20] Shaheen SM, Mosa A, El-Naggar A, et al. Manganese oxide-modified biochar: Production, characterization and applications for the removal of pollutants from aqueous environments-A review. Bioresource Technology. 2022;**346**:126581

[21] Fragkos P. Analysing the systemic implications of energy efficiency and circular economy strategies in the decarbonisation context. AIMS Energy. 2022;**10**(2):191-218

[22] Geissdoerfer M, Savaget P, Bocken NMP, et al. The circular economy–A new sustainability paradigm? Journal of Cleaner Production. 2017;**143**:757-768

[23] Korhonen J, Honkasalo A, Seppälä J. Circular economy: The concept and its limitations. Ecological Economics. 2018;**143**:37-46

[24] Corvellec H, Stowell AF, Johansson N. Critiques of the circular economy. Journal of Industrial Ecology. 2022;**26**(2):421-432

[25] MacArthur E. Towards the circular economy. Journal of Industrial Ecology. 2013;**2**(1):23-44

Section 2

Microscopic Study

Chapter 2

Use of Saline Waste from a Desalination Plant under the Principles of the Circular Economy for the Sustainable Development of Rural Communities

Lorena Cornejo-Ponce, Patricia Vilca-Salinas, María J. Arenas, Hugo Lienqueo-Aburto and Claudia Moraga-Contreras

Abstract

In the region of Arica and Parinacota, Chile (South America), concerned about the environment, the use of brine from a reverse osmosis plant was considered as irrigation water, which is generally discharged into the sea, sewers, or nearby rivers. In this sense, the integrated management of this waste was studied under the 3 principles and 11 strategies of the circular economy, for which it will be used to produce halophilic fodder (*Atriplex nummularia*), supporting the sustainability of livestock farmers in the sector. As for the results, it was estimated that with 86,400 Lh-1 in 20 days of brine, 400 *A. nummularia* plants would be irrigated, with an energy consumption of 31,319 kWh per day, through a photovoltaic system. In addition, of the 11 strategies of the circular economy, this study complies with 9 of them. It is noteworthy that the combination of brackish water desalination technologies and solar energy to produce *A. nummularia* would avoid the production of 1.5 tons of CO_2. Finally, this study opens potential opportunities for future research, for the implementation of this type of project in rural communities, considering an optimization in the management of saline waste and water.

Keywords: circular economy, halophytes, brine, management of resources

1. Introduction

Climate change is already present and will continue to change, affecting societies and the environment [1]. This occurs directly through changes in hydrological systems that are influencing water availability, water quality, and extreme events, and indirectly through changes in water demand, which in turn can have impacts on energy production, social and environmental damages, food security and the economy, among others [2]. On the other hand, communities have increased pressure on water resources, seeking new alternatives to mitigate the lack of this vital element. Among these alternatives is desalination technology, which is a solution to this problem [3], considering that the planet earth is 97.3% saltwater [4] and 2.5% freshwater [5]. However, in spite of being a solution that is becoming more and more common, this technology generates some environmental problems. On the one hand, it generates a product water or desalinated water that can be treated to be suitable for human consumption or irrigation, adding the necessary minerals, and on the other hand, a saline stream called brine that is generally disposed of in the sea, causing serious environmental problems [6]. It is estimated that for every 1 m^3 of desalinated water, between 0.3 and 1 m^3 of brine is generated [7]. Considering that the global product water capacity from seawater desalination plants as of 2020 was 9.72×10^9 m^3/d [4] and according to the above estimate, in the same year, there have been between 2.92×10^9 and 9.72×10^9 $m^3\ d^{-1}$ of brine. According to Ihsanullah 2021, reusing and recycling brine is presented as a good alternative to minimize the negative impacts it produces, being favorable on a small scale. However, he indicates that more work is needed to assess the feasibility of brine treatment in commercial or larger desalination plants [8].

On the other hand, today's economy is based on a circular model, which assumes that resources are abundant and that one must "take-make-consume-reuse." Therefore, given the large amount of brine produced today, reutilization is a matter of principle that is strongly linked to the circular economy [9]. In that sense, wastewater such as brine is a valuable water, energy, and material resource; therefore, it is essential to manage its use and final disposal, following strategies of reduction, reuse, recycling, recovery, restoration, and regeneration, among others of the circular economy [10]. In addition, it is worth noting that the idea of circular economy through business models that encourage reuse and recycling can be very relevant for arid regions [11], where water is a valuable resource for basic needs such as drinking and sanitation, or for irrigation.

The agricultural sector uses 70% of the world's water and is one of the most important sectors for human beings. According to the WHO, it is estimated that by the year 2050, the demand for food products will be approximately 70% higher than today, as a result of population growth [12]. On the other hand, FAO, in its reports "The State of Food and Agriculture," indicates that 1.2 million people live in agricultural areas with high levels of water stress and 520 millions of them live in rural areas [13]. In addition, special attention is paid to agri-food systems, where food-producing families engaged in small-scale agriculture are increasingly being put to the test due to the lack of water for irrigation [14]. These potential effects on agriculture are mainly due to climate change, which could lead to regions with increased salinization and desertification in arid areas of South American countries such as Chile and Brazil [15].

The Arica and Parinacota region is located in northern Chile and has arid characteristics. Although this region has available water resources such as the Lluta River or Camarones River, this water is limited and of poor quality due to high concentrations of arsenic, boron, and total dissolved solids (TDSs) [16] that exceed standards such as NCh 409.Of1.2005 for "drinking water" [17] or NCh 1333.Of1978mod1989 "water for irrigation" [18]. This condition limits their use to only a few crops such as corn, tomatoes, alfalfa, among others. Also, the soils of the Lluta Valley and the Camarones Valley, where these rivers are located, are affected by the poor quality of their waters, causing a lack of crop diversification [19]. This condition considerably affects the agricultural and livestock production sector and the local community. One of the most important crops in this region is alfalfa production, which is the main feed for bovines and goats [16]. On the other hand, there is *Atriplex nummularia*, a halophyte shrub with protein characteristics similar to alfalfa, which could be an alternative for crop diversification [20].

Consequently, to mitigate this lack of water in quantity and quality, research on desalination technologies for water production is being carried out at the Universidad de Tarapacá (Arica and Parinacota region). To this end, a desalination plant has been implemented for the production of drinking water or irrigation. However, one of the problems generated by this type of plant was what to do with the brine produced. Considering this question, this work is expected to evaluate the use of brine for the production of halophytes (*A. nummularia*) considering the principles of circular economy in the region of Arica and Parinacota.

2. Desalinization

Desalination is a process of removing dissolved salts and other minerals from seawater or brackish water, resulting in freshwater and a subproduct called brine [21, 22]. Seawater desalination is an alternative that can extend water supplies beyond what is available in the hydrological cycle, with a constant and climate-independent supply [23]. The main desalination technologies include thermal methods such as multistage flash distillation (MSF) and multi-effect distillation (MED) and within membrane methods, reverse osmosis (RO). These desalination technologies commercially cover almost 90% of the world market. RO processes lead with a 53% share, followed by thermal technologies with 33% [24], and RO is a technology that has lower energy requirements, low complexity and, therefore, lower economic cost [25]. This technique requires electrical energy to activate a high-pressure pump, whereby the saline water is forced through semipermeable membranes to separate the freshwater (or product) from the saltwater (brine) [26]. However, despite the benefits offered by desalination, it is still an environmental challenge to consider the disposal of coproduced brine to mitigate the environmental impacts attributed to discharges into the environment. Generally, brine is discharged to the sewer or to the sea [27]. Currently, desalination technologies are also applied to treat the large amount of brine generated in these processes, which can be by electrodialysis [28] or by membrane distillation crystallization (MDC) [29], among other alternatives, in order to recover a greater volume of product water.

On the other part, being RO the most widely used technology, its performance depends largely on the type of membrane, which have a pore size <1 nm, allowing the passage of small molecules such as water and rejecting larger species such as Na^+, K^+, Cl^-, or dissolved organic compounds. In that sense, there are several studies that seek to improve and optimize the membrane material to generate higher permeability, better selectivity, and anti-incrustant properties [30].

2.1 Brine disposal methods

The most commonly used methods of brine disposal are i) discharge to the sea (surface and through multiport diffusers installed on the deep sea floor), ii) disposal in sewers (wastewater collection system, low cost and energy), iii) injections into deep wells (injected into porous subsurface rock formations), iv) injections into deep wells (injected into porous subsurface rock formations) (v) sewage disposal (wastewater collection system, low cost and energy), (vi) deep well injections (injected into porous subsoil rock formations), (vii) land applications (irrigation of salt-tolerant crops and grasses), and (viii) evaporation ponds (evaporation of brine in ponds, salts accumulate at the base of the pond) [7]. In addition, when selecting the disposal technology, it is important to consider the location, quality, and volume of the brines [31].

2.1.1 Land applications

Among these applications, irrigation of crops with a concentrated solution of salts is a great solution in these times, considering that currently there is low-quality water available and that there is an increase in temperature worldwide, which is causing a greater demand for irrigation water [32], which is why having water, even if it is saline (brine), is a benefit to be considered.

Generally, the use of brine in sprinkler irrigation is common in parks, lawns, and golf courses, and also, in the cultivation of forage plants, which require low volumes of this solution. However, its use is limited for large volumes due to climatic conditions, plant size, seasonal demand, and depending on the stratigraphic and structural conditions where the subway aquifer is formed [33].

There are studies of halophyte plants such as *Arthrocnemum macrostachyum*, which indicate that this plant has a high capacity to desalinate soils. To this end, through an experimental analysis and under non-leaching conditions, soil salinity was reduced after 30 days of treatment by 31% (from 10.94 to 7.5 dS m^{-1}), regardless of whether the plant had been previously grown in the presence or absence of salt [34].

The means by which halophytes sequester salts and the degree of salt absorption differs according to plant species affect the efficiency of their use for remediation of affected soils. Halophytes have many productive applications: rehabilitating degraded lands, preventing desertification, providing firewood and timber, creating shade and shelter, and producing industrial crops and animal fodder. Halophytes can be grown on soils too saline for normal crops and pastures, from inland soils to soils near the sea, and thus can make a significant contribution to food security for living things [35].

Considering the above, it can be evaluated that this type of brine from desalination plants, when used in irrigation, presents advantages and disadvantages, which are described as follows:

Advantages

- Water availability (for irrigation).
- No environmental impact if brine is used for irrigation.
- Inland desalination plants compared to plants located in sectors avoid marine pollution.
- Soil degradation or seepage into groundwater is avoided if brine is added directly through injection from deep wells.
- Its use in aquaponics would allow to produce fish and at the same time to nourish the plants through an aquaculture recirculation system.

- There are plants that are tolerant to salinity (halophytes).
- Low capital cost by reusing the brine directly for irrigation of halophytes.
- Allows remediation of saline soils.

Disadvantages

- Not all plants are tolerant to high salinity concentrations.
- Risk of soil contamination if irrigated soils are microporous such as clay or silt soils.
- Not applicable for large volumes.

2.2 Brine disposal cost

One of the main problems in the installation of desalination plants is the cost of brine disposal, which is usually very high, ranging from 5 to 33% of the total cost of the desalination plant [7].

In addition, this cost depends on factors such as concentrate characteristics, treatment prior to disposal, disposal method, environmental regulations, location, concentrate volume, among others. It is also important to consider that the economic and environmental risks would be reduced if there is good management of brine use and final disposal. Así como también, es importante considerar que los riesgos económicos y ambientales se reducirían si existe una buena gestión del uso y disposición final de la salmuera [31].

2.3 Regulations applicable to brines

It is worth mentioning that among the few existing regulations worldwide, the Mexican regulation is a good option to start controlling the start-up of desalination plants and their waste. In this regulation called "PROY-NOM-013-CON AGUA/SEMARNAT-2015: that establishes specifications and requirements for intake and discharge works to be complied with in desalination plants or processes that generate brackish or saline rejection water," it indicates that it has 11 parameters and whose maximum limits include temperature, pH, total dissolved solids, turbidity, aluminum, copper, cadmium, among others. However, it does not refer to the main compound within the brine, NaCl [36].

Currently in Chile, there are no specific regulations related to desalination plants, as well as no regulatory system that considers the maximum concentration of brine expressed in NaCl, (mg L^{-1}) or salinity (dimensionless), or for the temperature (°C) for its final disposal, there is only a guide with minimum technical guidelines for desalination projects related to the jurisdiction of the maritime authority prepared by DIRECTEMAR [37] which includes desalination projects that may or may not be submitted to the Evaluación de Impacto Ambiental (SEIA) [38]. Cornejo-Ponce, et al. 2020 [7] proposed that both salinity and temperature, which are essential parameters, should have their upper limits expressed as follows: for salinity, the concentration should be less than or equal to that of the receiving mass. For example, if discharged into the sea, it should be lower than the salinity of the sea (35 mg L^{-1}), and for temperature, it should be considered approximately 2°C higher than that of the

Item	Equation	Definition
Charge balance	$Q_a = Q_p + Q_s$ (1)	
Rejection factor (R)	$R = (C_a - C_p)/C_a \times 100$ (2)	Corresponds to the rejection of salts from the membranes and in a membrane system, and it is the factor that determines the final quality of the product water of a distillation system.
Salt passage (SP)	$SP (\%) = 100 - R$ (3)	It corresponds to the ratio between the salt concentration of the product and the feed, measured as a percentage.
Conversion (Y)	$Y (\%) = Q_p/Q_a{*}100$ (4)	It corresponds to the percentage ratio between the permeate flow rate and the water flow rate entering the desalination process.
Concentration factor (CF)	$CF = 100/(100- Y)$ (5)	Corresponds to the number of times the brine is concentrated with respect to the feedwater.

Table 1.
Calculations involved in the desalination process [39, 40].

receiving mass, respecting the 2015 Paris agreement. In addition, once these parameters have been established, the different alternatives for their elimination can be evaluated.

2.4 Brine concentrate calculation

The calculations involved in the desalination process (**Table 1**) and specifically for obtaining the amount of brine produced consider a concentration of feedwater C_a (Kg m^{-3}), product water C_p (Kg m^{-3}), and brine C_s (Kg m^{-3}), as well as a flow rate of feedwater Q_a (m^3 h^{-1}), product Q_p (m^3 h^{-1}), and brine Q_s (m^3 h^{-1}) [39, 40].

3. Circular economy and brines

3.1 Why apply circular economy?

The world is changing; the economic, environmental, and social challenges facing today's society are becoming increasingly demanding. In this sense, the principle of the "circular economy" is a good way to make this approach more sustainable [39]. Whereas, over the past 10 years, private/public sector actors, governments, policymakers, citizens, the media, and the scientific community have been working to make the world more sustainable [41], changing the economic model from extract-use-dispose to an extract-use-reuse model. Thus, the circular economy seeks that system resources, energy, and materials are reused several times, considering a minimum processing for each subsequent use, through a closed loop. In other words, turning waste into a resource is an essential part of increasing our efficiency and moving toward a more circular economy [8].

In relation to the circular economy in water, in addition to complying with the reuse of this good, its quality and quantity must be prioritized [42]. Therefore, evaluating brine disposal management measures is an alternative to consider, depending on factors such as: (a) the volume or quantity of the concentrate, (b) quality of the concentrate, (c) physical and geographic location of the discharge point, (d) capital and operational costs, among others [43].

3.2 Circular economy principles

In addition, it is worth mentioning that the Office of Agricultural Studies and Policies, 2019 [44], proposed 3 principles and 11 strategies of circular economy, based on the World Economic Forum, 2018. Each principle is related to the strategies defined as follows:

Principle 1 Plan for the optimal use of resources

Design (R1): Integrate environmental impact in the development of products and services.

Reduce/Prevent (R2): Avoid use of unnecessary resources and prevent waste generation.

Optimize (R3): Maximize the usefulness of products, materials, resources, and assets.

Principle 2 Maximize the usefulness of materials at all times

Reuse/Distribute (R4): Take advantage of discarded or old products in good condition so that they fulfill their original function.

Repair (R5): Repair defective or old products to fulfill their original function.

Remanufacture (R6): Capture the value of components of discarded products to fulfill an original function, a new product.

Revaluate (R7): Transform discarded products, parts, or waste to condition a new function by capturing the value of materials.

Recycle (R8): Process materials to obtain products of equal or lower quality.

Recover (R9): Energy recovery by incineration of materials.

Principle 3 Preserve and improve the natural capital

Regenerate (R10): Regenerate natural ecosystems to promote positive impact on the environment.

Supply (R11): Procure sustainable supply of inputs with the least environmental impact.

3.3 Use of brine in halophyte plant cultivation under the principles of circular economy

The use of brines in saline agriculture can be beneficial, as it reduces the current demand for food production and maximizes water resources and the use of saline soils in accordance with the three principles of the circular economy (optimizing resources, maximizing the utility of materials, and preserving natural capital).

Today, it is possible to find salt-tolerant crops such as halophytes. These plants have developed a series of physiological and morphological adaptations that allow their tolerance to salt, and although they represent only 2% of terrestrial plant species, their domestication and cultivation in a context of saline agriculture may be interesting to consider [45].

Among the halophyte plants is the forage shrub *A. nummularia* (**Figure 1**), which grows in conditions of high salinity, requires little water, and has similar chemical properties to alfalfa. Despite being a shrub native to Australia, it is also grown in Chile, mainly in the north and can reach 3.5 m in height, is a common forage species in arid and semiarid regions, due to its tolerance to drought and salinity, can grow or can be planted in soil and/or saline water, and is also used as feed for bovine livestock [46].

In addition, there are studies in Brazil where they have cultivated forage plants irrigated with brine (obtained from RO), indicating that the yield for *A. nummularia* was 5.5–8.5 t. ha year^{-1}. The amount produced from the halophilic plant using brine is much higher than the value obtained in other arid parts of South America where it is grown as a wild crop [20, 47].

Figure 1.
Forage crop Atriplex nummularia *[46].*

4. Methodology

To achieve the objective of this work, it is proposed to follow the following flow chart of the research methodology to be carried out (**Figure 2**). For this purpose, the use of water from the Luta River, feedwater to be treated in the reverse osmosis desalination plant, from which product water and brine are obtained, is considered.

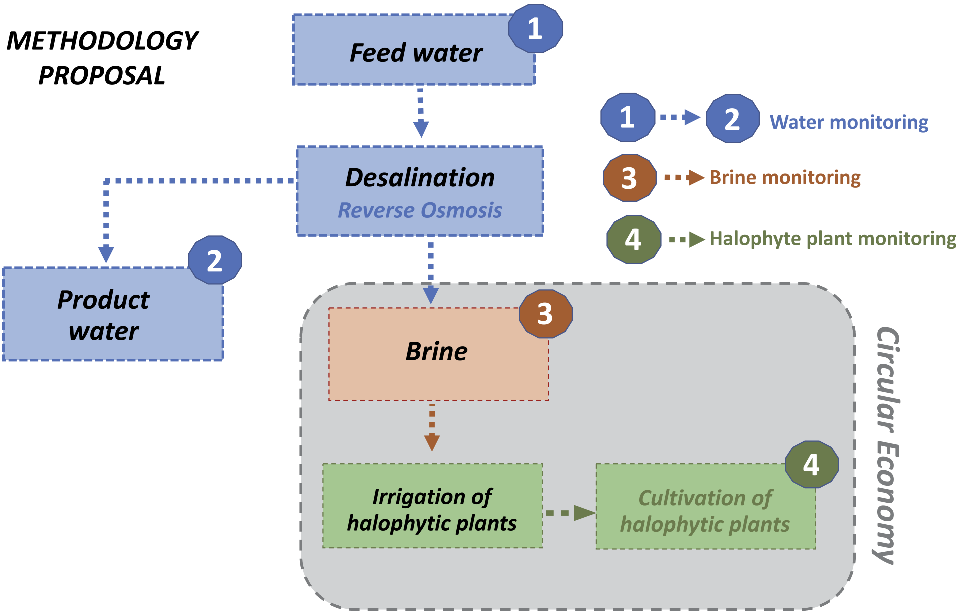

Figure 2.
Methodology for the use of brine for the production of halophyte plants (proper elaboration).

The latter is the subject of this publication. For this, according to the existing brine disposal factors, it is proposed as an alternative to minimize the potential environmental impacts to apply the 3 principles and 11 strategies of circular economy [44] for the cultivation of halophyte plants (*A. nummularia*).

In addition, the methodology is based on mathematical calculations to obtain information on flow rate and brine concentration, feed flow, among others, according to formulas in item 2.5 calculation of brine concentrate, considering the factors that influence brine disposal [43].

4.1 Reverse osmosis plant location

The reverse osmosis plant is located at the *"Plataforma Solar de Investigación y Entrenamiento: Tecnologías Solares para el Tratamiento de Agua"* at the Universidad de Tarapacá, city of Arica, in the region of Arica and Parinacota whose georeferencing is −18.4725111 latitude and − 70.3127704 longitude [48]. Among the activities developed in this platform is the applied research in solar water treatment, where several technologies have been implemented to obtain water, among which is the reverse osmosis; however, as mentioned earlier, the problem with this technology is: What to do with the brine generated?

4.2 Feedwater quality

The feedwater for the reverse osmosis plant was obtained from the Lluta River, which was transported by truck, in order to study real samples to generate information to support the rural communities that live in and use this water directly for their crops, limiting their diversification. The parameters used to determine the quality of the Lluta River feedwater were temperature, conductivity, pH, and total dissolved solids (TDSs). These were measured with a multiparameter apparatus (model HI 9828, HANNA Instruments, USA). The concentration of arsenic was also determined using the VARIAN FS 280 VGA 77 atomic absorption equipment with hydride generation and 950°C electrothermal blanket, which were analyzed according to international standards [49] at the Laboratorio de Investigación Ambiental de Zonas Áridas, LIMZA, of the Universidad de Tarapacá (Arica, Chile).

4.3 Soil quality in the lower Lluta River sector

To evaluate the quality of the soil in the sector adjacent to the Lluta River, samples were taken to determine parameters such as, texture, organic matter, pH, electrical conductivity, arsenic, available phosphorus, and total nitrogen, which were analyzed according to international standards [49] and the recommended methods of analysis for Chilean soils of the Comisión de Normalización y Acreditación (CNA), 2004 [50] at the Laboratorio de Investigación Ambiental de Zonas Áridas, LIMZA, of the Universidad de Tarapacá (Arica, Chile).

4.4 Reverse osmosis desalination plant characteristics

The pilot plant under study in this work corresponds to a reverse osmosis desalination plant, Wave Cyber Vessels, Model 300E 4" Side Port Housing, with 300 PSI (21 bar) maximum pressure, 49°C maximum temperature, −7°C minimum

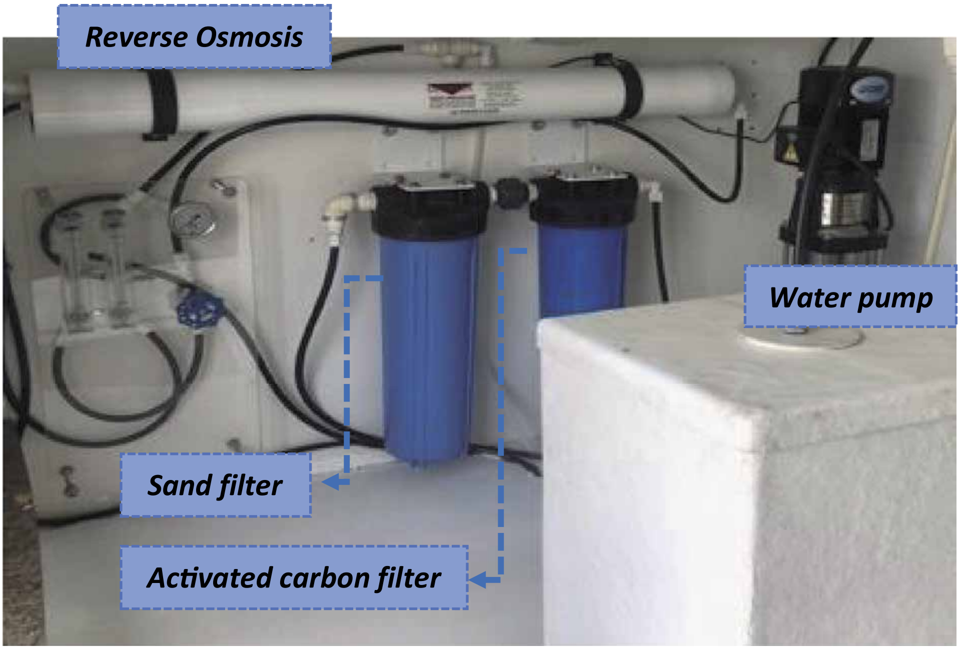

Figure 3.
Reverse osmosis plant (proper elaboration).

temperature, and dimensions of 328.2 cm in length. The product water yield is 360 L h^{-1} and the rejection factor is 50% brine [51].

The feedwater passes through a water pump first passing through sand and activated carbon filters, respectively. The 5-micron cartridge filter retains sediment (sand, sludge, and oxidation particles) to obtain clean water, and the granular carbon filter retains bacteria, chlorine, odors, and organic chemicals.

Subsequently, by reducing salts and compounds that can clog the membrane, it enters the osmosis system where arsenic and salts are reduced (**Figure 3**).

4.5 Application of the circular economy

The use of brine as irrigation water for the cultivation of halophytes (*Atriplex munmularia*) will be evaluated, considering the 3 principles and the 11 strategies of circular economy, taking into account point 3.2.

5. Results

5.1 Characterization of the water quality of the Lluta River

The Lluta River, located in the Lluta Valley, is a water system in which the physicochemical characteristics vary seasonally, mainly in summer due to the altiplanic summer rains. In addition, there are variations at different points along its course due to the presence of minor tributaries. The concentration of arsenic is notable, exceeding 29 times the value recommended by the WHO (10 mg L^{-1}) [52]. **Table 2** presents the physicochemical parameters of the Lluta River water.

Physicochemical parameters	Lluta River water values	NCh409/1.Of2005 drinking water	NCh1333. of 1978 Mod.1987 water for irrigation	Unit
pH	7.69	6.5 – 8.5	6.0 – 9.0	—
Electrical conductivity	1.52	—	—	$mScm^{-1}$
Temperature		—	30	°C
Chloride	528.1	400	200	mgL^{-1}
Sulfate	1,389	500	250	mgL^{-1}
Sodium	31.15	—	—	mgL^{-1}
Magnesium	41.14	125	—	mgL^{-1}
Calcium	174.05	—	—	mgL^{-1}
Arsenic	0.29	0.01	0.1	mgL^{-1}
Total dissolved solids	1,981	1,500	—	mgL^{-1}

Table 2.
Physicochemical characterization of the Lluta River water (proper elaboration).

5.2 Determination of soil quality in the Lluta Valley

In the Lluta Valley, mainly only corn (*Zea mays*) (*amylaceous*), alfalfa (*Medicago sativa*), onion (*Allium cepa L.*), garlic (*Allium sativum L.*), and beet (*Beta vulgaris var. Hortensis L.*) are grown. The soil use in the Lluta Valley is limited to these types of products due to high salinity, high concentrations of boron, chloride, and sodium, and drainage problems, as shown in **Table 3**, and physicochemical characteristics have historically affected the Lluta Valley, limiting the diversification of agricultural production systems.

5.3 Desalination process parameters

The calculation of the feed flow is made by means of Eq. (4), where Q_p is 360 L h^{-1} and the conversion is 50%, obtaining Q_a equal to 720 L h^{-1}. With the optimum flow rates of feedwater and plant product water, the brine flow rate is obtained by means of a load balance (Ec. (1)), with Q_s equal to 360 L h^{-1}.

To estimate the concentration of salts, present in the brine, a theoretical calculation was made, considering that the plant has a yield equal to Y (%) = 50. Through (Ec. (5)), the concentration factor (CF) is obtained, whose result is 2. This value was used to characterize the brine, multiplying its value by the initial concentration of each parameter of the Lluta River water (**Table 2**), where the results are expressed in **Table 4**.

Texture	Organic matter (% m/m)	pH	Electrical conductivity ($mScm^{-1}$)	Arsenic ($mgkg^{-1}$)	Available phosphorus ($mgkg^{-1}$)	Total nitrogen ($mgkg^{-1}$)
53.5% sand 14.5% clay 32% silt	1.80	6.88	2.34	276.6	26.5	0.61

Table 3.
Physicochemical characterization of the soil in the Lluta Valley (proper elaboration).

Physicochemical parameters	Values Brine	Unit
pH	7.9	—
Electrical conductivity	3.04	$mScm^{-1}$
Temperature	22.0	°C
Chloride	1,056.2	mgL^{-1}
Sulfate	2,778	mgL^{-1}
Sodium	62.30	mgL^{-1}
Magnesium	82.28	mgL^{-1}
Calcium	348.1	mgL^{-1}
Arsenic	0.58	mgL^{-1}
Total dissolved solids	2,962	mgL^{-1}

Table 4.
Theoretical characterization of the physicochemical parameters presents in the brine (proper elaboration).

5.4 Use of brine in halophyte cultivation

The present proposal considers the use of brine obtained from the RO plant, from which 360 L h^{-1} are generated (**Figure 4**). If we consider that the plant will operate 12 hours a day for 20 days a month, we obtain 86,400 L h^{-1} of this saline liquid waste, which can be stored in a pond to be used for irrigation.

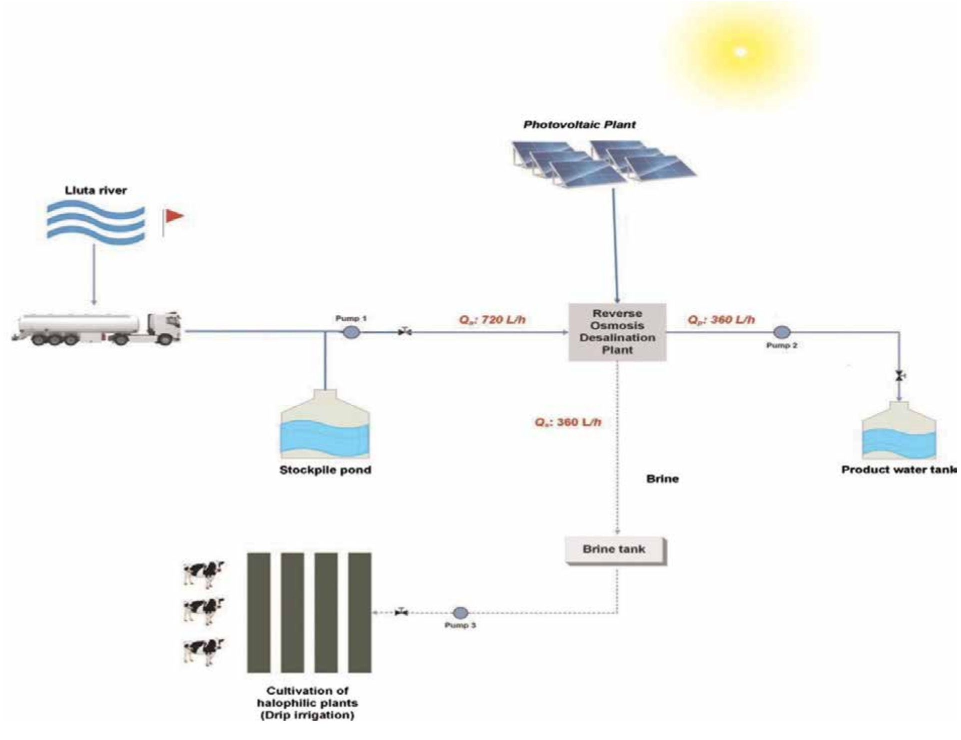

Figure 4.
Diagram of reverse osmosis plant and the use of brine in the cultivation of forage plants (proper elaboration).

The soil conditions for the cultivation of the fodder plant should be a fallowed, tracked, and leveled soil, where a drip irrigation system is established, whose Polyvinyl chlorid, PVC, lines could be at a depth of 40 cm. The plants can be produced in a nursery until they reach a size of 20 cm and then transplanted in furrows 1.5 m apart, conditions established for a cultivable land of 1000 m^2 [53]. In addition, the distance between plants should be 2.5 to 3 m because these forages generate a high volume of biomass [54]. It is proposed to cultivate 400 halophyte plants in a 1500 m^2 plot, considering an irrigation of 6 hours per week and a volume of 75 L $plant^{-1}$ $week^{-1}$ [19].

The production obtained from *A. nummularia* is 825 kg $year^{-1}$, according to information published by Sánchez et al., 2015 [20]. This fodder plant will be used to feed bovines or goats.

On the other hand, according to the comparison of the chemical analysis between alfalfa and *A. nummularia*, it can be observed that the latter has 4% more crude protein than alfalfa. Likewise, the dry matter and metabolizable energy of *Atriplex nummuralia* meet the optimal nutritional value for a dairy cow (**Table 5**).

It should be noted that the proposed system for the production of halophytes from brine will use 31.319 kWh day^{-1} (11,431.435 kWh $year^{-1}$) of electrical energy obtained from the photovoltaic system.

5.4.1 Effect of brines on soil physicochemical properties

Considering the chemical properties of the soil, the components detailed in **Table 3**, the Lluta Valley soil corresponds to the United States Department of Agriculture (USDA) textural triangle, being classified as a sandy loam soil [56].

In addition, it is worth mentioning that this type of soil has an apparent density of 1.50 g cm^{-3}, which indicates the space occupied by the pores in the soil in relation to the volume of water. In addition, these soils have a real density of 2.6 g cm^{-3}.

For the determination of the total porosity of the soil (ξ), it is calculated according to the following equation (Ec. (6)) [57]:

$$\xi = \left(1 - \frac{ad}{rd}\right) x\ 100 \tag{1}$$

Considering the equation x, we obtain a ξ =43% of total porosity.

This result indicates that they present spaces between the particles of 0.05–2 mm, increasing the size of the pore spaces between the particles and facilitating the drainage and aeration of the soil. This percentage also shows an adequate porosity for the development of halophyte plants. It is worth mentioning that halophyte plants are able to accumulate high concentrations of NaCl in their tissues, and there is

Nutrients	Alfalfa	*A. nummularia*	Optimum nutritional value for a dairy cow
Dry matter, %	89.7	88.1	20
Crude protein, %	16	20.2	18
Metabolizable energy, Mcal kg^{-1}	2.21	1.99	1.67–1.76

Table 5.
Chemical analysis of Atriplex nummularia *and alfalfa compared with optimal nutritional value for a bovine [20, 55].*

information of 39% in a shrub [58]. In addition, the use of halophytes plants for phytoremediation appears as a cost-effective, noninvasive alternative to other methods used for contaminated soils [34].

5.4.2 Effect of brine infiltration on soils

Each plant has a certain tolerance to salinity, depending on the plant species, the soil, and the characteristics of the brine. In general, some plants can tolerate TDS concentrations of 500 mgL^{-1}, and this is the case of halophytes that can be irrigated with a brine concentration higher than 2000 mgL^{-1} of TDS [58]. In general, soil texture is the main factor affecting the infiltration rate of soils, as well as soil depth, which makes the permeability characteristics of these different [59]. The soil under study has a sandy loam texture, whose infiltration rate is 0.8 to 1.2 cm h^{-1} (**Table 6**). This characteristic allows inferring that the soil for cultivation has a moderate infiltration rate, being optimal for drip irrigation [60].

On the other side, the capacity of the soil to retain water, called soil ponding capacity (PC), is another factor that influences infiltration, and in irrigation, it is always limited to a given depth (normally to the depth of roots). For the calculation of the ponding capacity (Ec. (7)), [61] was used, according to the data obtained in **Table 7** at a depth of 40 cm, obtaining a value of 48 mm. It is important to mention that the field capacity (FC) is the water content of a soil after having been abundantly irrigated and having drained freely for 24 to 48 hours, and the permanent wilting point (PWP) is the soil moisture condition in which the plants are unable to absorb water or do so with extreme difficulty, experiencing irreversible wilting:

Texture class	Basic infiltration rate (cm h^{-1})
Fine sand	1.2 a 1.9
Sandy loam soil	0.8 a 1.2
Silty loam soil	0.6 a 1
Clay	0.2 a 0.5

Table 6.
Basic infiltration rate according to soil texture class [60].

Texture	Ad Apparent density	FC Gravimetric soil water content at field capacity (%)	PWP Gravimetric soil water content at permanent wilting Point (%)
Sandy	1.5–1.8 (1.65)	6–12 (9.0)	2–6 (4)
Sandy loam	1.4–1.6 (1.50)	10–18 (14.0)	4–8 (6)
Loam	1.0–1.5 (1.25)	18–21 (19.5)	8–12 (10)
Clay loam	1.1–1.4 (1.25)	23–31 (27)	11–15 (13)
Sandy clay	1.2–1.4 (1.30)	27–35 (31)	13–17 (15)
Clayey	1.1–1.4 (1.30)	31–39 (35)	15–19 (17)

Table 7.
Physical properties for different textures [61].

Principles	Strategies	EC PRC
Plan for the optimal use of resources	R1 Design	The integrated design, which considers the use of photovoltaic panels to the reverse osmosis plant, allows to reduce the carbon footprint. In addition, the brine obtained from the RO process will be used to irrigate the *Atriplex nummularia* crop that will be used as feed for bovines and goats. It is worth mentioning that if the brine is disposed of in the local sewage system, environmental contamination is avoided.
	R2 Reduce/ Prevent	Avoiding the use of conventional electricity and using solar photovoltaic energy to generate electricity reduce greenhouse gases. Preventing brine from being disposed of in the sea or in sewage systems is a great relief for the environment and much better than using it to grow halophyte fodder crops for goats or bovines.
	R3 Optimize	Considering that if we have brackish water (720 L h^{-1}) and that when treated through RO, 50% product water (360 L h^{-1}) and 50% brine (360 L h^{-1}) are generated. The brine is generally disposed of in sewers, the sea or deep wells, but to maximize the resources, it is essential that the brine is used as irrigation water for halophyte plants, optimizing the use of feedwater by 100%.
Maximize the usefulness of materials at all times	R4 Reuse/ Distribute	Not applicable.
	R5 Repair	Parts such as water or brine storage ponds will be repaired, or any parts of the RO plant that have technical problems will be repaired. In addition, membrane regeneration periods will be provided due to membrane saturation, typical in brackish water use.
	R6 Remanufacture	The disused membranes will be used for applied research (new materials) and to generate new membranes in the laboratory LIMZA/UTA.
	R7 Revaluate	This project valorizes brine for irrigation of halophyte plants, reducing water consumption for irrigation and therefore reducing the cost of water consumption.
	R8 Recycle	Activated carbon bags are reused to store forage plants when they are available for animal consumption.
	R9 Recover	Not applicable.
Preserve and improve the natural capital	R10 Regenerate	The cultivation of halophyte plants helps to preserve the local natural resource and thus avoid environmental damage by disposing of the brine, for example, in the sea.
	R11 Supply	The electrical energy photovoltaic consumption of the system to produce halophyte is 11,431.435 kWh per year sustained with conventional energy would produce approximately 1.5 tons of CO_2 [62]

Table 8.
Principles and strategies of the circular economy applied to the cultivation of halophytes with brine obtained from the RO plant [44] (proper elaboration).

$$PC = \left(\frac{FC - PWP}{100}\right) x\ Ad\ x\ Sd \tag{2}$$

The PC value obtained indicates that the soil can store in a depth of 40 cm a height of water equivalent to 48 mm. However, not all of this water is available to the crop, since crops have different minimum water balances, for example, like halophyte, in the case of alfalfa, and in general, they require approximately 60% of the available water capacity to maintain evapotranspiration and avoid water stress.

5.5 Circular economy

This proposal was applied to the present work (**Table 8**), mentioning that strategies R1 to R3 are relevant for the optimal performance and utilization of the RO plant energetically sustained with solar energy, and that its resulting by-products are used for irrigation. From strategy R5 to R8, the products can be maximized through valorization, considering that the "brines" are allowed to produce "food" for other species such as "cattle or goats." In addition, membranes can be reused either by regenerating them or by using them to produce another type of membrane. As for strategies R10 and R11, they allow improving and preserving the natural ecosystem through the use of renewable energies, using the brine for irrigation, and reducing the use of conventional water.

Figure 5 is a proposal that considers three important components: 1. desalination plant, 2. photovoltaic system, and 3. halophyte cultivation. This integrated proposal

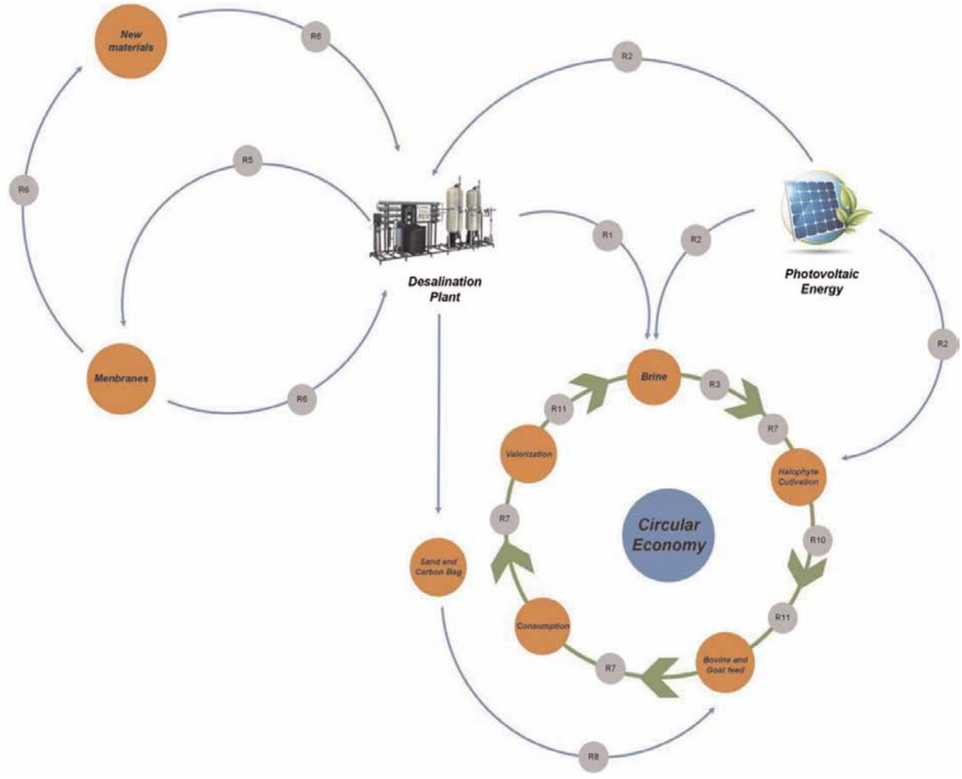

Figure 5.
Diagram of brine utilization in the cultivation of forage plants considering the principles of circular economy (proper elaboration).

would allow mainly rural communities to opt for the sustainable development of their products considering the circular economy in their processes.

Although, generally what is sought when implementing desalination plants is to obtain water for irrigation or human consumption; in this case, it is observed that the use of brine from this type of process serves for the cultivation of fodder plants. Therefore, environmental circularity would be achieved from the desalination plant by applying the different strategies of the circular economy.

Initially, the brine (R1) can be used for the cultivation of halophytes, reducing the consumption of irrigation water (R3 and R7). Subsequently, the fodder plant is used as feed for cattle and goats (R10 and R11), preserving the natural resource and reducing environmental pollution. It is worth mentioning that the valorization and consumption of animals fed with halophytes irrigated with brine should reduce production costs due to the water savings generated and the solar energy used as energy support for the system (R2).

Moreover, the desalination plant has parts that can be repaired (R5) or remanufactured (R6) or reevaluated (R7).

6. Conclusions and recommendations

The combination of the adaptation of technologies with natural brackish water and solar energy in the area would help mitigate the effects of climate change. In other words, the use of brine is a proposal that provides another source of water for irrigation and reduces the greenhouse effect. The proposed system to produce *A. nummularia* would avoid the production of 1.5 tons of CO_2 by using solar photovoltaic energy as the system's energy source.

The use of brine in the cultivation of the halophyte plant *A. nummularia* could generate a forage yield of 825 kg year^{-1}, occupying a volume of 75 L plant^{-1} week^{-1} of brine obtained from the RO plant. This forage obtained with *Atriplex* would contribute positively to the growth of bovines (cow), enhancing the sustainable development of the rural community.

In addition to the environmental benefits, the integrated scheme used in the semiarid region of Arica and Parinacota would produce a new source of food for the agricultural sector, thus, diversifying the fodder for livestock in rural areas and adding value to a waste stream with potential contaminating effects.

The use of brine as irrigation water for halophilic plants is an option to consider compared to conventional forage crops such as alfalfa. *A. nummularia* helps protect soils and subway aquifers, because it has a high salt absorption capacity, avoiding potential contaminating effects on the environment.

The circular economy can be considered as a valuable model to promote sustainable resource management, contributing to the construction of a vision for long-term sustainable development. Within this framework, the study complies with 9 of the 11 strategies of the circular economy.

The reverse osmosis technology produces a percentage of brine equal to that of the product water and researchers seek to improve and optimize the membranes to obtain more product water, in this particular case, it would not be necessary because the brine is used practically 100% in the irrigation of halophytes considering its cultivation in a sandy loam soil, with a pond capacity of 48 mm and a 43% of total porosity of the soil to be cultivated, introducing to this technology a new concept, circular economy, increasing its added value.

Finally, this study opens some potential opportunities for future research, such as the implementation of this type of projects in rural communities, considering the use of saline wastes as a source of water for irrigation, maintaining the circularity of RO desalination plants.

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Conflict of interest

"The authors declare no conflict of interest."

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References

[1] IPCC (Grupo Intergubernamental de Expertos sobre el Cambio climático, por sus siglas en inglés). 2018a. Summary for Policymakers. Global Warming of 1.5°C. an IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, y Efforts to Eradicate Poverty. Ginebra, IPCC. Available from: www.ipcc.ch/sr15/chapter/spm/. [Accessed: January 15, 2022]

[2] United Nations. The Sustainable Development Goals Report 2020, the United Nations Statistics Division (UNSD), a division of the Department of Economic and Social Affairs (DESA); 2015. [Internet] Available from: https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf. [Accessed: 22 January 19, 2022]

[3] Sola IA, Sáez C, Sánchez-Lizaso J. L: Evaluación de los requisitos ambientales y socioeconómicos para mejorar el desarrollo de la desalinización. Journal of Cleaner Production. 2021;**324**:129296. DOI: 10.1016/j.jclepro.2021.129296

[4] Zhang X, Jiang J, Yuan F, Song W, Dingyu X, Zhao L, et al. Gao X: Estimation of water footprint in seawater desalination with reverse osmosis process. Environmental Research. 2022;**294**:112374. DOI: 10.1016/j.envres.2021.112374

[5] Darre N, Toor G. Desalination of water: A review. Current Pollution Reports. 2018;**4**:104-111. DOI: 10.1007/s40726-018-0085-9

[6] Chenoweth JA, Al-Masri R. Cumulative effects of large-scale desalination on the salinity of semi-enclosed sea. Desalinización. 2022; **526**:115522. DOI: 10.1016/j.desal.2021.115522

[7] Cornejo-Ponce L, Moraga-Contreras C, Vilca-Salinas P. analysis of Chilean legal regime for brine obtained from desalination processes. Desalination and Water Treatment. 2020;**203**:91-103. DOI: 10.5004/dwt.2020.26202

[8] Ihsanullah IA, Atieh M, Sajid MK, Nazal M. Desalination and environment: A critical analysis of impacts, mitigation strategies, and greener desalination technologies. Science of The Total Environment. 2021;**780**:146585. DOI: 10.1016/j.scitotenv.2021.146585

[9] Makropoulos C, Rozos E, Tsoukalas I, Plevri A, Karakatsanis G, Karagiannidis L, et al. Sewer-mining: A water reuse option supporting circular economy, public service provision and entrepreneurship. journal of. Environmental Management. 2018;**216**:285-298. DOI: 10.1016/j.jenvman.2017.07.026

[10] Kakwani NS, Kalbar PP. Review of circular economy in urban water sector: Challenges and opportunities in India. Journal of Environmental Management. 2020;**271**:111010. DOI: 10.1016/j.jenvman.2020.111010. Available from: https://www.sciencedirect.com/science/article/pii/S0301479720309385?via%3Dihub

[11] Al-Saidi M, Das P, Saadaoui I. Circular economy in basic supply: Framing the approach for the water and food sectors of the Gulf cooperation council countries. Sustainable Production and Consumption. 2021;**27**:1273-1285. DOI: 10.1016/j.spc.2021.03.004

[12] FAO. Secretaría del foro de alto nivel de expertos - cómo alimentar al mundo en 2050 [Internet]. 2009. Available from: https://www.fao.org/wsfs/forum2050/wsfs-background-documents/wsfs-expert-papers/es/. [Accessed: January 19, 2022]

[13] FAO. El estado mundial de la agricultura y la alimentación 2020. Superar los desafíos relacionados con el agua en la agricultura: Roma; 2020. DOI: 10.4060/cb1447es

[14] FAO. El estado mundial de la agricultura y la alimentación 2021. Lograr que los sistemas agroalimentarios sean más resilientes a las perturbaciones y tensiones. Roma: FAO; 2021. DOI: 10.4060/cb4476es

[15] FAO. Resumen. "El estado mundial de la agricultura y la alimentación". Cambio Climático, Agricultura y Seguridad Alimentaria. Organización de las Naciones Unidas para la Alimentación y la Agricultura [Internet]. 2016. Available from: https://www.fao.org/3/i6132s/i6132s.pdf. [Accessed: January 19, 2022]

[16] Cornejo L, Lienqueo H, Vilca P. Hydro-chemical characteristics, water quality assessment and water relationship (HCA) of the Amuyo lagoons, Andean Altiplano, Chile. Desalination and Water Treatment. 2019;**153**:36-45. DOI: 10.5004/dwt.2019.24014

[17] INN. NCh409/1. Drinking Water - Part 1: Requirements. Santiago, Chile: Instituto Nacional de Normalización; 2005

[18] INN. NCh1333. Water Quality Requirements for Different Uses. Santiago, Chile: Instituto Nacional de Normalización; 1987

[19] Torres A, Acevedo E. El problema de salinidad en los recursos suelo y agua que afectan el riego y cultivos en los valles de Lluta y Azapa en el norte de Chile. IDESIA. 2008;**26**(3):31-44

[20] Sánchez AS, Nogueira IBR, Kalid RA. Uses of the reject brine from inland desalination for fish farming, spirulina cultivation, and irrigation of forage shrub and crops. Desalination. 2015;**364**:96-107. DOI: 10.1016/j.desal.2015.01.034

[21] Ahmadvand S, Abbasi B, Azarfar B, Elhashimi M, Zhang X, Abbasi B. Looking beyond energy efficiency: An applied review of wáter desalination technologies and an introduction to capillary-driven desalination. Water. 2019;**11**(4):696. DOI: 10.3390/w11040696

[22] Castro M, Alcanzare M, Esparcia E, Ocon J. A comparative techno-economic analysis of different desalination technologies in off-grid islands. Energies. 2020;**13**(9):2261. DOI: 10.3390/en13092261

[23] Jones E, Qadir MTH, Van Vliet M, Smakhtin V, Kang S. The state of desalination and brine production: A global outlook. Science of the Total Environment. 2019;**657**: 1343-1356. DOI: 10.1016/j.scitotenv.2018.12.076

[24] Wakil M, Burhan M, Choon K. Pushing desalination recovery to the maximum limit: Membrane and thermal processes integration. Desalination. 2017;**416**:54-64. DOI: 10.1016/j.desal.2017.04.024

[25] Saadat AHM, Islam MS, Islam MS, Parvin F, Sultana A. Desalination Technologies for Developing Countries: A review. Journal of Scientific Research.

2018;**10**(1):77-97 DOI. DOI: 10.3329/jsr.v10i1.33179

[26] Ayodha Ajiwiguna T, Lee G, Lim B, Choi S, Chang-Dae P. Estrategia de diseño y análisis económico en varias configuraciones de sistemas PV-RO autónomos. Desalinización. 2022;**526**: 115547. DOI: 10.1016/j.desal.2022.115547

[27] Das S, Ray A, De S. Optimización tecnoeconómica del proceso de desalinización alimentado por energía renovable: un estudio de caso para un pueblo costero del sur de la India. Sustainable Energy Technology Assessment. 2022;**51**:101966. DOI: 10.1016/j.seta.2022.101966

[28] Panagopoulos A, Haralambous K-J, Loizidou M. Desalonation brine disposal methods and treatment technologies - a review. Science Total Environment. 2009;**603**:133545. DOI: 10.1016/j.scitotenv.2019.07.351

[29] Balis E, Griffin JCR, Hiibel S. R: Membrane distillation-crystallization for inland desalination brine treatment. Separation and Purification Technology. 2022;**290**:120788. DOI: 10.1016/j.seppur.2022.120788

[30] Shahabi S, Azizi N, Vatanpour V. Synthesis and characterization of novel g-C_3N_4 modified thin film nanocomposite reverse osmosis membranes to enhance desalination performance and fouling resistance. Separation and Purification Technology. 2019;**215**:430-440. DOI: 10.1016/j.seppur.2019.01.031

[31] Al-Absi RS, Abu-Dieyeh MA, Al-Ghouti M. Brine management strategies, technologies, and recovery using adsorption processes. Environmental Technology and Innovation. 2021;**22**: 101541. DOI: 10.1016/j.eti.2021.101541

[32] El-Fakharanya ZM, G. Salem: Mariam. Mitigating climate change impacts on irrigation water shortage using brackish groundwater and solar energy. Energy Reports. 2021;**7**:608-621. DOI: 10.1016/j.egyr.2021.07.091

[33] Ladewig B, Asquith B. Desalination Concentrate Management. Heidelberg, Germany: Springer Science & Business Media; 2012

[34] Barcia-Piedrasa JM, Pérez-Romero JA, Mateos-Naranjo E, Camachoa M, Redondo-Gómez S. Effect of prior salt experience on desalination capacity of the halophyte *Arthrocnemum macrostachyum*. Desalination. 2019;**463**: 50-54. DOI: 10.1016/j.desal.2019.03.006

[35] Sarpong KA, Amiri A, Ellisa E, Idowu OJ, Brewer C. Short-term leachability of derived Atriplexbiochars salts. Science Total Environment. 2019; **688**:701-707. DOI: 10.1016/j.scitotenv.2019.06.273

[36] PROY-NOM-013-CONAGUA/SEMARNAT-2015, Which Establishes Specifications and Requirements for Supply and Discharge Installations in Desalination Plants or Processes Hat Generate Brackish or Saline Wastewater, Draft of Official Mexican Standard. National Consultative Committee for Standardization of the Water Sector. 2015. [Internet] Available from: https://www.cmic.org.mx/comisiones/Sectoriales/infraestructurahidraulica/Normas/Seguimiento_CMIC_en_las_Normas/NOM_3_Plantas_Desalinizadoras/15_reunion/PROY-NOM-013-CONAGUA-2015%20c.pdf. [Accessed: January 19, 2022]

[37] DIRECTEMAR. Armada de Chile. "Guía sobre lineamientos técnicos mínimos para la Evaluación Ambiental de Proyectos Industriales de Desalación

en jurisdicción de la Autoridad Marítima" [Internet]. Available from: https://www.directemar.cl/directemar/site/docs/20211115/20211115120951/gu__a_desaladoras_2021__vf.pdf. [Accessed: January 25, 2022]

[38] Evaluación de Impacto Ambiental (SEIA) [Internet]. Available from: https://www.sea.gob.cl/informacion-estadistica-del-seia. [Accessed: January 26, 2022]

[39] Cornejo-Ponce L, Vilca-Salinas P, Lienqueo-Aburto H, Arenas MJ, Pepe-Victoriano R, Carpio E, et al. Integrated aquaculture recirculation system (IARS) supported by solar energy as a circular economy alternative for resilient communities in arid/semi-arid zones in southern South America: A case study in the Camarones town. Water. 2020;**12**: 3469. DOI: 10.3390/w12123469

[40] MSPS. 2009. Ministerio de Sanidad y Política Social. Guía de Desalación: aspectos técnicos y sanitarios en la producción de agua de consumo humano. Informes, Estudios e Investigación. España (Internet). Available from: https://www.sanidad.gob.es/profesionales/saludPublica/docs/Guia_desalacion.pdf. [Accessed: January 25, 2022]

[41] Salminen J, Maatta K, Haimi H, Maidell M, Karjalainen A, Noro K, et al. Water-smart circular economy – Conceptualisation, transitional policy instruments and stakeholder perception. Journal of Cleaner Production. 2022;**334**: 130065. DOI: 10.1016/j.jclepro.2021.130065

[42] Sauvéa S, Lamontagne S, Dupras J, Staheld W. Circular economy of water: Tackling quantity, quality and footprint of water. Environmental Development. 2021;**39**:100651. DOI: 10.1016/j.envdev.2021.100651

[43] Arnal M, Sancho M, Iborra I, Gozalvez JM, Santafe A, Lora J. Concentration of brines from RO desalination plants by natural evaporation. Desalination. 2005;**182**: 435-439. DOI: 10.1016/j.desal.2005.02.036

[44] ODEPA. Informe Final: Estudio de Economía Circular en el Sector Agroalimentario Chileno. Elaborado por UC Davis Chile y Equipo Cadenas de Valor Más Sustentables (CAV+S). Ministerio de Agricultura (Internet). ODEPA: María Emilia Undurraga Marimón; UC Davis Chile: Mauricio Cañoles, Olivia Valdés, Leticia Rojas, Juan Carlos Galáz, Fernando Coz y Natalia Díaz; Cadenas de Valor Más Sustentables (CAV+S): Catalina Giraldo, Nicole Bañados, Francisca Leiva y Consultora independiente: Constanza Carrasco; 2019. Available from: https://www.odepa.gob.cl/wp-content/uploads/2019/12/EstEconomiaCircular2019.pdf. [Accessed: January 20, 2022]

[45] Atzori G, de Vos AC, van Rijsselberghe M, Vignolini P, Rozema J, Mancuso S, et al. Effects of increased seawater salinity irrigation on growth and quality of the edible halophyte Mesembryanthemum crystallinum L. under field conditions. Agricultural Water Management. 2017;**187**:37-46. DOI: 10.1016/j.agwat.2017.03.020

[46] Australian Government, Department of Agriculture, Water and the Environment. Atriplex nummularia. Growing Native Plants. Australian National Botanic Gardens. Australian National Herbarium. 2017. (Internet). Available from: https://www.anbg.gov.au/gnp/interns-2007/atriplex-nummularia.html.. [Accessed: January 26, 2022]

[47] Soliz D, Glenna E, Seamana R, Yoklic M, Nelsona S, Brownb P. Water

consumption, irrigation efficiency and nutritional value of *Atriplex lentiformis* grown on reverse osmosis brine in a desert irrigation district. Agriculture, Ecosystems and Environment. 2011; **140**:473-483. DOI: 10.1016/j.agee.2011.01.012

[48] Google Earth. Universidad de Tarapacá [Internet]. 2022. Available from: https://earth.google.com/web/@-18.47247314, 70.31317911,19.02938823a,1000d,30y,0h,0t,0r/data=MicKJQojCiExNHFHVnVZSUdaRWRKc1JWUkxSbGkwa19IUXJ1bGlOdkQ. [Accessed: January 16, 2022]

[49] APHA. Standard Methods for the Examination of Water and Wastewater. 21st ed. Washington, DC, EEUU: American Public Health Association; 2005

[50] Sadzawka A, Grez R, Mora M, Saavedra N, Carrasco M, Rojas C, editors. Métodos de Análisis Recomendados para los Suelos Chilenos, Comisión de Normalización y Acreditación (CNA), Sociedad Chilena de la Ciencia del Suelo. Santiago: Salesiano S.A; 2006 ISSN0717-4810

[51] Lenntech. Wave Cyber Vessels Wave Cyber MPV 4″ 300 E [Internet]. 2022. Available from: https://www.lenntech.com/Data-sheets/Wave-Cyber-300-Psi-4'-MPV-Side-port-L.pdf. [Accessed: January 19, 2022]

[52] Guidelines for drinking-water quality: fourth edition incorporating the first addendum. Geneva: World Health Organization; 2017. Licence: CC BY-NC-SA 3.0 IGO. Available online: https://www.who.int/publications/i/item/9789241549950

[53] Saucedo R, Gutiérrez E, Rubio H, Quintana R, Jurado P. Jurado: Uso de plantaciones de Numularia (Atriplex nummularia) bajo riego y fertilización como banco de proteína para el sistema vaca cría. Tecnociencia Chiguagua. 2011; **5**(1):9-18

[54] FAO. Halofitas arbustivas forrajeras: un recurso potencial para agroforesteria Chaqueña y para otras zonas sub humedas y semi aridas. USER/FAO. Editores: Shirley Roman, Marco Flores, Ubaldina Ruiz, Einstein Tejeda @FAO Bolivia, 2014; p. 72. (Internet). Available from: https://issuu.com/ucerbolivia/docs/07_atriplex_final. [Accessed: January 26, 2022]

[55] Perulactea. Claves para el Manejo Alimenticio de la Vaca [Internet]. 2022. Available from: Lactante http://www.perulactea.com/2019/02/28/claves-para-el-manejo-alimenticio-de-la-vaca-lactante/. [Accessed: January 27, 2022]

[56] USDA, United States Department of Agriculture. Soil Quality Test Kit Guide [Internet]. 2001. Available from: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_050956.pdf. [Access April 2022]

[57] Angella G, Frías C, Salgado, Ramiro. Conceptos básicos de las relaciones agua-suelo-planta. Editorial: Instituto Nacional de Tecnología Agropecuaria (INTA), Ministerio de Agricultura, Ganadería y Pesca, Gobierno de Argentina. Conceptos básicos de las relaciones agua- suelo-planta,Colección Divulgación. 2016; p. 34. ISBN: ISSN 1850-4086

[58] Halophytes for Food Security in Dry Lands (pp.317-329), Chapter: 19, Publisher: Elsevier Science Publishing Co Inc, Editors: Muhammad Ajmal Khan, Munir Ozturk, Bilquees Gul and Muhammad Zaheer Ahmed. DOI: 10.1016/B978-0-12-801854-5.00019-4

[59] Angelone S, Garibay M, Cauhapé M. Geología y geotecnia: permeabilidad de

suelos. Universidad Nacional de Rosario; 2006. p. 39 (Internet) Available from: http://www.fceia.unr.edu.ar/geologiaygeotecnia/Permeabilidad%20en%20Suelos.pdf

[60] Fundamentals of soil physics. Departament of Plant and Sciences, University of Massachusetts Amherst. Nueva York, EEUU: Academic Press; 1980

[61] Ortega Farías S, Acevedo Opazo C. Programación del riego en sistemas por surco y goteo. Comisión Nacional de Riego Departamento de Proyectos. Universidad de Talca, Facultad de Ciencias Agrarias. Servicio Integrado de Agroclimatología y Riego (SIAR); 1999. p. 16 (Internet) Available from: http://bosques.ciren.cl/bitstream/handle/123456789/9924/CNR0287.pdf?sequence=1&isAllowed=y

[62] US EPA, 2020. Greenhouse Gas Equivalencies Calculator. United States Environmental Protection Agency (Internet). Available from: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator. [Accessed: January 20, 2022]

Chapter 3

The Role of Biochar Systems in the Circular Economy: Biomass Waste Valorization and Soil Remediation

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Abstract

The circular economy is considered as an alternative model to the unsustainable linear "take–make–waste" approach that characterizes contemporary economic systems. It aims to achieve sustainable development by promoting the responsible and cyclical use of resources to maintain their value in the economy and minimize pressures on the environment. Biochar systems offer opportunities for operationalizing the CE model. They are multifunctional systems that can be used for bioenergy and biochar production using an extensive range of biomass feedstocks, including biowaste. They can contribute to climate change mitigation, as producing biochar and mixing it with soil is a means for sequestering atmospheric CO_2. Moreover, the produced biochar has a wide range of applications, including its use for agricultural soil amendment, wastewater treatment, manufacturing of cement, and remediation of contaminated soils. This versatility of biochar systems creates great opportunities for developing circular models of waste management that can valorize different waste streams. This chapter provides an overview of the CE concept and describes biochar systems, focusing on systems for the synergistic valorization of wood waste and contaminated soils. It also discusses the role of these systems in the CE indicating that they can contribute to the transition toward the CE.

Keywords: circular economy, sustainable development, biochar systems, wood waste, contaminated soil

1. Introduction

The CE has emerged as an alternative model to the prevailing "take–make–waste" approach to production and consumption in contemporary economic systems, which is an unsustainable path leading to resource depletion and severe environmental problems, such as climate change, air and water pollution, and biodiversity loss [1, 2]. In the linear economy, resources are extracted from nature, transformed into products that are then consumed within the human economic system until they are finally disposed of as waste back to nature [2]. By contrast, the CE model fosters the responsible and cyclical use of resources to maintain their value within the economy, while minimizing pressures on the environment [3, 4]. It operates at three system levels; the micro level (products, consumers, companies), the meso level (eco-industrial parks), and the macro level (cities, regions, countries), with the ultimate aim to achieve sustainable development [5].

The transition toward the CE requires, among others, the development of new technologies [6, 7]. An emerging technology that could promote the operationalization of the CE model is biochar systems. These are multifunctional systems that can produce bioenergy and biochar through the thermochemical conversion of different types of biomass feedstocks (e.g., wood, agricultural residues, and wastewater sludge) in an oxygen-limited environment [8, 9]. Biochar is a porous solid carbonaceous material with versatile physicochemical properties that has a multitude of applications, including its use for amendment of agricultural soils, water purification and wastewater treatment, concrete and steel production, and remediation of contaminated soils [10]. The application of biochar to soils is probably its most prominent application, as, apart from improving soil quality, it sequesters atmospheric CO_2, thereby contributing to climate change mitigation [11]. The multi-functionality of the biochar systems offers opportunities for developing integrated systems for valorizing different waste streams [12, 13], which is vital for the implementation of the CE model.

In this chapter, biochar systems, for valorizing wood waste and contaminated soils, are presented, and the potential role of these systems in the CE is explored. The rest of the chapter is structured as follows: Section 2 provides an overview of the CE concept and its principles to set the context of the study; Section 3 provides a brief description of different biochar systems; Section 4 focuses on biochar systems for valorizing wood waste and contaminated soils, and describes a case study, where the environmental performance of such systems is assessed; Section 5. discusses the role of biochar systems in the CE; and Section 6 summarizes the conclusion of the study.

2. The circular economy

The concept of CE originates in different schools of thought, including industrial ecology, general systems theory, and ecological and environmental economics [14]. Its conceptual roots can be traced back to notions put forth decades ago, such as the "Spaceship economy," [15] the irreversible degradation of natural resources when used by economic activities [16], the economy of loops [17], and the analogy between ecosystems and industrial systems [18]. The contemporary conceptualizations of CE include features from relevant concepts, including, but not limited to, the regenerative design [19], industrial symbiosis [20], "cradle to cradle" design [21], and performance economy [22].

Over the past 10–15 years, the CE has been attracting increasing attention from academia, companies, citizens, and policymakers [23]. It is regarded as a potential solution to the challenges of resource depletion and environmental degradation caused by the unsustainable linear "take–make–waste" paradigm that has dominated the contemporary economic systems [1, 2]. To address these challenges, the CE promotes system innovations that aim to maximize resource value, promote the cascading use of renewable resources and minimize waste generation to reduce negative environmental impacts and build natural, social, and economic capital [1, 24].

Overall, there is a general understanding that the CE is connected to sustainability and sustainable development. Geissdoerfer et al. [23] identified three different general types of relationships between the CE and sustainability; 1) conditional, where the CE is seen as one of the main conditions to attain sustainability, 2) beneficial, where the CE is regarded as beneficial in regard to sustainability, and 3) trade–off, where the CE is seen as a concept that can generate both benefits and costs in terms of sustainability. Having this study as a point of departure, Suárez-Eiroa et al. [25] suggested that there is a close relationship between the CE and sustainability and that the CE is at least beneficial for achieving sustainable development, as it can address some of the causes of current sustainability-related problems. The relevance of CE for achieving sustainable development was also confirmed by Schroeder et al. [26], who demonstrated that CE practices can contribute to achieve a significant number of Sustainable Development Goal targets. Despite these perspectives, the exact relationship between the CE and sustainability and sustainable development remains still unclear and debatable [27, 28].

Moreover, there is a lack of consensus in defining the CE. Kirchherr et al. [5] provided evidence of the heterogeneity in the definitions of the CE, by identifying 114 different definitions within academic articles, policy documents, and reports. The scholars also found that only a few of the identified definitions show explicit linkages between the CE concept and sustainable development. They also highlighted that the social dimension of sustainable development is highly overlooked, compared to the environmental and economic dimensions.

There is also a lack of consensus in conceptualizing the CE principles. A principle is defined “as a basic idea or rule that explains or controls how something happens or works” [29]. Reike et al. [30] analyzed 69 academic articles and identified that divergent approaches in conceptualizing the CE principles dominate the literature. More specifically, the scholars focused on the R-principles of the CE and found varying numbers of these R-imperatives, ranging from 3Rs (Reduce–Reuse–Recycle) through 5Rs (Reduce–Reuse–Remanufacture–Recycle–Recover) to the more nuanced 10Rs (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover). In addition, they revealed that different authors ascribe different meanings in their conceptualizations of the R-principles and that some authors apply a clear hierarchy when defining them, while others are more vague and suggestive.

Apart from the R-principles, alternative CE principles have also been proposed in the literature. Suárez-Eiroa et al. [25] used the term operational principles to define theoretical strategies that explain how CE operates. They proposed seven operational principles: (1) Adjusting inputs to the system to regeneration rates, (2) Adjusting outputs from the system to absorption rates, (3) Closing the system, 4) Maintaining the value of resources within the system, (5) Reducing the system’s size, (6) Designing for CE, and (7) Educating for CE. Moreover, Bocken et al. [31] introduced the three principles: (1) Narrowing loops, (2) Slowing loops, and (3) Closing loops, to guide business strategists and designers in the transition from a linear to a CE. In a recent study, Velenturf and Purnell [28] proposed 10 principles for the design, implementation, and evaluation of sustainable CE. These are: 1) Beneficial reciprocal flows of resources between nature and society, 2) Reduce and decouple resource use, 3) Design for circularity, 4) Circular business models to integrate multi-dimensional value, 5) Transform consumption, 6) Citizen participation in sustainable transitions, 7) Coordinated participatory and multi-level change, 8) Mobilize diversity to develop a plurality of circular economy solutions, 9) Political economy for multi-dimensional prosperity, and 10) Whole system assessment.

According to Kalmykova et al. [32], the divergent approaches in defining and conceptualizing the CE can hamper the advancement of the CE. However, the CE is an evolving and dynamic field that involves different stakeholders with different interests and priorities and thus the adoption of a single unifying definition is perhaps impossible and undesirable, as it would disregard some interests and fail to capture recent developments [33]. This, of course, is not a reason to stop striving for greater conceptual clarity on the CE. In this context, it is important to define explicitly the concept and its principles early in a study.

In this chapter, we embrace the definition proposed by Kirchherr et al.[6(p229)]:

> *"A circular economy describes an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers."*

We adopt this definition as a basis for exploring the role of biochar systems in the CE, as we consider it as one of the most comprehensive and insightful definitions of the CE in the literature. It highlights that the transition toward the CE requires the implementation of the model at three system levels (micro, meso and macro level). Moreover, it clearly relates the CE with the three dimensions of sustainable development (social, economic, environmental) and indicates that the CE has a key role as a means to achieve sustainable development. It is also important that it has an explicit reference to the 4Rs (Reduce–Reuse–Recycle–Recover) principle of the CE.

3. Biochar systems

Biochar is the porous solid carbonaceous material derived from the thermochemical conversion of biomass in an oxygen-limited environment [9]. It can be produced from various biomass feedstocks, including wood, wood waste, agricultural wastes (e.g., straw, rice husk), wastewater sludge, and food waste [8]. The most commonly used thermochemical conversion process for biochar production is pyrolysis, though other processes, such as gasification, torrefaction, and hydrothermal conversion, can also be used [34]. Pyrolysis is the thermochemical decomposition of biomass into condensable liquids, non-condensable gases, and biochar in the absence of oxygen [35]. The distribution of these end products and their properties depends on the process conditions (i.e., temperature, heating rate, and residence time) and the type of biomass feedstock [36]. Based on the process conditions, pyrolysis is classified as slow, fast, rapid, or flash, with slow pyrolysis being more appropriate for a biochar targeted product [37].

Biochar systems using pyrolysis can be deployed at different scales (small-, medium- and large–scale) and can perform multiple functions, as they can be used for biowaste treatment and bioenergy generation, along with biochar production and use [38]. Bioenergy can be produced through the combustion of the pyrolytic gas and oil products, known as syngas and bio-oil (or bio-tar), respectively. Moreover, bioenergy can be produced by using the produced biochar as solid fuel [9]. In addition to bioenergy production, biochar can be used for a variety of applications, mainly because of its versatile physicochemical properties [8, 10].

The most prominent application of biochar is probably its application to soils. Biochar can be used as a soil amendment for agricultural soils, as it can improve their physicochemical properties and structure, increasing soil fertility and crop productivity [34, 37, 39]. At the same time, the production of biochar and its incorporation into soils sequesters carbon. More specifically, the thermo-chemical conversion of biomass into biochar increases the recalcitrance of carbon, enhancing its resistance to chemical and biological degradation [34]. Thus, when biochar is incorporated into the soil, the return of biomass carbon to the atmosphere as CO_2 is impeded [11, 40]. In this way, biochar can act as a carbon sink, thereby contributing to climate change mitigation, and for that reason, the production of biochar with its incorporation in soils has been recognized as a carbon dioxide–removal (CDR) technology [41].

Besides soil amendment and carbon sequestration, biochar has numerous applications across various sectors. Biochar can be used as an additive for production of cement [13], cement mortar [42] and concrete [43], adsorbent for wastewater treatment and water purification, coke replacement in metallurgical processes, raw material for the manufacture of activated carbon, and novel specialty materials for electronic devices, such as carbon nanotubes and nanosheets [10], and platform material for energy storage and conversion, including hydrogen storage and production, fuel cells and lithium/sodium-ion batteries [44]. It can also be used as a feed supplement for poultry or ruminants to improve the health and productivity of the animals, reduce odors and nutrient losses from the manure, and serve, in combination with the manure, as a slow-release fertilizer [45]. Moreover, the sorption properties of biochar have sparked an interest in the use of biochar for remediating soils contaminated with organic and/or inorganic pollutants [9, 46, 47].

4. Biochar systems for synergistic valorization of wood waste and contaminated soil

Contamination of soils from human activities is a widespread environmental problem around the globe [47]. Only in EU-28, it has been estimated that 2.8 million potentially contaminated sites exist [48]. A widely applied technique for remediating contaminated sites worldwide is the “dig and dump” technique, where the contaminated soil is excavated and landfilled, and the excavated site is usually backfilled with virgin material [49]. However, this technique is not sustainable because of high-energy requirements, scarcity of landfill space, high costs, and decreasing availability of natural resources for backfilling [49]. Hence, various alternative techniques are being explored, including the application of biochar to contaminated soils.

Biochar exhibits good sorption properties for organic compounds, such as polycyclic aromatic hydrocarbons (PAHs), and inorganic substances, such as heavy metals, because of their large surface area, porous structure, and cation-exchange capacity [9, 46, 47]. Therefore, the mixing of biochar with soils contaminated with these substances is considered a potential option for stabilizing the contaminants. The efficacy of this technique depends on the properties of the utilized biochar and the type and concentration of contaminants in the soil [50]. For example, the efficacy of biochar for sorption of PAHs and heavy metals, such as Cd, Zn, Pb, and Cu, have been reported as good [51, 52], while for negatively charged metal(loid)s, such as As and Mo, the sorption capacity of biochar is low [47, 50]. Furthermore, the interplay between positive and negative effects has been reported for contaminated soils with multiple contaminants [46]. This indicates that the utilization of biochar for remediation of contaminated soils may not be suitable for all types of contaminated soil and thus case–specific assessments are generally required.

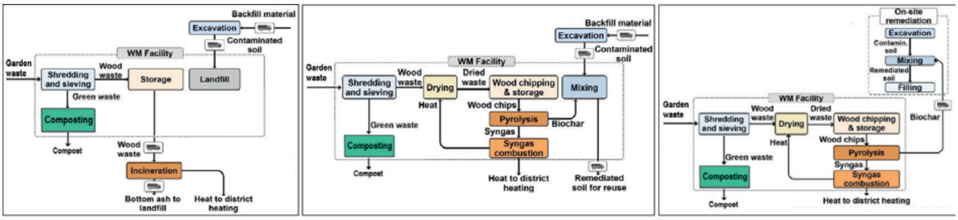
To explore the potential of using biochar for remediating contaminated soils with PAHs, heavy metals and metal(loid)s in Sweden, the research project "Biochar-RE: Source" was carried out between 2018 and 2020 [53]. The purpose of the project was to test and assess a new technique for remediation of contaminated soils excavated in urban areas, which is based on biochar made from urban wood waste. As part of the research, different biochar systems that use pyrolysis were designed and their environmental performance was assessed and compared to that of the "dig and dump" technique, which is the prevailing method for handling contaminated sites in Sweden [54]. The assessment of these systems is described by Papageorgiou et al. [55]. The following sections of this chapter (4.1 and 4.2) describe these systems and provide an overview of the methodological approach followed for the assessment and a summary of the results of the assessment. For more details see Papageorgiou et al. [55].

4.1 Systems description

Figure 1 depicts three different systems for the management of urban wood waste and contaminated soil. System 1 (S1) depicts how these two waste streams are currently managed in the urban area of Helsingborg in southern Sweden, which was the case study area for the research project. Systems 2 and 3 (S2 and S3) depict two alternative options for managing wood waste and contaminated soil based on biochar systems. More details for each system are provided below.

- *S1: "Dig and dump"*. In S1, contaminated soil with PAHs and metal(loid)s is excavated from various sites in Helsingborg and the excavated sites are backfilled with virgin material (gravel). The excavated soil is transported to the local waste management (WM) facility, where it is landfilled. Moreover, garden waste from the urban area is transported to the WM facility and is sorted, via shredding and sieving, into wood waste and green waste (mostly leaves and soil). The sorted waste is then transported to an incineration facility, where it is combusted for district heating. The green waste is processed through windrow composting.

- *S2: Off-site remediation with biochar.* In S2, the collected wood waste is first dried and processed into woodchips and then converted via pyrolysis (slow) into biochar and syngas. The syngas is combusted, and the generated heat is partly used for district heating and partly for drying the wood waste before pyrolysis.



S1: "Dig and dump" **S2**: Off-site remediation with biochar **S3**: On-site remediation with biochar

Figure 1.
The three studied systems for the management of wood waste and contaminated soil.

The biochar is mixed with contaminated soil (6% biochar, 94% soil, weight-to-weight), which is transported to the WM facility from excavation sites in Helsingborg. It is assumed that the excavated soil is transported for treatment to the facility due to technical or/and legislative restrictions that do not allow its mixing with biochar on-site and its direct reuse for backfilling. Instead, virgin soil (gravel) is used to backfill the excavated sites and the biochar-soil mix is reused in other applications (e.g., for noise barrier construction).

- *S3: On-site remediation with biochar.* The main difference between S3 and S2 is that the produced biochar is transported to the excavation sites and there it is mixed with the contaminated soil (6% biochar, 94% soil). The biochar-soil mix is then reused on-site for backfilling.

4.2 Environmental performance

4.2.1 Methods

The environmental performance of the three above–described systems was assessed by combining three Industrial Ecology tools, that is, Material and Energy Flow Analysis (MEFA), Substance Flow Analysis (SFA), and Life Cycle Assessment (LCA).

The goal of the MEFA was to map and quantify material and energy flows in the three systems in order to provide an understanding of the functioning of the systems and create the quantitative basis for the application of the LCA. The system boundaries of the MEFA included all processes for managing the contaminated soil (e.g., excavation and mixing) and wood waste (e.g., incineration and pyrolysis) and transportation between processes. However, they did not include the composting of the green waste, as the focus of the assessment was on the sorted wood waste, and the leaching of PAHs and metal(loid)s from the landfilled contaminated soil (S1) or the reused soil (S2 & S3), as it was studied through an SFA. The time boundary of the assessment was annual. The estimation of the material and energy flows was done by combining primary data and data from the literature.

The LCA was a comparative process-based LCA and its goal was to assess the life cycle environmental impacts of the studied systems. The system boundaries of the LCA were the same as those of the MEFA. They also included upstream impacts from the supply of backfill material, downstream impacts from the disposal of wood waste incineration ash, and impacts from capital goods (e.g., machinery). The functional unit was set as "1 year of operation of the pyrolysis plant (0.8 t/h dry wood, 1250 t/year biochar)." This functional unit is equivalent to the treatment of 5,650 t wood waste for district heating and remediation of 12,240 m^3 contaminated soil with biochar. To handle allocation issues and keep the functional unit constant the system expansion approach was followed. The modeling of the Life Cycle Inventory (LCI) was carried out using the LCA software Brightway2 [56] based on the Ecoinvent database (version 3.6 – cut-off) [57]. For the Life Cycle Impact Assessment (LCIA), the ILCD 2.0 impact assessment method [58] was used. From the 15 impact categories, the toxicity-related impact categories carcinogenic effects, non-carcinogenic effects, and freshwater ecotoxicity were not included, as the fate of the contaminants in the soil was investigated separately through an SFA.

The SFA was conducted to map and quantify the flows of the contaminants (PAHs and metal(loid)s) in the landfilled contaminated soil and the remediated soil.

The analysis was carried out taking a life cycle perspective, as the system boundaries included flows from all the processes included in the LCA. In addition, they included leaching of the contaminants from the soils, which was excluded from the MEFA and LCA. The amounts of contaminants leaching from the soils were calculated within a 100-year timeframe, using data from leaching experiments that were performed in the context of the "Biochar-RE: Source" research project and assuming a certain degree of water infiltration in the soils.

4.2.2 Results

The main results from the application of the MEFA are summarized in **Table 1**. The analysis revealed that on-site remediation with biochar (S3) can deliver significant fuel (diesel and biodiesel) savings, as it involves less transportation of materials than the "dig and dump" system (S1) and off-site remediation (S2). Moreover, on-site remediation minimizes the use of virgin material (gravel) for backfilling, as the remediated soil is directly reused on-site. By contrast, in S1 and S2, virgin material is required for backfilling. In addition, the analysis indicated that the pyrolysis of wood waste can supply less heat to the district heating network than incineration and that a considerable amount of auxiliary electricity is needed for the operation of the pyrolysis plant.

Table 2 presents the results of the LCA for the three systems and **Figure 2** shows the environmental impacts of S2 and S3, normalized to S1 (S1 = 100%), as well as the contribution of each process. Overall, biochar systems (S2 & S3) perform better than the "dig and dump" system (S1) in 10 out of 12 environmental impact categories. When comparing off-site (S2) and on-site remediation (S3), the former has lower environmental impacts in all impact categories. The main reason is that S3 entails less transportation of materials and saves virgin soil. Notably, both biochar systems have negative scores for climate change, as carbon sequestration in the biochar is 2.3 and 4.5 times higher than direct greenhouse gas emissions in S2 and S3, respectively. The biochar systems S2 and S3 had more impacts than S1 only in the impact categories Ionizing radiation and Fossils. The principal cause is the increased consumption of electricity for the operation of the pyrolysis plant, as a significant share of electricity in Sweden is from nuclear power, which is associated with these two impacts.

Material and energy flows	S1	S2	S3
Wood waste (t)	5,650	5,650	5,650
Contaminated soil (t)	19,580	19,580	19,580
Biochar produced (t)	—	1,250	1,250
Fossil fuels (diesel) used (t)	84.1	131	5,9
Biofuels (biodiesel) used (t)	90.3	15,8	13,1
Virgin material (gravel) used (t)	19,580	19,580	—
Landfilled contaminated soil (t)	19,580	—	—
Reused remediated soil (t)	—	19,580	19,580
District heating supply (TJ)	58.2	36	36
Electricity consumed (TJ)	—	14.2	14.2

Data source: Papageorgiou et al. [55].

Table 1.
Main material and energy flows of the three systems.

Impact categories	**S1**	**S2**	**S3**
Climate change (10^6 kg CO_2-eq)	1.01	−2.02	−2.31
Freshwater and terrestrial acidification (10^3 mol H+-eq)	25.35	7.2	5.96
Freshwater eutrophication (kg P-eq)	53.49	39.85	36.63
Marine eutrophication (10^3 kg N-eq)	13.76	2.78	2.34
Terrestrial eutrophication (10^3 kg N-eq)	124.96	27.84	23.71
Ionizing radiation (10^3 kg U235-eq)	169.42	781.07	763.55
Ozone layer depletion (kg CFC-11)	0.19	0.18	0.12
Photochemical ozone creation (10^3 kg NMVOC)	26.63	6.67	5.54
Respiratory effects, inorganics (Disease incidences)	0.27	0.09	0.07
Fossils (TJ)	17.46	30.4	26.13
Land use (10^6 points)	115.64	24.46	17.73
Minerals and metals (kg Sb-eq)	44.18	18.45	11.29

The negative scores for Climate change mean that the uptake of greenhouse gases is larger than direct emissions to the atmosphere (Data source: Papageorgiou et al. [55]).

Table 2.
Life cycle environmental impacts of the three systems.

Moreover, transportation and the incineration of wood waste are the most significant contributors in almost all impact categories for S1 (c.f., **Figure 2**). For the biochar systems S2 and S3, pyrolysis of wood waste and heat substitution are significant contributors. Heat substitution represents the additional heat that needs to be generated to compensate for the reduced heat production in S2 and S3, as pyrolysis produces less energy than incineration because a large share of the initial energy content in the biomass remains in the biochar. For S2, transportation is another significant contributor, as off-site remediation requires transportation of large quantities of materials, for example, virgin soil for backfilling.

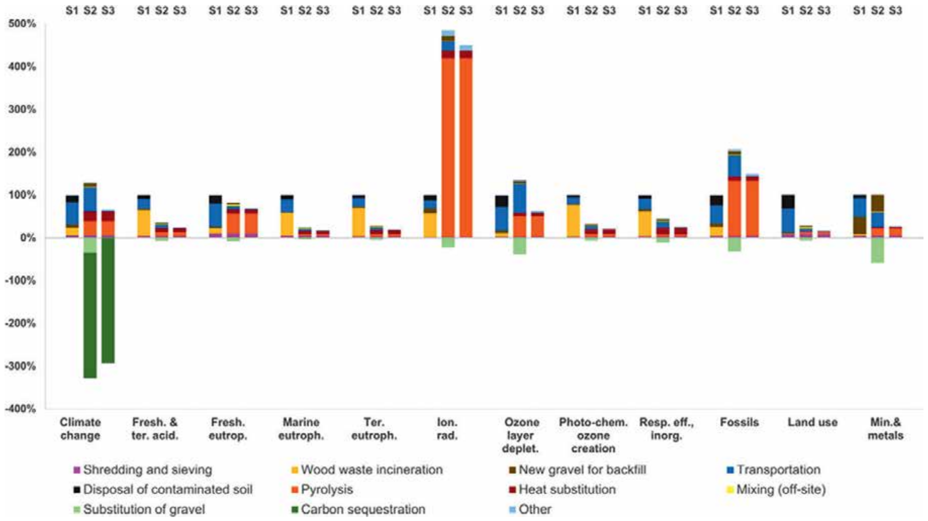


Figure 2.
Life cycle environmental impacts of the biochar systems (S2 and S3), normalized to the "dig and dump" system (S1) (S1 = 100%) with process contributions (Data source: Papageorgiou et al. [55]).

The results of the SFA for PAHs are summarized in **Table 3**. The analysis showed that for all PAHs, except benzo(a)pyrene, the leached amounts from the contaminated soil and the biochar-remediated soil are significantly higher than their life cycle emissions from the other processes of the systems. However, the leached amounts of PAHs constitute only a small part of their initial content in the soils. The analysis showed that remediation with biochar can stabilize PAHs in the soil, as less than 0.1% of the initial content of these contaminants in the soil will leach out within a 100-year period.

For the metal(loid)s the results of the SFA are presented in **Table 4**. Contrary to PAHs, the leached amounts of most metal(loid)s from the landfilled or remediated soil are lower than their life cycle emissions. The only exceptions are Mo and Ba. Moreover, the analysis showed that less than 0.8% of the initial content of metal(loid)s in the contaminated soil leaches out, except for Ba where 1.1% leaches out in S2 and S3, and Mo where 4.7% and 25% of the initial content leaches out in S1, S2, and S3, respectively. Furthermore, the SFA indicated that the application of biochar can reduce the leaching of Cu, Zn, Ni, and Hg, while it does not have the same positive

PAHs	Life cycle emissions, without emissions from disposal of contaminated soil or reuse of biochar-remediated soil (kg)			Initial amount in the contaminated soil (kg)	Amount released from the disposed contaminated soil (kg)	Amount released from the reused remediated soil (kg)
	S1	S2	S3		S1	S2 & S3
Naphthalene	1.0E–04	3.2E–05	2.1E–05	2.9E+01	9.4E–02	1.4E–02
Acenaphthylene	1.9E–05	6.0E–06	3.5E–06	1.6E+01	1.9E–02	5.5E–03
Acenaphthene	1.6E–04	8.8E–05	4.4E–05	1.4E+00	1.6E–02	9.3E–04
Fluorene	6.9E–05	3.3E–05	2.1E–05	4.3E+00	3.5E–02	6.6E–04
Phenanthrene	1.7E–04	8.0E–05	5.1E–05	7.0E+01	2.5E–01	4.1E–03
Anthracene	7.6E–06	4.2E–06	2.6E–06	2.7E+01	8.7E–02	5.4E–04
Pyrene	1.1E–04	6.4E–05	4.0E–05	2.5E+02	5.7E–01	5.8E–03
fluoranthene	1.5E–04	8.5E–05	5.3E–05	1.9E+02	7.1E–01	6.0E–03
Chrysene	2.8E–07	5.5E–08	4.2E–08	1.3E+02	1.6E–01	9.9E–04
Benz[a]-anthracene	1.9E–07	6.4E–08	4.6E–08	1.5E+02	1.7E–01	1.0E–03
Benzo[k]-fluoranthene	1.1E–07	3.7E–08	2.7E–08	7.1E+01	2.1E–02	2.5E–04
Benzo[b]-fluoranthene	1.5E–07	5.2E–08	3.7E–08	1.1E+02	4.7E–02	6.5E–04
Benzo[a]-pyrene	1.6E–01	8.6E–02	7.7E–02	9.6E+01	4.9E–02	6.5E–04
Benzo[ghi]-perylene	3.1E–08	6.7E–09	5.1E–09	7.5E+01	3.5E–02	1.1E–03
Dibenz[ah]-anthracene	4.0E–08	2.0E–08	1.4E–08	1.8E+01	1.1E–02	3.0E–04
Indeno[1,2,3-cd]-pyrene	3.1E–08	1.2E–08	8.6E–09	9.4E+01	3.0E–02	8.4E–04

Data source: Papageorgiou et al. [55].

Table 3.
Results of the SFA for PAHs.

Metal(loid)s	**Life cycle emissions, without emissions from disposal of contaminated soils (kg)**			**Initial amount in the contaminated soil (kg)**	**Amount released from the disposed contaminated soil (kg)**	**Amount released from the reused amended soil (kg)**
	S1	**S2**	**S3**		**S1**	**S2 & S3**
As, Arsenic	2.5	8.1	7.9	144.9	0.3	1
Ba, Barium	61.8	75.7	64.6	5180.3	13.0	68.2
Cd, Cadmium	1.8	2.3	2.2	7.3	0.05	0.1
Cr, Chromium	74.3	387.5	386.7	285.2	0.3	2.3
Co, Cobalt	293.6	1629.7	1625.3	90.8	0.3	0.6
Cu, Copper	357.4	768.1	749.1	4132.6	12.8	2.7
Pb, Lead	119.8	151.4	137.1	8265.3	0.1	0.5
Hg, Mercury	0.2	0.4	0.4	29.1	0.002	0.001
Mo, Molybdenum	3.6	7.0	6.3	36.7	1.7	9.3
Ni, Nickel	41.9	39.6	37.0	232.8	1.4	0.8
V, Vanadium	6.3	5.5	4.7	372.5	0.3	1.3
Zn, Zinc	250.4	326.7	306.1	7275.8	27.6	20.7

Data source: Papageorgiou et al. [55].

Table 4.
Results of the SFA for metal(loid)s.

effects for the other metal(loid)s. A sensitivity analysis showed that the results for metal(loid)s were sensitive to the assumed degree of water infiltration in the soils, contrary to the results for PAHs, which showed low sensitivity.

Overall, the SFA showed that the treatment of contaminated soils with biochar is effective for stabilizing PAHs. For metal(loid)s, however, the results of the SFA were more varied and sensitive to modeling assumptions. Therefore, further investigation is required to evaluate the effectiveness of this technique for remediating contaminated soils with metal(loid)s and identify and assess potential ecological and human health risks associated with it.

5. The role of biochar systems in the circular economy

To explore the role of biochar systems in the CE, the definition of the CE by Kirchherr et al. [5] (see Section 2) is used as a conceptual basis. More specifically, it is examined how the studied biochar systems can satisfy key elements of the definition.

The definition has an explicit reference to the 4Rs (Reduce–Reuse–Recycle–Recover) principle highlighting that, in the CE, a top priority is given on reducing the use of materials, and then on reuse, recycling, and recovery. On-site remediation with biochar (S3) can contribute to both reduction and reuse of materials, as the remediated soil can be reused on-site preventing the use of virgin soil for backfilling. Moreover, on-site remediation can generate significant fuel savings, as it involves less transportation compared to off-site remediation (S2) and landfilling of contaminated soil with the incineration of wood waste (S1). Off-site remediation cannot offer the same benefits as on-site remediation, as the remediated soil is not used on-site for backfilling. Nonetheless, the remediated soil can be reused in other applications (e.g., construction of noise barriers), preventing the use of virgin soil for these applications. In addition, both off-site and on-site remediation recover energy from the sorted wood waste and at the same time prevent the landfilling of the contaminated soil. Hence, it is evident that both biochar systems, especially S3, contribute to fulfilling the 4Rs principle of the CE.

The definition also indicates that a multi-level implementation of the CE model at the micro, meso and macro level is required for the transition to the CE. The versatility of biochar systems offers opportunities for the operationalization of the CE model at different system levels. The studied systems in this chapter demonstrate how biochar systems could form the basis of circular models for valorizing different waste streams in urban areas (macro level). Nonetheless, similar systems based on pyrolysis of biomass waste or other biomass feedstocks could also be developed in symbiosis with other industrial facilities in eco-industrial parks (meso level). For example, biomass waste (e.g., from a paper or pulp mill) could be pyrolyzed to supply heat and/or electricity for industrial processes within the eco-industrial park, while the produced biochar could be used as a resource for the manufacture of other materials, such as concrete, steel or activated carbon (see Section 3). In addition, biochar systems offer circular economy pathways at the micro level. It has been reported that decentralized biochar systems using agro-industrial wastes could be deployed in farms and small and medium enterprise (SME) activities to generate bioenergy and produce biochar that can be used as amendment of agricultural soils [12] or feed supplements for poultry or ruminants [45]. For example, a pyrolysis-biochar system could be integrated into an olive–grove farm in symbiosis with an olive mill, where residues from the olive grove and oil extraction are used as feedstock for the pyrolysis to produce heat and power for olive milling operations and biochar for amending the soil in the olive grove [37].

Moreover, according to the definition, the ultimate goal of operationalizing the CE model at different levels is to achieve sustainable development. One aspect of this goal is the creation of environmental quality. The assessment of the environmental performance of the biochar systems described in this chapter highlighted that these systems have great potential to improve environmental quality. First, they can contribute substantially to climate change mitigation through carbon sequestration in the biochar. Moreover, when compared to the conventional "dig and dump" system, the biochar system for on-site remediation can provide additional greenhouse gas emission savings, as it delivers fuel and virgin material savings. Apart from contributing to climate change mitigation, the assessed biochar systems can also provide additional environmental benefits, as they perform better than the "dig and dump" system in 10 out of 12 analyzed impact categories (see Section 4.2.2). However, there are also trade–offs associated with these systems, as they cause more impacts in the impact categories of ionizing radiation and fossils. The reason is that the technology for pyrolysis of wood waste used in this specific case requires considerable amounts of auxiliary electricity, which in Sweden is derived to a large extent from nuclear power, which is associated with these environmental impacts. Furthermore, the efficacy of biochar to stabilize certain metal(loid)s was not as high as for PAHs, and, in general, the extent of potential ecological and human health risks from the reuse of the remediated soil is still unknown.

To understand the role of biochar systems in CE it should be noted that CE, as defined here, does not imply "re–circulation of everything." One of the key benefits of biochar is to remove carbon from the atmosphere, thus contributing to climate change mitigation, by turning biomass into a stable material with a long lifetime in soils. Thus, the carbon cycle from atmospheric carbon dioxide to organic matter and back to the atmosphere is not closed, but slowed down, fitting into the CE concept of "slowing loops" [31].

Apart from environmental quality, other aspects of the desired goal to achieve sustainable development are the creation of economic prosperity and social equity. These aspects were not included in the scope of the above–described assessment, as it was focused only on the environmental sustainability of the studied systems. Nevertheless, it has been reported in the literature that biochar systems can generally have positive economic effects, as they can create new revenue opportunities, cut costs by reducing resource use and improving logistics, and create new business opportunities [34, 37]. Moreover, they can deliver social benefits, as they can create employment, promote food security through improved crop production from enhanced soil productivity, and offer energy diversification and security of supply [34, 37]. Moreover, the creation of new job opportunities and the associated increase in income are important factors for poverty reduction, which can help in reducing inequalities in society [59].

The above–mentioned environmental, social, and economic benefits of biochar systems are good indications that these systems have the potential to contribute to achieving sustainable development, which is the ultimate goal of the CE. Nevertheless, further research is required to identify and assess potential risks and drawbacks with these systems. From an environmental perspective, it is essential to investigate further various types of biochar systems to ascertain whether they could create risks to environmental quality. For example, in the case of the studied biochar systems, in this chapter, further research could be directed toward identifying and assessing the magnitude of potential risks associated with the reuse of the remediate soils within urban environments. From a social and economic perspective, further research is needed to identify and assess potential socio-economic implications of biochar systems, including those described in this chapter.

6. Conclusion

The CE has emerged as an alternative development model to the unsustainable "take–make–waste" approach that characterizes the contemporary economic systems. The transition toward the CE requires the implementation of new innovative technological solutions that can foster CE principles and help operationalize the CE model at different system levels. One emerging technology that can have a role in the transition toward the CE is biochar systems. These are multifunctional systems that can be deployed for biowaste treatment, and bioenergy and biochar production. As the produced biochar has versatile physicochemical properties, it can be used in various applications. Perhaps, the most prominent application of biochar, is its incorporation into soils, as it can contribute to climate change mitigation through carbon sequestration and at the same time amend the properties of soils. Overall, the multifunctionality of biochar systems, in combination with the versatility of the produced biochar, makes them suitable to function as a basis for developing circular models of waste management.

This chapter describes two biochar systems that could be developed for valorizing wood waste and contaminated soil in an urban area in Sweden. In the studied systems, wood waste is converted via pyrolysis into syngas and biochar. The syngas is used as the energy source for district heating supply. The produced biochar is applied to contaminated soil, either on-site or off-site, to sequester carbon and at the same time to remediate the soil to enable its reuse and prevent its landfilling.

The environmental performance of the two biochar systems was assessed and compared to the conventional “dig and dump” system, where the wood waste is incinerated for energy recovery and the contaminated soil is disposed of in a landfill. The assessment was carried out by combing LCA with MEFA and SFA. The MEFA showed that the biochar system for on-site remediation could provide large fuel and virgin soil savings, compared to the biochar system for off-site remediation and the “dig and dump” system. The LCA revealed that the two biochar systems performed better than the “dig and dump” system in 10 out of 12 analyzed impact categories. The two biochar systems performed remarkably well in the climate change category, as they can achieve net negative GHG emissions, because of carbon sequestration in the biochar. Between the two biochar systems, on-site remediation with biochar performs better than off-site in all impact categories, as the former provides fuel and virgin soil savings. However, there are also trade–offs with the biochar systems, as the pyrolysis of wood waste contributes to ionizing radiation and fossils depletion due to increased consumption of auxiliary electricity. Moreover, the SFA showed that the efficacy of biochar to stabilize certain metal(loid)s is not as good as for PAHs. Hence, the extent of potential risks (e.g., ecological and human health) associated with the reuse of biochar-remediated soils is still unknown.

Based on the findings from the assessment of the studied biochar systems and using the definition of the CE by Kirchherr et al. [5] as a conceptual basis, it was highlighted that these systems can have an important role in the transition toward the CE. It was established that these systems, especially the one for on-site remediation, fulfill the 4Rs principle of the CE. It was also suggested that the versatility of biochar systems creates opportunities for operationalizing the CE model at different system levels. Furthermore, based on the findings of the environmental assessment and findings from the literature, it was inferred that the biochar systems have the potential to provide environmental, social, and economic benefits and thus to contribute to achieving sustainable development, the ultimate goal of the CE. Nevertheless, further research is required to assess whether the reuse of the biochar-remediated soil creates potential risks to ecosystem quality and human health. Moreover, further research could assess potential social and economic implications from the development of these systems.

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References

[1] Kristensen HS, Mosgaard MA. A review of micro level indicators for a circular economy: Moving away from the three dimensions of sustainability? Journal of Cleaner Production. 2020;**243**:118531

[2] Korhonen J, Honkasalo A, Seppälä J. Circular economy: The concept and its limitations. Ecological Economics. 2018;**143**:37-46

[3] Moraga G, Huysveld S, Mathieux F, Blengini GA, Alaerts L, Van Acker K, et al. Circular economy indicators: What do they measure? Resources, Conservation and Recycling. 2019;**146**:452-461

[4] Petit-Boix A, Leipold S. Circular economy in cities: Reviewing how environmental research aligns with local practices. Journal of Cleaner Production. 2018;**195**:1270-1281

[5] Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling. 2017;**127**:221-232

[6] Paiho S, Mäki E, Wessberg N, Paavola M, Tuominen P, Antikainen M, et al. Towards circular cities: Conceptualizing core aspects. Sustainable Cities and Society. 2020;**59**:102143

[7] Homrich AS, Galvão G, Abadia LG, Carvalho MM. The circular economy umbrella: Trends and gaps on integrating pathways. Journal of Cleaner Production. 2018;**175**:525-543

[8] Moreira MT, Noya I, Feijoo G. The prospective use of biochar as adsorption matrix: A review from a lifecycle perspective. Bioresource Technology. 2017;**246**:135-141

[9] Yuan P, Wang J, Pan Y, Shen B, Wu C. Review of biochar for the management of contaminated soil: Preparation, application and prospect. Science Total Environment. 2019;**659**:473-490

[10] Nanda S, Dalai AK, Berruti F, Kozinski JA. Biochar as an exceptional bioresource for energy, agronomy, carbon sequestration, activated carbon and specialty materials. Waste and Biomass Valorization. 2016;**7**(2):201-235

[11] Woolf D, Lehmann J, Ogle S, Kishimoto-Mo AW, McConkey B, Baldock J. Greenhouse gas inventory model for biochar additions to soil. Environmental Science & Technology. 2021;**55**(21):14795-14805

[12] Fytili D, Zabaniotou A. Circular economy synergistic opportunities of decentralized thermochemical systems for bioenergy and biochar production fueled with agro-industrial wastes with environmental sustainability and social acceptance: A review. Curr Sustain Energy Reports. 2018;**5**(2):150-155

[13] Dixit A, Gupta S, Pang SD, Kua HW. Waste valorisation using biochar for cement replacement and internal curing in ultra-high performance concrete. Journal of Cleaner Production. 2019;**238**:117876

[14] Marin J, De Meulder B. Interpreting circularity: Circular city representations concealing transition drivers. Sustainability. 2018;**10**(5):1310

[15] Boulding KE. The economics of spaceship earth. In: Jarrett H, editor. Environmental Quality Issues in a

Growing Economy. Baltimore: Johns Hopkins University Press; 1966

[16] Georgescu-Roegen N. The Entropy Law and the Economic Process. Cambridge MA: Harvard University Press; 1971

[17] Stahel WR, Reday G. Jobs for Tomorrow: The Potential for Substituting Manpower for Energy. Brussels: Report to the Commission of the European Communities; 1976

[18] Frosch RA, Gallopoulos NE. Strategies for manufacturing. Scientific American. 1989;**261**:144-153

[19] Lyle JT. Regenerative Design for Sustainable Development. New York: John Wiley & Sons; 1996

[20] Chertow MR. Industrial symbiosis: Literature and taxonomy. Annual Review of Energy and the Environment. 2000;**25**:313-337

[21] McDonough W, Braungart M. Cradle to Cradle: Remaking the Way We Make Things. 1st ed. New York: North Point; 2002

[22] Stahel WR. The Performance Economy. New York: Palgrave Macmillan; 2010

[23] Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ. The circular economy: A new sustainability paradigm? Journal of Cleaner Production. 2017;**143**:757-768

[24] EMF - Ellen MacArthur Foundation. Towards a Circular Economy: Economic and Business Rationale for an Accelerated Transition. Cowes, UK: EMF; 2013

[25] Suárez-Eiroa B, Fernández E, Méndez-Martínez G, Soto-Oñate D. Operational principles of circular economy for sustainable development: Linking theory and practice. Journal of Cleaner Production. 2019;**214**:952-961

[26] Schroeder P, Anggraeni K, Weber U. The relevance of circular economy practices to the sustainable development goals. Journal of Industrial Ecology. 2019;**23**(1):77-95

[27] Pauliuk S. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resources, Conservation and Recycling. 2018;**129**:81-92

[28] Velenturf APM, Purnell P. Principles for a sustainable circular economy. Sustainable Production Consum. 2021;**27**:1437-1457

[29] Cambridge University Press. Cambridge Dictionary [Internet]. [cited 2022 Jan 24]. Available from: https://dictionary.cambridge.org/dictionary/english/principle

[30] Reike D, Vermeulen WJV, Witjes S. The circular economy: New or Refurbished as CE 3.0?: Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resources, Conservation and Recycling. 2018;**135**:246-264

[31] Bocken NMP, de Pauw I, Bakker C, van der Grinten B. Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering. 2016;**33**(5):308-320

[32] Kalmykova Y, Sadagopan M, Rosado L. Circular economy - From review of theories and practices to development of implementation tools. Resources, Conservation and Recycling. 2018;**135**:190-201

[33] Korhonen J, Nuur C, Feldmann A, Birkie SE. Circular economy as an essentially contested concept. Journal of Cleaner Production. 2018;**175**:544-552

[34] Lehmann J, Joseph S. Biochar for Environmental Management: Science and Technology. Sterling, VA: Earthscan; 2009

[35] Mandal S, Kunhikrishnan A, Bolan NS, Wijesekara H, Naidu R. Application of Biochar Produced From Biowaste Materials for Environmental Protection and Sustainable Agriculture Production. Environmental Materials and Waste: Resource Recovery and Pollution. 2016:73-89

[36] Weber K, Quicker P. Properties of biochar. Fuel. 2018;**217**:240-261

[37] Zabaniotou A, Rovas D, Libutti A, Monteleone M. Boosting circular economy and closing the loop in agriculture: Case study of a small-scale pyrolysis-biochar based system integrated in an olive farm in symbiosis with an olive mill. Environment and Development. 2015;**14**:22-36

[38] Azzi ES. Biochar Systems across Scales in Sweden: An Industrial Ecology Perspective. KTH Royal Institute of Technology; [PhD thesis] 2022

[39] Joseph S, Cowie AL, Van Zwieten L, Bolan N, Budai A, Buss W, et al. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. GCB Bioenergy. 2021;**13**(11):1731-1764

[40] Smith P, Adams J, Beerling DJ, Beringer T, Calvin KV, Fuss S, et al. Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. Annual Review of Environment and Resources. 2019;**44**(1):255-286

[41] IPCC. In: Calvo Buendia E, Tanabe K, Kranjc A, Baasansuren J, Fukuda M, Ngarize S, Osako A, Pyrozhenko Y, Shermanau P, Federici S, editors. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Switzerland: IPCC; 2019

[42] Gupta S, Kua HW, Low CY. Use of biochar as carbon sequestering additive in cement mortar. Cement and Concrete Composites. 2018;**87**:110-129

[43] Kua HW, Gupta S, Aday AN, Srubar WV. Biochar-immobilized bacteria and superabsorbent polymers enable self-healing of fiber-reinforced concrete after multiple damage cycles. Cement and Concrete Composites. 2019;**100**:35-52

[44] Liu WJ, Jiang H, Yu HQ. Emerging applications of biochar-based materials for energy storage and conversion. Energy & Environmental Science. 2019;**12**(6):1751-1779

[45] Hagemann N, Spokas K, Schmidt H-P, Kägi R, Böhler M, Bucheli T. Activated carbon, biochar and charcoal: Linkages and synergies across pyrogenic carbon's ABCs. Watermark. 2018;**10**(2):182

[46] Beesley L, Moreno-Jiménez E, Gomez-Eyles JL, Harris E, Robinson B, Sizmur T. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environmental Pollution. 2011;**159**(12):3269-3282

[47] Zama EF, Reid BJ, Arp HPH, Sun GX, Yuan HY, Zhu YG. Advances in research on the use of biochar in soil for remediation: A review. Journal of Soils and Sediments. 2018;**18**(7):2433-2450

[48] Pérez AP, Eugenio NR. Status of local soil contamination in Europe:

Revision of the indicator "Progress in the management Contaminated Sites in Europe". Luxemburg: Publications Office of the European Union; 2018

[49] Hodson ME. The need for sustainable soil remediation. Elements. 2010;**6**(6):363-368

[50] Hilber I, Bastos AC, Loureiro S, Soja G, Marsz A, Cornelissen G, et al. The different faces of biochar: Contamination risk versus remediation tool. Journal of Environmental Engineering and Landscape Management. 2017;**25**(2):86-104

[51] Beesley L, Marmiroli M. The immobilisation and retention of soluble arsenic, cadmium and zinc by biochar. Environmental Pollution. 2011;**159**(2):474-480

[52] Thomas E, Borchard N, Sarmiento C, Atkinson R, Ladd B. Key factors determining biochar sorption capacity for metal contaminants: A literature synthesis. Biochar. 2020;**2**(2):151-163

[53] Enell A, Azzi ES, Dan Kleja SD, Ekblad A, Flyhammar P, Fröberg M, et al. Biochar - from organic waste to a resource for utilization of soil waste, Synthesis Report (Report in Swedish: Biokol - från organiskt avfall till resurs för nyttiggörande av jordavfall, Syntesrapport). Linköping: SGI (Statens geotekniska institut); 2020

[54] Anderson R. Efficient Remediation of Contaminated Sites: A Literature Review. Göteborg: Chalmers, University of Technology; 2017

[55] Papageorgiou A, Azzi ES, Enell A, Sundberg C. Biochar produced from wood waste for soil remediation in Sweden: Carbon sequestration and other environmental impacts. Science Total Environment. 2021;**776**:145953

[56] Mutel C. Brightway: An open source framework for life cycle assessment. Journal of Open Source Software. 2017;**2**(12):236

[57] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. International Journal of Life Cycle Assessment. 2016;**21**(9):1218-1230

[58] European Commission, Joint Research Centre, Institute for Environment And Sustainability. Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment Methods. Luxemburg: Database and Supporting Information - First Edition; 2012

[59] Kamali M, Sweygers N, Al-Salem S, Appels L, Aminabhavi TM, Dewil R. Biochar for soil applications-sustainability aspects, challenges and future prospects. Chemical Engineering Journal. 2022;**428**:131189

Section 3

Mitigation Strategies

Chapter 4

Circular Economy - Recent Advances in Sustainable Construction Waste Management

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Abstract

With time, construction waste is increasing massively and its dumping is a serious issue globally. Utilizing the waste in various products and construction projects is boosting, but still, the amount of waste is much higher. Transitions to more sustainable construction can assist in attaining the specific goal of slowing down natural resources depletion, reducing environmental damage by extracting and recycling new materials, and minimizing pollution from the processing, use, and disposal of materials once they complete their useful life period. An important way to do this is to improve efficiency and bring productivity in the utilization of resources. The circular economy is more productive and healthier, where raw materials are stored longer in the production cycle and can be recycled, thus producing less waste. Due to potential benefits through enhanced quality and productivity in the processes, the concept of circular economy is grabbing the attention of construction industry stakeholders to attain sustainable construction waste management. This chapter focuses on the significance of a circular economy for the attainment of sustainable waste management in the construction sector. Moreover, the impact of construction waste and its utilization through recent sustainable solutions which also impact the economy has also been highlighted.

Keywords: circular economy, construction waste management, sustainable waste management

1. Introduction

Waste generation through human activities has become a global issue because it has a direct influence on the environment, society, and economy, i.e. overall sustainability [1]. Waste can be any material by-product of human and industrial activity that has no residual value. Both the government and industry see opportunities to reduce one of the sources of global warming through the implementation of waste management strategies. In recent years, there has been increasing scientific evidence that human activity is harming the environment with the excessive production of waste that results in pollution [2]. For this reason, waste management is a fundamental aspect of sustainability within the construction industry. Because by controlling the waste generation, it is possible to reduce the number of pollutants being released into the environment. Effective waste management will help in the reduction of landfill waste as well as minimize the costs associated with the construction of the project [3]. The global market is largely driven by the growing construction activity and the tendency of governments in different regions of the world to strive for sustainability. The growing demand for sustainable and recycled building materials for commercial construction projects continues to drive the construction waste market. It is estimated that the global solid waste market will reach \$2.01 billion by 2021 [4] and is expected to touch \$3.40 billion by 2050, an increase of about 59% [5] as shown in **Figure 1**.

THE WORLD GENERATES 2.01 BILLION TONNES OF MUNICIPAL SOLID WASTE ANNUALLY, WHICH IS EXPECTED TO GROW TO ABOUT 3.40 BILLION TONNES BY 2050.

Some 37 percent of waste is disposed of in some form of a landfill, 8 percent of which is disposed of in sanitary landfills with landfill gas collection systems. Open dumping accounts for about 33 percent of waste, 19 percent is recovered through recycling and composting, and 11 percent is incinerated for final disposal.

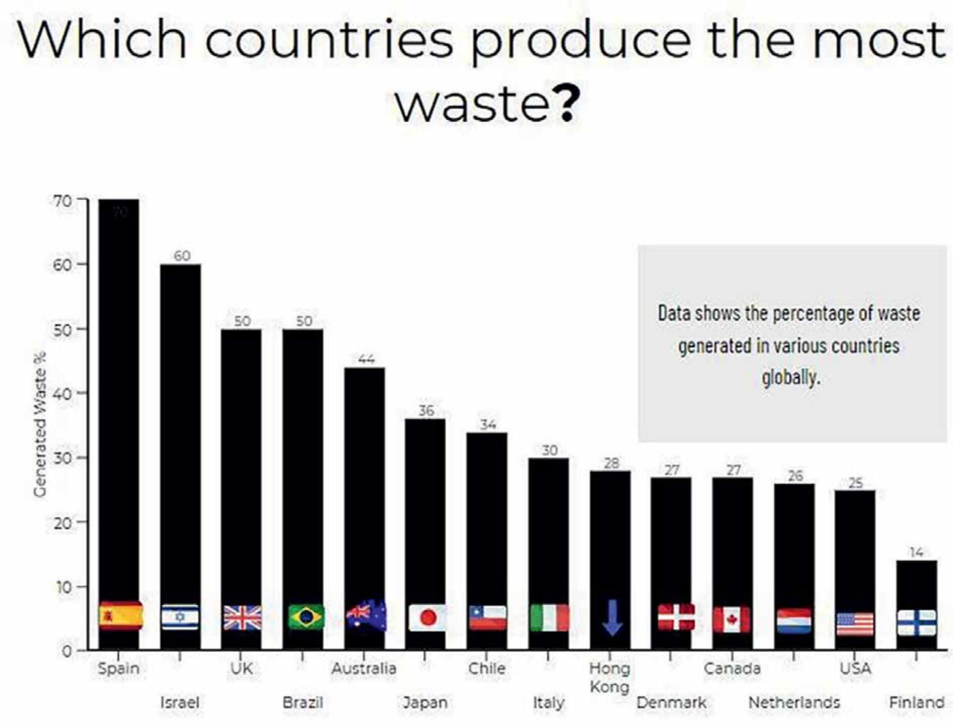
Figure 1.
Global annual waste by 2050 [5].

Moreover, 50–80% of construction and demolition waste can be recycled or reused thus indicating that mismanagement of construction waste can result in the loss of valuable economic resources [6]. Therefore, through the successful implementation of a waste management plan, project managers can often reduce the amount of waste being created within the project and the amount sent to landfills [7]. Both the environment agencies and academics globally believe that through sustainable waste management plans, construction organizations develop an understanding of the quantity of waste generated. This will enable everyone within the company from the top down to be focused and aligned with the same goals such as reuse, recycling, or reducing construction waste [8].

Waste could become a potential source of profit and a financial benefit. Because of reducing the amount of waste going to landfills, there will be a reduction in the costs of the project due to lower landfill taxes. It is also possible to recover costs by selling waste such as scrap metal, the contractor can offset construction costs, which can make them more competitive. Based on the amount of waste generated, its composition, and its treatment, the solid waste treatment and disposal estimated in 2016 was equivalent to about 1.6 billion tons of carbon dioxide (CO_2) greenhouse gas emissions, or 5% of world emissions [5]. This is mainly due to landfills and non-landfill gas collection systems' unavailability. Food waste is responsible for almost 50% of emissions. Solid waste emissions are projected to increase to the equivalent of 2.38 billion tons of CO_2 per year by 2050 if no progress is made in this area [5].

In many countries, solid waste management is usually under local responsibility, with almost 70% of countries setting up institutions responsible for regulatory oversight of waste policy development [5]. Nearly two-thirds of the countries have adopted specific solid waste management laws and regulations, the implementation of which varies considerably. In addition to regulatory oversight, and tax transfers, it is not uncommon for the central government to be directly involved in waste disposal services, and about 70% of waste disposal services are directly overseen by local governments [5]. At least half of the services, from primary waste collection to treatment to disposal, are provided by government agencies, and about one-third through public-private partnerships. However, successful financing with the private sector and operational partnerships are usually successful only under certain conditions, with appropriate incentives and implementation mechanisms, therefore, are not always the ideal solution.

Financing solid waste management systems is a major challenge, especially because of ongoing operating costs rather than capital investment; operating costs must be forecast [9]. According to The World Bank [5] in high-income countries, the operating costs of integrated waste management, including collection, transportation, treatment, and disposal, typically exceed $100 per ton. Low-income countries (Sub-Saharan Africa) spend less on waste management at about $35/ton, but in these countries, the costs are much harder to recover. Waste management is labor-intensive, with transportation costs of $20–50 per ton. The cost-effectiveness of removal services varies greatly depending on the level of revenue. In low-income countries, costs for users range from an average of $35 a year to $170 a year, and full or near-total cost recovery is generally limited to high-income countries [5]. User payment models can be fixed or variable depending on the type of user invoice. Communities typically cover about 50% of the investment costs of waste disposal systems, with the remainder coming primarily from national private sector subsidies. Globally, the production of waste varies from country to country. **Figure 2** highlights the country-wise production of waste in which Spain generates the maximum percentage of waste i.e., 70%.


Which countries produce the most waste?

Data shows the percentage of waste generated in various countries globally.

Figure 2.
Country wise waste production [10].

Hao et al. [11] argue that for too long waste management has focused on the construction practices and processes but overlooks the critical human attitudes. For a labor-intensive industry, how people perceive the importance of waste management is a definitive decider over its success, in particular how the Project Manager conveys this message. Mousavi et al. [12] make note that the success of waste reduction is down to the project manager's ability to value waste reduction as importantly as construction materials ordered. This, therefore, illustrates how attitudes and values within construction are just as critical as legislation. Therefore, the government should focus more on educating the Project Managers. Furthermore, the implementation of sustainable waste management can be bureaucratic and costly. One of these relevant pieces of legislation that construction projects within the UK have had to adhere to has been the Waste Management Plans Regulations 2008 [13], which meant obliged projects over £300,000 were required to plan how much waste the project was to produce and where it would go [14]. For some within the industry, this was considered a burden and bureaucratic and too often left out of the design stage but the design stage is a critical stage whereby waste can often be eliminated and opportunities should be taken. As already stressed on the economic opportunities from the circular economy, **Figure 3** illustrates further the circular economy opportunities by 2030 [15].

The project team along with the Project Manager can now structure the waste management plan on the dependencies within each project, which can often be unique and unpredictable. However, it should be noted that the lack of government enforcement has been a barrier to sustainable waste management, this current

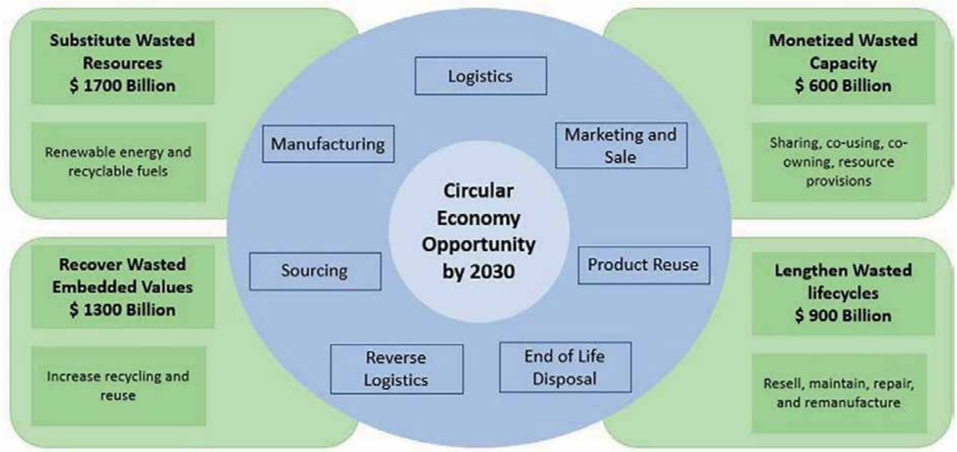


Figure 3.
Circular business model for 2030 vision [15].

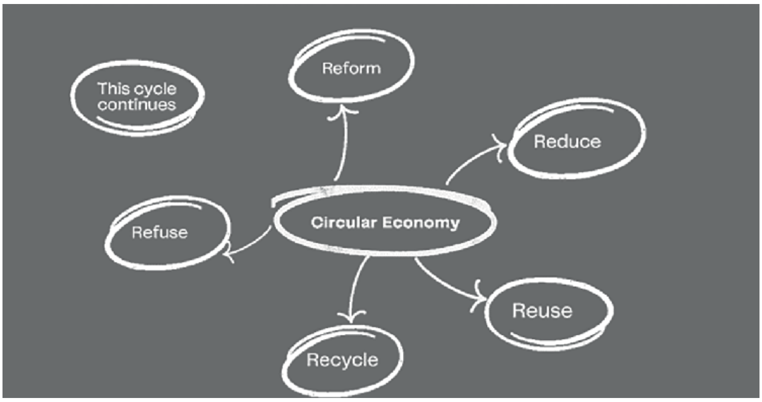


Figure 4.
Circular economy principles.

government is trying to remove this. Over the last few years, the importance of sustainability within the construction industry has grown to become with it now being a critical aspect of many companies' policies and ideals. Sustainable Waste Management is something that companies are now looking to promote within the company such as 'zero waste' to improve their public image [16]. Though some may state these theories of zero waste are unrealistic, Kannan [17] arguably makes note that sustainable procurement in the future will become ever-increasingly important and therefore companies who promote themselves as green may take advantage of these future projects. As well as future procurement rules, construction waste management should be looked at as a cost-savings initiative as well as sustainability. The contractors should not just look at improving productivity or compressing schedules but instead first look into using their sustainable waste management as a way of making huge cost savings. In other words, the contractors and associated project managers should look at waste as not just a problem but as an asset to the project. Therefore, considering the principles of circular economy as shown in **Figure 4**, it is a closed-looped system in which raw materials, components, and products lose minimum value with maximized utilization of renewable energy resources. The circular economy will contribute to a more sustainable world as the focus of both concepts is people, planet, resources, and economy.

2. Impact of construction waste on the economy

While the circular economy is gaining more and more attention, mining and primary commodity prices continue to rise. The circular economy estimates that 9% of all raw materials have been fully recycled in 2019. In 2018, the proportion was slightly higher at 9.1% [18]. Theoretically, 100% of the raw materials in the circular economy are fully recycled and no new raw materials are needed. The implementation of this scenario will take a very long time, as methods must be found to completely recycle the materials currently used in the products. Circular economy and sustainability go hand in hand. This is clearly illustrated in **Figure 5** in which circular economy contributions include: strategic planning (SP), cost management (CM), circular supply chain management (CSCM), quality management (QM), environment management (EM), process management (PM), logistic and reverse logistic (L&RL), service management (SM), and research and development (R&D).

2.1 Economic growth

An important principle of the circular economy is that economic growth must be separated from the use of raw materials. As a result, the economy is not hampered by a lack of raw materials for growth. The transition to a circular economy is expected to accelerate economic growth. The United Nations Environment Program (UNEP) [20] estimates that by 2050, the global economy will benefit from about $2 trillion

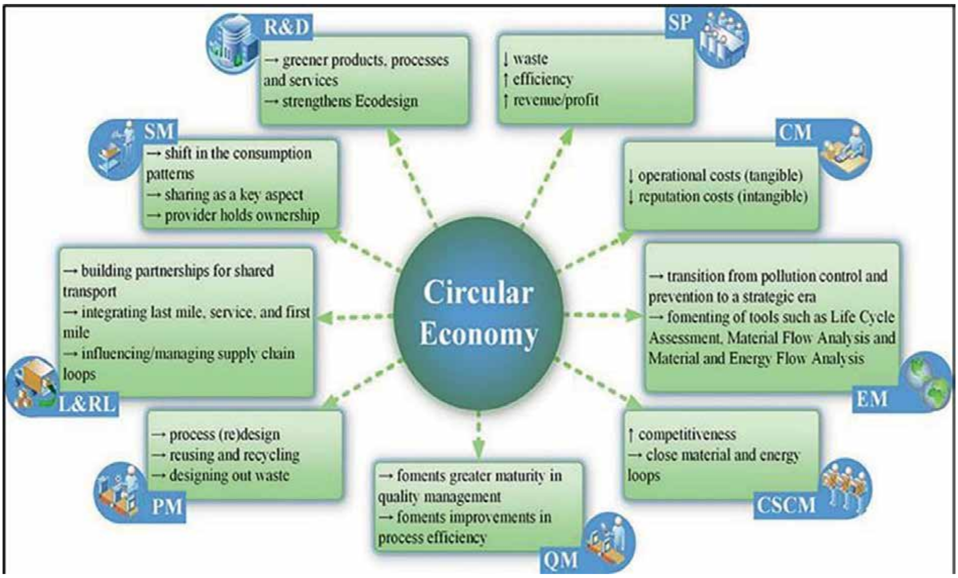


Figure 5.
Circular economy and sustainable development [19].

a year and more resource efficiency. In a circular economy, this growth is bound to happen. On the one hand, by increasing revenue from new circular operations, and on the other hand - by creating more functions on the same number of materials and production capacity. The development, production, and maintenance of these circular products require a special workforce that expands these jobs. On the other hand, the need for extraction and processing of raw materials decreases, which reduces the amount of less specialized work [21]. This increases labor costs, which is good for job opportunities and gross national product (GNP).

2.1.1 Growth in employment

In a circular economy, labor is valued more than raw materials. As a result, employment is rising. These jobs go back to a time- and quality-intensive patchwork; Employment in logistics through the recycling of local products; new businesses through innovation, the service economy, and new business models.

2.1.2 Innovation growth

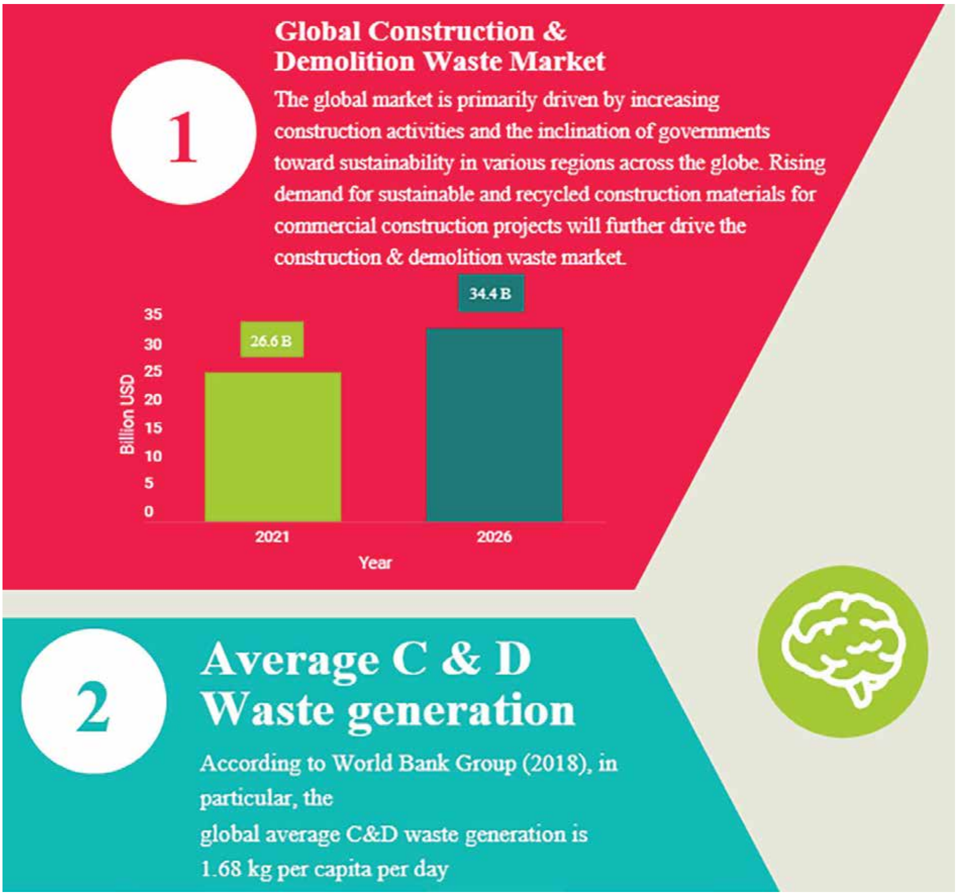
The circular economy is a challenge for innovative solutions based on a new way of thinking. This means thinking about circular instead of linear value chains and trying to optimize the whole system. This leads to new ideas, interdisciplinary collaboration between designers, manufacturers, and processors, and thus to environmental innovation.

2.1.3 Demand change

The final key factor in the economic benefits of a circular economy is a better understanding of the shift and demand side. Since companies deal with their customers and their role throughout their lives, this ultimately leads to less resource use, less waste production, and production change.

The construction industry is the highest storage of materials and waste in the economy. The large city of Amsterdam alone processes 1.4 million tons of mining material every year, with a value of up to €688 million. At the same time, the production of new building materials has a significant impact on the environment. Thanks to the high-quality processing, foldable and modular design, this value can be capitalized on and protect the environment. According to Kaza et al. [5], in a report published by The World Bank Group, the global per capita per day of waste generation is 1.68 kg. Additionally, the global C & D market will also expand at a compound average growth rate of 5.30% between 2021 and 2026 with a market value of about $34.40 billion as shown in **Figure 6**.

The benefits of a circular economy create opportunities for businesses. This creates new profit opportunities, a more stable supply of materials, increasing demand for a range of services, and stronger relationships with customers. In the transition to a circular economy, companies are reducing material costs and creating entirely new, profitable markets. Raw materials are expensive in many industries. The extraction of new raw materials and the uncertainty of their supply in the linear economy increase the price of these materials. Revenues can, for example, offer new profit opportunities through lower costs, greater security of raw material supply, closer supply chain collaboration, and stronger supply chains. The circular economy ensures that a company uses less raw materials and more recycled raw materials and maximizes the



The global market is primarily driven by increasing construction activities and the inclination of governments toward sustainability in various regions across the globe. Rising demand for sustainable and recycled construction materials for commercial construction projects will further drive the construction & demolition waste market.

According to World Bank Group (2018), in particular, the global average C&D waste generation is 1.68 kg per capita per day

Figure 6.
Average C & D waste generation [5].

value of these raw materials throughout its life cycle. As a result, the entrepreneur has relatively fewer material costs than labor costs, so the price and availability of materials have less impact on the stability of the business model. With greater stability, a firm can make more profitable and targeted long-term investments. The circular economy offers new business models and opportunities to retain customers. The transition from product delivery to services, leasing, and leasing models creates a long-term relationship between the buyer and the supplier, as more relationships are established over the life of the product. If the supplier remains responsible for the product delivered, intermediate service, maintenance, repair, and good communication can lead not only to customer satisfaction but also to customer loyalty, ensuring that the customer repurchases products after the end of the contract.

3. Construction waste prevention in the circular economy

In construction, life cycles significantly reduce material costs and environmental impact. Having said that, mining materials are of great value, provided they are recycled in a quality manner. The Ellen MacArthur Foundation [22] also appreciates the significant benefits of moving toward a circular economy. Their "circular scenario" could reduce Europe's annual net consumption to €32 trillion by 2030, with an additional €0.7 trillion due to the slowdown in financial markets and, €0.5 trillion due to other external issues. Similarly, the EMF [22] discusses €320 billion of "potential investments" for Europe by 2025. They are prone to speculation about the cost of capital and equipment. European GDP is expected to grow by 11% in 2030 and 27% in 2050 if they adopt a circular economy, compared to 4% and 15% in the current circumstances, which is driven by higher consumption, mainly as a result of tight market regulations and huge competition creating issues in the adoption of profitable opportunities in the circular economy. Under the conditions of a circular economy, GDP could increase by 7 percentage points more than the current rate in 2030 and the gap could widen by 12% by 2050. Moreover, the cost-saving for China, if they adopt a circular economy, could be $5.31 trillion by 2030 and $11.20 trillion by 2040 [23].

In addition to this economic value, the quality recycling of building materials also significantly reduces the environmental impact of the sector. The construction industry currently accounts for 5% of total CO_2 emissions in the Netherlands. Most of them are intended for the production of building materials. Therefore, these emissions would be much lower if recycled materials were used in the construction industry. According to the principles of the circular economy, global greenhouse gas emissions are automatically reduced. Climate change and material use are closely linked. According to Circle Economy [24], 62% of global greenhouse gas emissions (excluding land use and forestry) come from the extraction, processing, and production of goods to meet society's needs; only 38% is spent on providing and using products and services [18]. For example, if the economy became a circular reality, EU emissions would fall by 56% by 2050. The reduction in global pollution will be even greater as the EU stops importing raw materials from non-EU countries, which will also reduce greenhouse gas emissions in these countries. Moreover, the storage of raw materials and the disposal of waste have a negative impact on inventories. These natural areas are important for the preservation of ecosystem services and the natural and cultural heritage.

Many governments and organizations today are primarily concerned with protecting nature from the extraction and disposal of soil and waste. To systematically protect nature, this extraction and production must be stopped completely. This is achieved in a circular economy. Construction has so many facets that companies and administrators can use a variety of strategies to make it more circular. Five main methods:

1. Recycling of high-quality waste to reduce the need for primary raw materials

2. Processing of materials to preserve the value of raw materials

3. Demountable structures so that parts of the building can be reused

4. Modular design to adapt buildings to new functions

5. Collective design usage so that residents can share buildings and objects

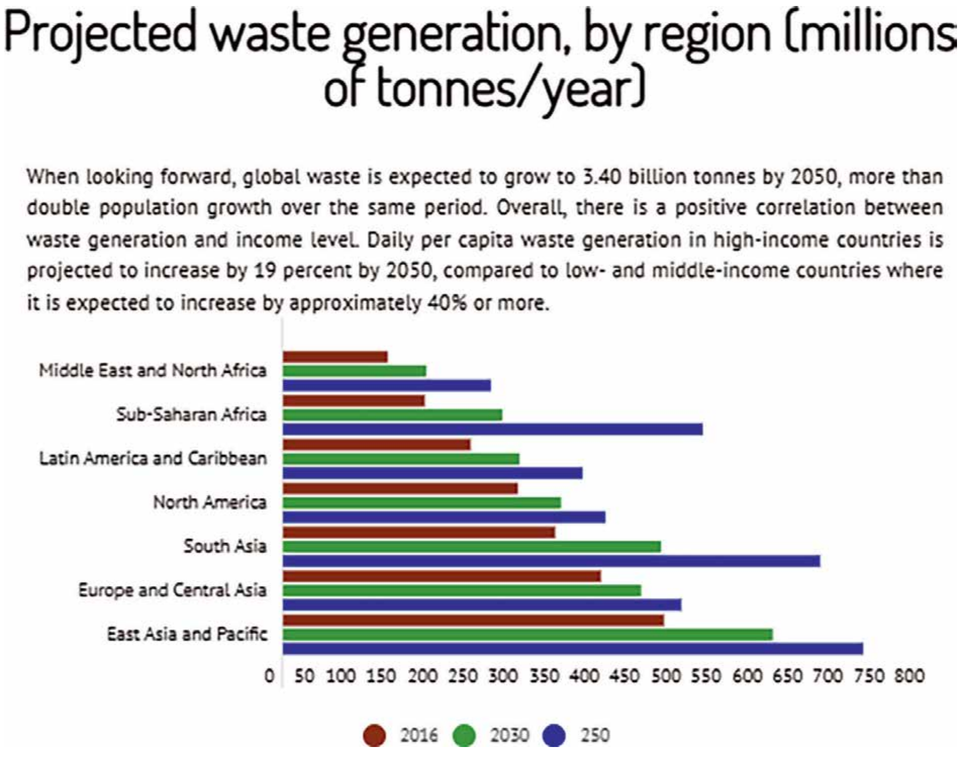
Although the efforts are being done globally by the stakeholders to control the waste generation, still more robust contributions are needed. The projected global waste generation region-wise is highest in East Asia and the Pacific region i.e., 500 million tons/year in 2016, which is expected to reach approximately 240 million tons/year in 2030, and 750 million tons/year by 2050 as shown in **Figure 7**.

Despite the benefits of the circular construction sector, there are still four factors hampering its development: market development, measurement methods, policy, and knowledge.

3.1 Market development

The demand for circular construction projects is still very much dependent on public supply because modular or foldable construction projects are often even more expensive than the linear construction approach. The innovative nature and limited range of circular construction solutions lead to higher investment costs. However, it takes years to renovate or tear down the building's savings or benefits. The circular design must therefore create added value to be accepted in the market. In addition, it is important to have a measurement method and more knowledge about this value between builders, builders, financiers, and other parties in the chain.

To talk about the market value of construction waste after recycling, it is expected that with the adoption of circular economy adoption, waste can be minimized by saving $100 billion per year with improved construction productivity [25]. Moreover, in the USA alone, 76% of construction and demolition waste was recovered and recycled in 2020 which created 681,000 jobs and outnumber the conventional waste disposal jobs 9 to 1, generating $37.80 billion in wages, and $5.50 billion in tax revenue collection [26]. As steel is the major element in construction, 650 million tons of steel is recycled and reused



Projected waste generation, by region (millions of tonnes/year)

When looking forward, global waste is expected to grow to 3.40 billion tonnes by 2050, more than double population growth over the same period. Overall, there is a positive correlation between waste generation and income level. Daily per capita waste generation in high-income countries is projected to increase by 19 percent by 2050, compared to low- and middle-income countries where it is expected to increase by approximately 40% or more.

Figure 7.
Region-wise projected waste generation [5].

globally which approximates 98% of recycling and reuse from steel waste [27] and helped generate billions of dollars thus significantly contributing to the economic growth.

3.2 Methods of measurement

If the added value of circular construction can be demonstrated in terms of environment, health, comfort, safety and operating costs, the demand for circular construction will increase. If the lender is unable to assess the value of the raw materials in the movable building, they cannot include them in the calculation. Therefore, standard measurement methods are needed. However, for an effective and accepted measurement method, all partners in the chain must be involved.

3.3 Knowledge

Market development and standardized measurement methods require knowledge construction at all stages of the chain. The building can still be designed in a circular shape, but it is also not circular when the subcontractor seals the gaps with foam. To achieve this level of knowledge, courses must be upgraded at all levels, from university to pre-vocational secondary education. In addition, special reinforcement courses should be offered.

3.4 Policies

The circular design becomes interesting only when the plus value is measured and recognized. Public policy can contribute by acting as an initial customer and guiding the development of measurement methods and chain knowledge. In addition, there is room for experimentation with rules, so that companies can experiment with new construction methods and cost-effective projects. In addition, the benefits of ring design will only be felt in the long run. Thus, the government is primarily the country that can give meaning to the development of circular constructions.

4. Approaches related to the circular economy

4.1 Traditional approach

The circular economy is fundamentally different from the linear economy. In short, in a linear economy, raw materials are extracted and discarded into a product after use. In a circular economy, we close all these raw materials. Completing these circuits requires much more than recycling. It changes the way value is created and maintained, how production becomes more sustainable, and how business models are used. The circular system and the linear system differ in value creation or retention. The linear economy traditionally follows a "take-produce-throw" stepwise procedure. This means that the raw materials are collected and then converted into products that are used until they are finally disposed of as waste. In this economic system, value is created by producing and selling as many products as possible. Whereas, the 3R approach is followed in the circular economy: reduce, reuse and recycle. Minimum resource utilization (reduced). Ensure reuse of materials and products as much as possible (reuse). And lastly, the raw materials are highly processed (recycle).

The sustainability perspective in the linear economy is different from the circular economy. When we operate sustainably in a linear economy, the emphasis is on

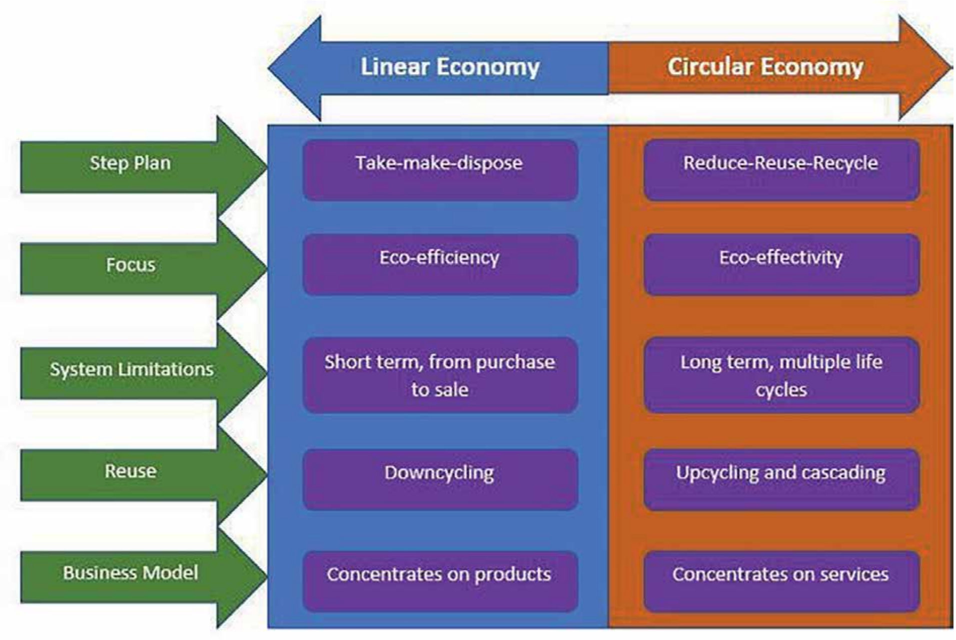


Figure 8.
Comparison between conventional and sustainable circular economy approaches.

eco-efficiency, meaning we try to minimize our environmental impact to achieve the same result. This extends the time in which the system becomes overburdened [28]. The system of eco-efficiency usually works during downcycling: part of the product(s) is recycled due to poor quality use, which reduces the value of the material and makes it difficult to reuse and recycle the flow of materials as shown in **Figure 8**.

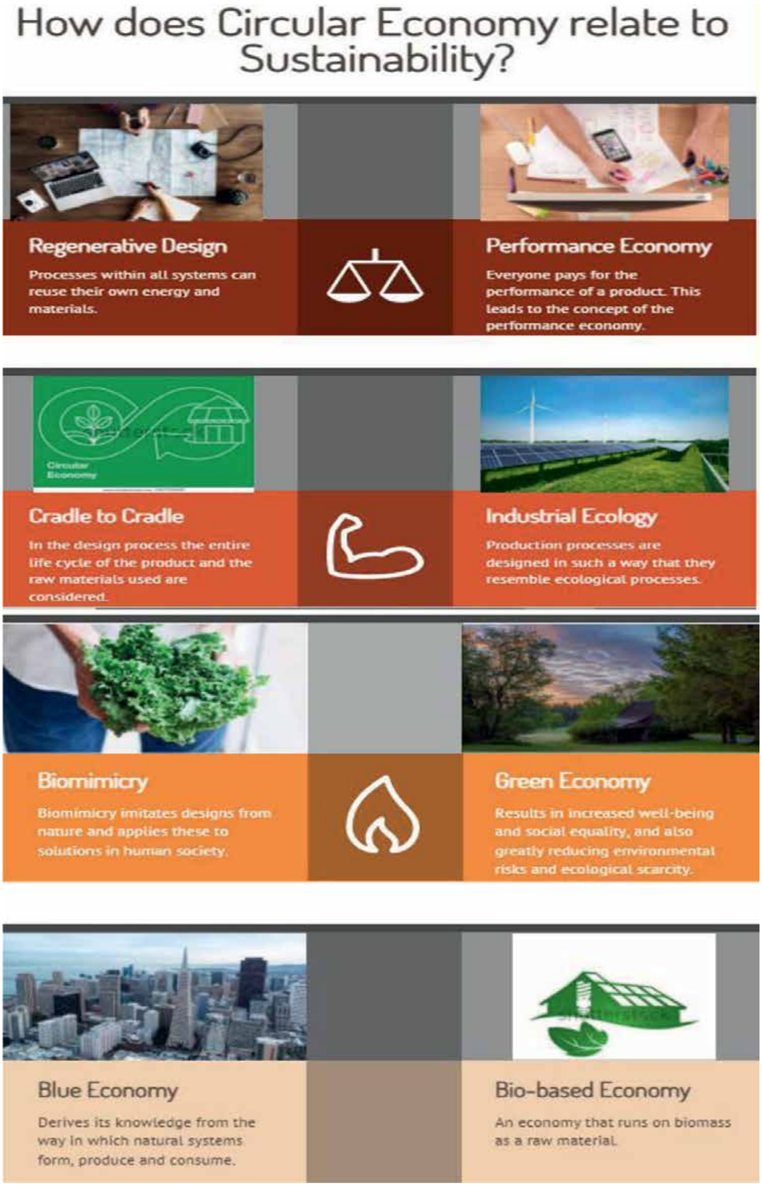
4.2 Sustainable approach

4.2.1 Life cycle assessment (LCA)

LCA is the most popular method for sustainable waste management. LCA has become a significant waste management tool that studies the environmental characteristics and potential effects throughout the product life cycle, from the supply of raw materials to production, utilization, and disposal. LCA can point out the current environmental impact of emissions and waste. It is widely used to compare the environmental impact of waste with treatment options for efficient energy management (WtE). The results can provide an overview and scientific support for various environmental aspects of waste management strategies for the attainment of sustainable waste management. It has been used to assess many aspects of WtE systems, including greenhouse gas emissions, energy performances [29], circular economy [30], and impact on global warming [31].

4.2.2 Waste to energy approach (WtE)

Waste to energy or energy from waste is one of the sustainable approaches to waste management that has the potential to meet future energy needs and is economically and environmentally sustainable. It is a mass burnt waste to energy process of converting waste into electricity or heat energy or it can also be said as "fuel from waste". It is not only a sustainable waste management solution, but also economically viable, especially for developed nations. One of the world's primary energy sources is currently fossil fuels, which account for about 84% of total electricity production [32]. Due to the rapid depletion of fossil fuel reserves, the world needs alternative energy sources, such as the WtE, to address the future energy crisis.


How does Circular Economy relate to Sustainability?

Regenerative Design
Processes within all systems can reuse their own energy and materials.

Performance Economy
Everyone pays for the performance of a product. This leads to the concept of the performance economy.

Cradle to Cradle
In the design process the entire life cycle of the product and the raw materials used are considered.

Industrial Ecology
Production processes are designed in such a way that they resemble ecological processes.

Biomimicry
Biomimicry imitates designs from nature and applies these to solutions in human society.

Green Economy
Results in increased well-being and social equality, and also greatly reducing environmental risks and ecological scarcity.

Blue Economy
Derives its knowledge from the way in which natural systems form, produce and consume.

Bio-based Economy
An economy that runs on biomass as a raw material.

Figure 9.
Sustainable approaches to circular economy.

Baran et al. [10] indicated that energy recovery through waste incineration (a WtE technology) is an integral part of an environmentally sustainable waste management method. Nevertheless, Yay [19] indicated in his study that this method is not always economically sustainable due to high operating and maintenance costs. But, the WtE method is a way of recovering energy from waste in the form of heat, electricity (bypassing gas or steam through a turbine), or fuel [33]. WtE technologies are now considered suitable for solving waste-related issues. Impact of Sustainable construction waste management on Economy. Other sustainable approaches to the circular economy presented in **Figure 9** include:

1. Regenerative design: Regenerative design is focused on the concept of developing a project that mimics the restorative characteristics of nature to achieve a positive effect.

2. Performance economy: In the performance economy, the aim of the sale is not the product itself, but the performance it delivers, and the benefits it provides to the consumer.

3. Cradle to cradle: The main goal of the cradle-to-cradle approach is to create products that are 100% beneficial to humans and the ecosystem, which will actually improve the quality of life, not just cause less harm.

4. Industrial ecology: It focuses on the natural level of production processes and services and mimics the natural system for conserving and reusing resources.

5. Biomimicry: In biomimicry, the inspiration is taken from nature and natural systems.

6. Green economy: The relationship between people and the environment is established through low carbon, resource-effective, and socially inclusive processes.

7. Blue economy: Sustainable utilization of ocean resources for optimizing economic development, enhanced livelihoods of inhabitants, and employment opportunities while conserving the health of the ocean ecosystem.

8. Bio-based economy: It is defined as an economy in which materials, chemicals, and energy come from renewable biological resources.

5. Government role in the circular economy

The Circularity Gap Report [24] states that by 2019, only 9.1% of the world's raw materials will be fully recycled. In 2018, it was still 9.5 percent. Internationally, the world of circular economy is changing. In addition to developing policies, governments can use their role as buyers and customers to stimulate the circular economy. The state as a buyer must take into account the entire process from production to disposal. To be able to play an effective role as a new partner, it is important that governments actively collaborate with companies. The concept of purchasing power clearly shows how purchasing power can influence prices, affordability, and development.

Local governments buy more than €40 billion a year and central governments more than €20 billion. Traditionally, buying is the best value for money. Today, government procurement is being used to change the world. As a result, dozens of government bodies signed a Green Procurement Agreement 2.0 in 2018 [18]. In the context of the circular economy, it is important to use the term purchasing in the broadest sense of the word. Attention at the time of purchase is not limited to the time of purchase (transaction) or even the course of demand at the time of purchase. Procurement starts with the initial description of the requirements and ends when the end product is reused or reissued. Governments should therefore see public procurement as a process in which:

1. The government body formulates a demand based on the need to provide work, goods, or services; it is then procured by a government agency in cooperation with the supplier.

2. The supplier delivers the goods, works, or services following the conditions laid down in the performance of the contract.

3. The product is used at the end of its life.

Moreover, the government should invest in an organizational culture where innovation is important. Make sure that policy and implementation work together to set ambitious and responsible goals and create space for personalization and experimentation. Support those who want to innovate and strengthen communication and collaboration. Governments must make clear to the market what their ambitions are. Stimulate the market to get moving and contribute to these ambitions. Join less frequent suppliers, describe their profit potential, and provide opportunities for innovation in procurement processes. Sometimes the government itself must be actively involved in realizing the desired innovations. It is about supporting innovation efforts that help market countries build a cartel set up by the government. Together with the market, it maintains the development (ideas), concludes role and turnover-sharing agreements, and organizes the management of the innovation portfolio. Governments can deploy additional and sometimes different policies to promote the transition to a circular economy. For example, definitions of waste and raw materials and legislation and regulations are outdated. In addition, the policy focuses mainly on recycling and traditional partnerships and the transition from taxation to employment has not yet taken place. In addition to the national level, the global governments must continue to formulate their international role in the circular economy. The number of raw materials extracted worldwide is increasing year after year. The following recommendations to strengthen public policy and the circular economy:

1. Make sure the prices of the products and services include environmental damage.

2. Use more compulsion and enforcement in policies such as mandatory taxes, more legislation, and standards. Currently, the vast majority of initiatives are not yet mandatory.

3. Step-by-step confirmation of government requirements for circularity of tenders and auctions, including in the context of producer responsibility.

4. Develop a detailed overview of the circular economy, widely supported by civil society organizations, and develop it for specific purposes.

5. There must be a clear division of roles between the implementing bodies, for example between the different sectors.

6. Develop decision criteria and measurement system. This results in goal setting, evaluation, and peer review.

7. Promote international knowledge transfer. This will accelerate the international dissemination of effective policy.

8. Build a global coalition for diverse and inclusive action. This coalition will increase the capacity of the leaders.

9. Project managers should try to eradicate the production of waste and pollution from the original designs of the projects.

10. Top management should prioritize only those materials that can are durable, reusable, and recyclable.

11. The environment should be transformed and improved through regeneratable natural systems.

12. Stakeholders should strive for higher technological development, renewable material resources, and energy-efficient processes.

13. Through circular economies, production costs can be lowered, which will directly expand economic growth.

14. Technical and knowledge regarding circular economy should be spread globally at all levels in the companies will pave way for the adoption of circular economy principles.

15. Financial structures should be improved to remove all hurdles for those investors and companies who are willing to adopt a circular economy as part of their business cultures.

Figure 10 shows a model for the design and disposal of waste material throughout the value chain. This method comprised the triple value system, making clear interdependence of the three types of dynamic systems i.e., industry, society, and the environment. Resources are withdrawn from nature, go through production processes to develop a value for markets, and then the generated wastes are moved to the reuse or recycle phase.

The role of governments in linking enterprises to the circular economy market is significant. By establishing the legal frameworks, developing strategic plans and public services guidelines, and making sound decisions about the functioning of organizations in the circular economy, governments can respond to the needs of the circular products and impact the business functioning ways. Large municipalities, in particular, have a positive impact on the community and industry, with maximized

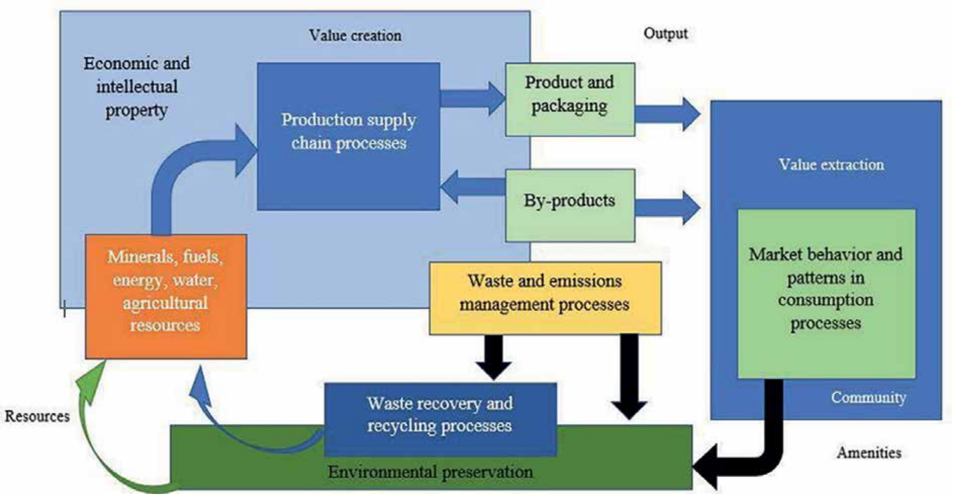


Figure 10.
Sustainable waste management model [15].

purchasing power and can influence millions of shareholders through effective policies and procedures. Moreover, public dedication, policies and regulations, programs specifically targeting the particular materials, environment-friendly purchasing in procurement, and long-term processing contracts can link the circular market with the enterprises. These steps from governments will pave way for the companies and will motivate them to join hands in sustainable construction waste management.

6. Role of enterprises toward circular economy

In our consistently growing industrialized and densely populated world, the present pattern of manufacturing and consumption of goods and materials by people around the world may not fulfill the necessities of consumers. The supply chain around the world is predominated by the linear economy, an economic model in which raw materials are treated, utilized, and then disposed of as waste. Due to the high cost of processes in a linear economy, and heavy dependence on fossil fuels, this unique method is a major producer of greenhouse gas emissions globally.

If businesses around the world continue normally with the same concept of linear economy till 2050, global demand for resources will continue and it could almost triple resulting in the land reserves being depleted by more than 400% [34]. If the world does not transition to a purely circular economy, it can stop a functioning society, not just the economy. Linear approaches such as further deforestation for agriculture, and persistent use of non-renewable resources in construction projects, which contributes to habitat degradation and contributes to climate change, are already in the sixth mass extinction. However, investors can support the global acceptance of the circular economy in several areas i.e., public and private equity, fixed income, etc. Such investment strategies, along with discouragement of businesses and interests that sustain the linear economy, can lead to a future of environmental, social, and economic sustainability [35].

Organizations globally are taking steps to adopt the circular economy practices in their manufacturing, production, and logistics procedures to obtain the benefits of the circular economy and help preserve the environment. According to Mazonni [36], the companies like Nike, Burger King, Loop, Ikea Furniture, Adidas, Puma, Patagonia, H&M, HP, and The North Face have successfully adopted the circular economy principles to get closer to optimizing their operations in which nothing becomes waste. This step will motivate other companies to follow as well. Furthermore, many cement and concrete manufacturing companies in Colombia are adopting sustainable product development goals with minimized energy and water consumption [37]. Apart from this, the flooring company Desso has adopted circular economy principles by utilizing the cradle-to-cradle approach in its operations. Similarly, the ventures like Cycle Up, Waste Marketplace, and Backacia are encouraging construction waste to recycle, reuse, and circularity adoption [38].

7. Conclusion

Sustainable waste management is a key concept in the circular economy and offers many opportunities and benefits for the economy, society, and the environment. This is a systemic approach to economic development that utilizes the waste management model and seeks to optimize economic growth from limited resources. Sustainable waste management helps meet the far-reaching challenges of a linear consumer society, but also offers a faster solution to many of the problems that waste causes. It includes collection, sorting, reuse, recycling, and, with the appropriate availability of facilities, provides energy and resources. This will create jobs, improve waste management techniques, and reduce the effect of human activities on the environment, leading to better air and water quality. It minimizes waste, protects against high environmental costs, and protects from dangerous health problems, thus improving the overall state of human life.

The goal of sustainable waste management is to use materials for as long as possible and to minimize the amount of solid waste that is discharged or incinerated in landfills. But in our current linear economy, waste is generated just before the product is produced. A deeper approach to sustainable waste management must focus on the entire product life cycle to help reduce the negative impacts of waste on the environment, society, and economy. Moreover, sustainable waste management reduces the utilization of natural resources. Recycling and reusing of materials extracted from nature should be ensured and the generation of as little waste as possible must be attained. We have to maintain sustainability for our environment and future generations. A sound and well-functioned sustainable waste management system should integrate feedback loops, concentrate on processes and procedures, adaptability and constructability, and divert waste from disposal.

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Conflict of interest

The authors declare no conflict of interest.

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References

[1] Tan CS, Ho ST, Hashim WS, Lee H, Taib CT, Ho MR. Energy, economic and environmental (3E) analysis of waste-to-energy (WTE) strategies for municipal solid waste (MSW) management in Malaysia. Energy Conversion and Management. 2015;**102**:111-120

[2] Luangcharoenrat C, Intrachooto S, Peansupap V, Sutthinarakorn W. Factors influencing construction waste generation in building construction: Thailand's perspective. Sustain. 2019;**11**(13):3638. DOI: 10.3390/su11133638

[3] Di Foggia M, Beccarello G. Designing waste management systems to meet circular economy goals: The Italian case. Sustain. Prod. Consum. 2021;**26**:1074-1083

[4] Research and Markets. Construction & Demolition Waste Market Report 2021: Opportunity in Innovations for Sorting and Recycling Technologies for Efficient Treatment of Construction & Demolition Waste. Dublin: GlobeNewswire; 2021. [Online]. Available from: https://www.globenewswire.com/news-release/2021/09/13/2295592/28124/en/Construction-Demolition-Waste-Market-Report-2021-Opportunity-in-Innovations-for-Sorting-and-Recycling-Technologies-for-Efficient-Treatment-of-Construction-Demolition-Waste.html [Accessed: March 4, 2022]

[5] Kaza Silpa F, Yao Lisa C, Bhada-Tata P. Van Woerden. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development. Washington, DC; 2018. [Online]. Available from: https://openknowledge.worldbank.org/handle/10986/30317?outputType=amp&locale-attribute=es. [Accessed: March 5, 2022]

[6] Kofoworola SH, Gheewala OF. Estimation of construction waste generation and management in Thailand. Waste Management. 2009;**29**(2):731-738

[7] Liu XJ, Yi Y, Wang. Exploring factors influencing construction waste reduction: A structural equation modeling approach. Journal of Cleaner Production. 2020;**276**:123185

[8] Fikri Hasmori M et al. The on-site waste minimization practices for construction waste. IOP Conference Series Materials Science Engineering. Melaka, Malaysia: Material and Structural Engineering. 2020;**713**(1):012038. DOI: 10.1088/1757-899X/713/1/012038

[9] Cheng Y, Hu H. Municipal solid waste (MSW) as a renewable source of energy: Current and future practices in China. Bioresource Technology. 2010;**101**(11):3816-3824

[10] Baran BB, Mamis B, Alagoz MS. Utilization of energy from waste potential in Turkey as distributed secondary renewable energy source. Renewable Energy. 2016;**90**:493-500

[11] Hao JR, Tam JL, Yuan VW, Wang HP, Li JY. Dynamic modeling of construction and demolition waste management processes: An empirical study in Shenzhen, China. Engineering Construction and Architectural Management. 2010;**17**(5):476-492

[12] Mousavi IM, Almasi S, Karim A. Survey of solid waste management in Mahabad, Iran. International Journal of Health and Life Sciences. 2015;**1**(1):50

[13] Shiers L, Weston D, Wilson J, Glasson E, Deller J. Implementing new

EU environmental law: The short life of the UK site waste management plan regulations. Journal of Environmental Planning and Management. 2014;**57**(7):1003-1022

[14] Hayward S. The Site Waste Management Plans Regulations 2008: A Summary. UK: IBB Solicitors; 2008

[15] Fiksel K, Sanjay J, Raman P. Steps toward a resilient circular economy in India. Clean Technologies and Environmental Policy. 2021;**23**(1):203-218

[16] Awasthi M, Cheela AK, D'Adamo VS, Iacovidou I, Islam E, Johnson MR, et al. Zero waste approach towards a sustainable waste management. Resour. Environ. Sustain. 2021;**3**:100014

[17] Kannan D. Sustainable procurement drivers for extended multi-tier context: A multi-theoretical perspective in the Danish supply chain. Transp. Res. Part E Logist. Transp. Rev. 2021;**146**:102092

[18] Kenniskaarten. Circular Economy. Knowledge Map. [Online]. Available from: https://kenniskaarten.hetgroenebrein.nl/en/knowledge-map-circular-economy/related-schools-of-thought/. [Accessed: January 9, 2022]

[19] Yay ASE. Application of life cycle assessment (LCA) for municipal solid waste management: A case study of Sakarya. Journal of Cleaner Production. 2015;**94**:282-293

[20] United Nations Environment Programmme (UNEP). Smarter Use of Resources Can Add $2 Trillion Annually to the Global Economy. 2017. [Online]. Available from: https://www.resourcepanel.org/reports/resource-efficiency. [Accessed: March 5, 2022]

[21] Sulich L, Sołoducho-Pelc A. The circular economy and the green jobs creation. Environmental Science and Pollution Research. 2021;**29**(10):1-17

[22] EMF. Growth Within. 2015. [Online]. Available from: https://unfccc.int/sites/default/files/resource/Circular%20economy%203.pdf. [Accessed: March 6, 2022].

[23] EMF. Circular Economy Opportunity for Urban and Industrial Innovation in China, A Report. 2018. [Online]. Available from: https://docplayer.net/184435479-The-circular-economy-what-why-how-and-where.html. [Accessed: March 6, 2022].

[24] Circle and Economy. Circularity Gap Report. 2021. [Online]. Available from: https://www.circularity-gap.world/2021 [Accessed: March 7, 2022]

[25] Guerra C, Shahi BC, Mollaei S, Skaf A, Weber N, Leite O, et al. Circular economy applications in the construction industry: A global scan of trends and opportunities. Journal of Cleaner Production. 2021;**324**:129125

[26] United States Environmental Protect Agency. Recycling Economic Information (REI) Report. 2020. [Online]. Available from: https://www.epa.gov/smm/recycling-economic-information-rei-report-and-methodology. [Accessed: March 6, 2022]

[27] AISC. Structural Seel: The Premier Green Construction Material. American Institute of Steel Construction. 2022. [Online]. Available from: https://www.aisc.org/why-steel/sustainability/ [Accessed: April 4, 2022]

[28] Niero PP, Kalbar M. Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product

level. Resour. Conserv. Recycle. 2019;**140**:305-312

[29] Sun S, Fujii L, Tasaki M, Dong T, Ohnishi H. Improving waste to energy rate by promoting an integrated municipal solid-waste management system. Resour. Conserv. Recycle. 2018;**136**:289-296

[30] Pan PC, Du SY, Huang MA, Liu IT, Chang IH, Chiang EE. Strategies on implementation of waste-to-energy (WTE) supply chain for the circular economy system: A review. Journal of Cleaner Production. 2015;**108**:409-421

[31] Lausselet AH, Cherubini C, Oreggioni F, del Alamo Serrano GD, Becidan G, Hu M, et al. Norwegian waste-to-energy: Climate change, circular economy, and carbon capture and storage. Resour. Conserv. Recycle. 2017;**126**:50-61

[32] Ouda NE, Raza OK, Nizami SA, Rehan AS, Al-Waked M, Korres R. Waste to energy potential: A case study of Saudi Arabia. Renewable and Sustainable Energy Reviews. 2016;**61**:328-340

[33] Zhao L, Jiang XG, Li GW, Wang A. Economic analysis of the waste-to-energy industry in China. Waste Management. 2016;**48**:604-614

[34] Forbes. How Companies Can Support a Circular Economy. 2021. [Online]. Available from: https://www.forbes.com/sites/forbesbusinesscouncil/2021/01/26/how-companies-can-support-a-circular-economy/?sh=78b4a6d44660 [Accessed: February 13, 2022]

[35] Pieroni MPP, McAloone TC, Pigosso DCA. Circular economy business model innovation: Sectorial patterns within manufacturing companies. Journal of Cleaner Production. 2021;**286**:124921

[36] Mazzoni M. 10 Brands That Embraced the Circular Economy in 2020. Tripple Pundit. The Business of Doing Better. 2022. [Online]. Available from: https://www.triplepundit.com/story/2020/brands-circular-economy-2020/709596 [Accessed: April 4, 2022]

[37] Maury-Ramírez JA, Illera-Perozo A, Mesa D. Circular economy in the construction sector: A case study of Santiago de Cali (Colombia). Sustainability. 2022;**14**(3):1923

[38] Lopez K. 5 Examples of Circular Economy Solutions in the Construction Industry. ConstructConnect; 2021. [Online]. Available from: https://www.constructconnect.com/blog/5-examples-of-circular-economy-solutions-in-the-construction-industry. [Accessed: April 4, 2022]

Chapter 5

Circular Economy in Buildings

Noah Gethsemane Akhimien, Ahmed Abdullah Al Tawheed, Eshrar Latif and Shan Shan Hou

Abstract

This chapter is centred on waste management in buildings. It discusses the principles of applying circular economy in buildings toward resource efficiency with regard to the building sector. The study investigates a series of building assessments and reviews different aspects of energy efficiency as it relates to circular economy in buildings. It recommends the best practices to ensure the reuse and recycling of building components during and after the life of a building. The world is experiencing huge resource depletion and it is eminent to research the waste management practices in the building industry, Circular Economy offers major interventions in buildings which are explored in this chapter, another aspect of the discussion in this chapter is the design for disassembly and design for recycling under the concepts of circular economy.

Keywords: building, waste, recycle, reuse, circular economy, sustainability

1. Introduction

Building construction and demolition industries are the largest contributors to overall waste among the other industries globally [1]. Due to the non-recyclability of building materials, almost 50% of the entire waste is generated by the construction industries [2]. In 2016, European member countries have generated 2.54 billion tons of waste which are expected to rise to 3.4 billion tons per year by 2050 [3]. The journal of the European Union [4] suggested a waste hierarchy to deal with materials in the following order: prevention, preparing for re-use, recycling, recovery and, finally, disposal. Moreover, European Commission (2018) prepared a protocol and guideline for waste management to implement circular economy.

Globally, the construction sector has been developing environmental burdens by consuming primary resources, and energy and producing a significant amount of waste [5]. This industry is accountable for 36% of CO_2 emissions and 40% of total energy consumption in Europe [4]. As this sector is consuming a huge amount of primary resources, especially minerals, wood and ferrous metals, it is of utmost importance to figure out ways to minimize the consumption rate and impact on climate change [5]. Using recyclable materials and utilizing the building waste after demolition can help to reduce this burden and impact on our climate [5]. To increase the material values and use available resources in a circular material flow by recycling process, [6] proposed the concept of the circular economy (CE). Moreover, European Commission [4] prepared a protocol and guideline for waste management to

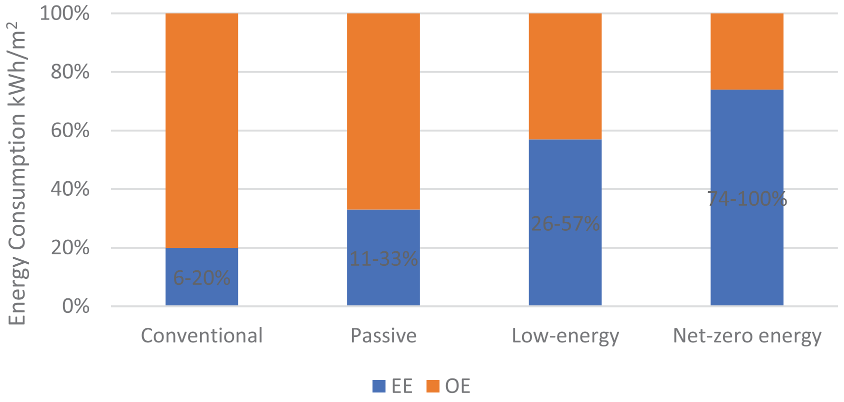


Figure 1.
Energy use accountability of EE and OE [11].

implement circular economy. Utilizing recovered building materials directly is more beneficial than recycling options as the reusing of building materials requires minimal energy usage than the recycling process [7]. Building deconstruction is preferable to the demolition process because of the economic and environmental benefits [8].

The alarming increase rate of building energy use and carbon emission has raised the issue to create new policies and strategies for sustainable and zero-energy building design and construction [9]. Energy-efficient buildings and constructions can change the energy use prospects in the coming decades and ensure the sustainability of the built environment [10]. Consequently, low-energy buildings can be one of the solutions to achieve the carbon reduction targets for the coming decades. But low energy buildings often use strategies like plastic insulation, energy-efficient service systems, and shading devices which reduce their operating energy demand at the expense of increasing the rate of embodied energy emission [11] (**Figure 1**).

Due to the high embodied carbon emission of low-energy buildings, the concept of reusing, and recycling building materials have been developed globally by many researchers to increase the resilience and durability of building materials. Building designers can contribute to minimizing the number of resources and materials used in construction by following the principles of circular economy [12]. Therefore, there are many scopes for researchers and designers to figure out the possibilities of designing low-energy buildings with lower embodied carbon emissions by reusing or recycling the same building materials or waste.

To address this issue, developing a material matrix will help to quantify the circularity of materials and enable the designers to be informed to prevent the harmful impact of the buildings on our environments [13]. Although the feasibility of circular economy may face several barriers like cost-effectiveness, quality, legislation and required time, this can contribute to protecting our natural resources and preventing global climate change.

2. Circular economy in buildings

The consumption rate of natural resources is at twice the rate they are produced, and it would be three times by 2050 [14]. To minimize the rising demand for natural resources, pressure is increasing on the built environment. Ellen MacArthur foundation generated a circular approach to building materials to reuse the resources and reduce the carbon footprint. According to the Eurostat waste statistics (2011) [6], 60% of the total waste is not recycled, composted, or reused. A continuous loop of material use, repair and recycling can retain their optimum intrinsic value and this circular process of using materials can reduce waste and carbon emission [15]. The aim of the circular economy strategy is to maximize the potentialities of the materials and utilization of available resources through the circular flow of building materials, decreasing waste, reduction of primary resource consumption, and environmental burden [6]. To ensure material sustainability and reduce embodied energy, the circular economy is significant to consider in any building design phase [16].

High-rise buildings are often associated with higher initial embodied energy [11]. Embodied energy (EE) is defined as the total energy used for the production, transportation, and installation of building material [11]. Ellen Macarthur Foundation [6, 14] proposed eco-effectiveness of building materials which will create metabolism to use the material repeatedly at a high level of quality. Using the material repeatedly can increase the quality of environmental quality, economic prosperity, and social equity at different levels like cities and nations [17].

2.1 Circularity of building materials

Building components should be selected with their potentialities of circularity by following the 3Rs (reduce, reuse, recycle) hierarchy of circular economy [15]. An extensively clean life cycle strategy of circulating building materials in society, excluding contaminants and adulteration, is required to reduce the consumption of primary

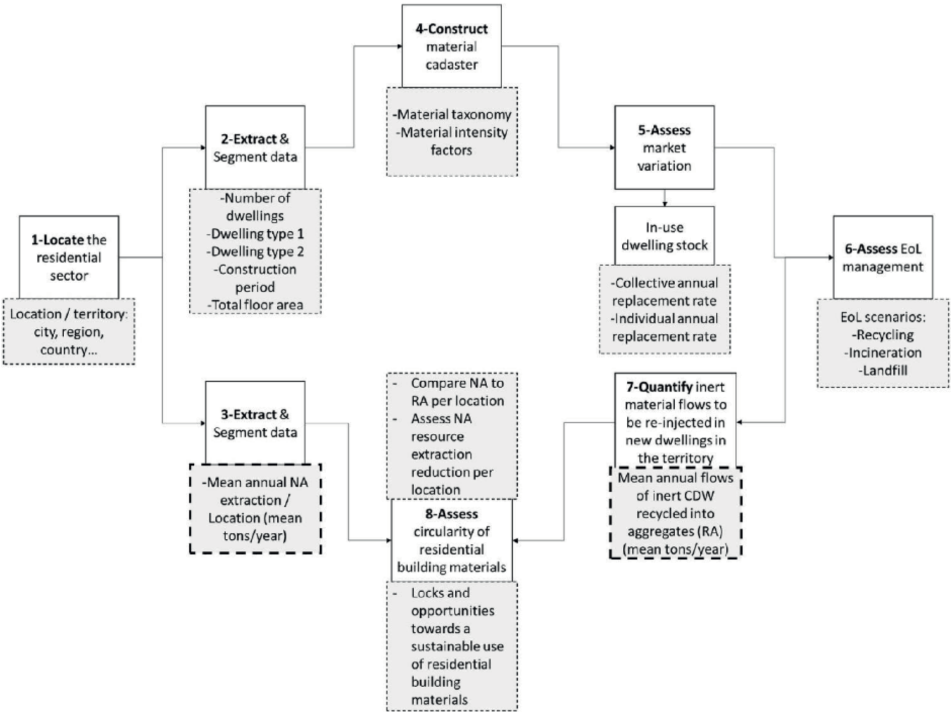


Figure 2.
Model framework to assess circularity of the building materials [16].

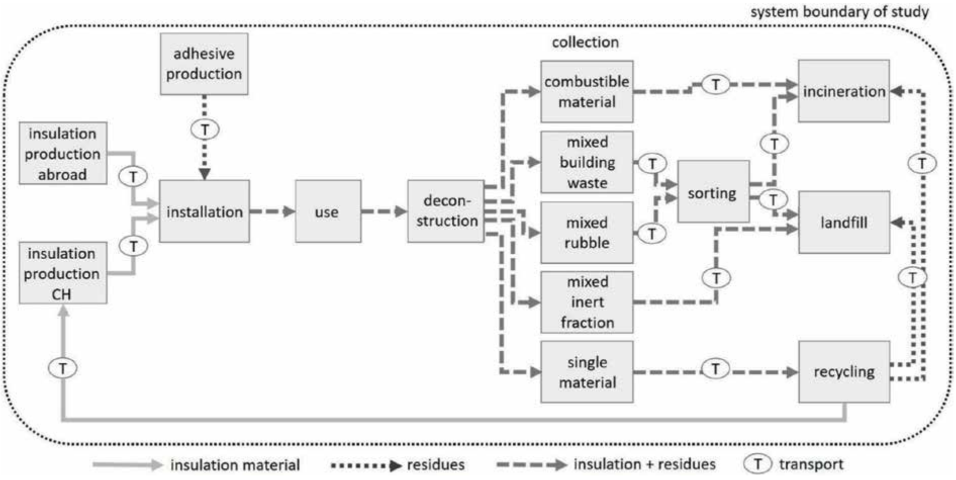


Figure 3.
Representation of processes, material flows, transport and system boundary of the thermal insulation material case study.

resources [18]. Tazi [16] used a replicable methodology to locate, extract, construct and assess the end-of-life (EOL) and circularity of the building material (**Figure 2**).

He also created a model map flow, based on a material flow analysis (MFA) and a STAN (State-of-the-art platform) software run for uncertainty assessment, which can thus be used by decision-makers in cities in order to yield an outlook of material stock and flows which were contained in French residential buildings over a time period extending from 1919 until late 2013 [16] (**Figure 3**).

Wiprachtiger M. et al. [19] suggested the sustainable circular system design (SCSD) method in three structured phases to provide an extensive assessment of material flow, impact and circular economy strategies. One-third of the 60 metals studied by Eurostate (2011) [20], showed a global end-of-life recycling rate of 25% or more. Taking a closer look at various ferrous and non-ferrous metals reveals that even for metals that already have high recycling rates, it was found that significant value has been already lost [6].

2.2 Evaluation of circular economy of building materials

From a circular economy perspective, the major criteria to consider in the selection of construction materials for all types of buildings should include local availability, embodied energy, recyclability potential, recycled content, renewability potential, potential to reduce construction waste, life span and durability, and maintenance needs [11]. According to Potting et al. [21], the circular economy (CE) principle is based on the assessment of 10 circularity strategies which are refuse, rethink, reduce, re-use, repair, refurbish, re-manufacture, repurpose, recycle, and recover.

Recyclability- Generally, recyclability means converting waste materials into new products, materials or ingredients [22]. Recyclability is one of the prime strategies to establish the design of a circular economy through a closed loop [20]. From the analysis by [22, 23], the thermal recycling process was identified as one of the best processes and the mechanical recycling process was found as the least energy-consuming process.

Reusability- The concept of reusing materials is one of the most sustainable and established methods to reduce the waste and use of primary resources [24]. Reusing contraction materials can reduce not only the building materials but also the overall cost of the project [24].

Toxicity- Toxicity of the material is defined as the behavior to release sufficient harmful chemicals or ingredients during the production or end of life which can directly or indirectly impact the environment negatively [25]. Incinerated wastes, slags, dust, sludges and other hazardous products are considered toxic waste [22].

Assembly and disassembly- Assembly refers to the installation or construction of individual parts and disassembly refers to the detachment of individual parts of building fabric including wall cladding, non-structural wall panels, flooring, kitchens and internal finishes [26]. Disconnecting of different materials may take place at any time in the whole life cycle of the building, including renovation or the end of the building's life.

Wastage- The number of materials that cannot be used or recycled or reused in the construction process is counted as wastages. Analyzing the construction and demolition waste, Noor et al. [26] have identified the major construction wastes which are plastic, wood, steel, surplus mortar, surplus concrete, broken bricks, green waste and excavated soil.

Finishing- Finishing refers to the additional layer of materials over the real materials which is generally used to enhance the durability and esthetic aspects of the materials.

From the analysis of [2], the highest reusability ratio was found in the buildings with the structural components largely made of steel structure. Other building structural components like timber structure have 0.65 reusabilities and 0.35 recyclability, and concrete structure has 0.42 reusability and 0.58 recyclability (**Figure 4**). The concrete structures are difficult and unsuitable to reuse as it has the least reusability of 0.42 [26]. By comparing the recyclability and reusability quality of different materials, designers will have a clear understanding of the building materials which can increase the circularity of the building materials.

The whole life performance of the buildings and required adjustment opportunities can be analyzed with a BIM-based whole life performance estimator (BWPE) model which also leads to an efficient material recovery system for the circular economy [2]. Akanbi et al. [2] prepared a table to establish the recyclability, reusability, toxicity, finishing and connection typology of the building materials for the building structure, floor, roof, frame, wall, doors, windows and ceiling systems (**Table 1**).

End-of-life scenarios can demonstrate the possibility of reusing or recycling existing building materials which help to select the materials in line with circular economy strategies. But due to the lack of sufficient research on the end-of-life treatment of each building material, it is not possible to decide on the end-of-life scenarios of all the materials of the building precisely. Tazi [16] investigated end-of-life treatment on some of the building materials which are listed in **Table 2**.

Based on the design science approach of Hever et al. [31], the Circularity Assessment Tool (CAT2022) was prepared by Tokazhanov et al. [32]. The circular economy in the construction industry was the focal point of this assessment tool which was a process and practitioner-based assessment tool. The third-party assessment was also involved to include the responses from the construction industry at different positions and levels. This proposed tool can also complement the existing certification method circular economy by providing specific and required information.

However, the 3DR method can be different due to the local recycling and reuse regulations and facilities. Northern European countries can recover almost 80%

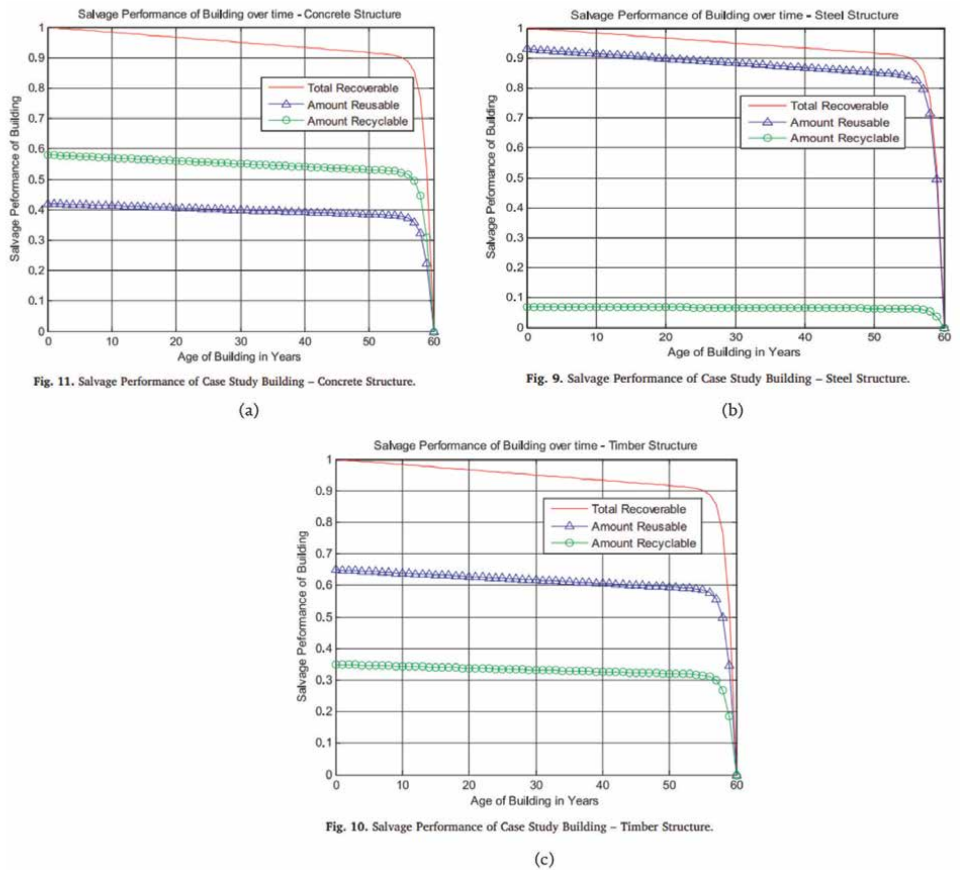


Figure 4.
Salvage performance of materials (a) concrete (b) steel (c) timber [2].

Systems and options	Recyclable (r_1)	Reusable (r_2)	Toxic (x)	Sec. Finish (s)	Connection type
1. Structural Foundations H-Pile foundation	✓	✓	×	×	*cb*
Concrete ground beam	✓	×	×	×	*cf*
Concrete with mastic tanking	✓	×	×	×	*cf*
2. Floor system Insitu Concrete floor with ceramic tiles	✓	×	×	×	*cf*
Precast Concrete slab with carpet	✓	×	×	×	*cd*
Timber floor with ceramic tiles	✓	✓	×	×	*cn*
3. Structural frame system Exposed Steel with fixed connections Concrete Encased Steel	✓	✓	×	×	*cf*
Exposed Steel with bolted connections	✓	×	×	×	*cf*
Concrete Encased Steel with bolted	✓	✓	×	×	*cb*
Timber with bolted connections	✓	✓	×	×	*cd*

Systems and options	Recyclable (r_1)	Reusable (r_2)	Toxic (x)	Sec. Finish (s)	Connection type
Timber with nailed connections	✓	×	×	×	*cb*
Reinforced Concrete with bolt	✓	✓	×	✓	*cf*
4. Wall system Demountable dry internal wall – Steel Curtain wall	✓	✓	✓	✓	*cb*
Brick/block cavity wall	✓	✓	×	×	*cb*
Cladded timber cavity wall	✓	×	×	✓	*cb*
Steel framed wall	✓	×	×	✓	*cn*
5. Doors and windows Glass with aluminum frame Timber with timber frame – Softwood	✓	✓	×	×	*cb*
Timber with timber frame – Hardwood	✓	✓	×	✓	*cn*
6. Ceiling system Aluminum strips with steel frame	✓	×	×	✓	*cf*
Soffit plaster and paint	✓	✓	×	×	*cf*
Timber planks with timber frame	✓	✓	×	✓	*cn*
Ceiling tiles with metal frame	✓	✓	×	✓	*cn*
7. Roof system Flat galvanized steel on Z profile beams	✓	✓	×	×	*cn*
Reinforced concrete roof	✓	✓	×	×	*cn*
Pitched roof timber structure	✓	×	×	✓	*cf*
Tiles covering on a pitched roof	✓	✓	×	×	*cn*

Table 1.
Material selection options for building [2].

Materials	Treatment	Materials	Treatment
Stone [27]	88% recycled þ 12% landfilled	Concrete and block concrete [27]	88% recycled þ 12% landfilled
Solid and hollow bricks from baked clay [27]	88% recycled þ 12% landfilled	Tiles from baked clay	100% recycled
Gypsum [28]	100% recycled	Mortar and mineral plaster	100% recycled
Glass [29] Wood and conglomerated wood	85% recycled þ 15% landfilled 61% recycledfilled þ 28% incinerated þ 11% land	Mineral wool [30] Metals (steel, aluminum and zinc)	100% recycled 98% recycled þ 2% landfilled
Polymers (PVC þ PS þ PU) [29]	70% recycled þ 30% incinerated	Asphalt þ Sand [29]	100% recycled

Table 2.
End of life scenarios for construction and demolition waste [16].

Description	**Mass (kg)**	**Tools needed**	*DIt*	**Transport tools**	*DIm*	**Resilience**	*Ri*
Structural materials							
Steel chassis and load-bearing structure	16,138.9	Gas/ pneumatic tool	0.5	Forklift	0.4	Infinitely reusable	1
Stairway steel structure	422.8	Gas/ pneumatic tool	0.5	Forklift	0.4	Recyclable	0.6
Lightweight steel structure, internal walls	3590.3	Power tool	0.8	Two people	0.9	Infinitely reusable	1
Bolts and nuts	97.7	Power tool	0.8	One person	1	Recyclable	0.6
Pressed fiber particle board used as floor structure	4102.6	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glass wool used in all external walls and ceiling	2325.6	No tool	1	One person	1	Recyclable	0.6
Glass wool used in the roof	190.4	No tool	1	One person	1	Recyclable	0.6
Screw pile lightweight steel foundations	735	Hydraulic plant	0.2	One person	1	Recyclable	0.6
Finishes							
Carpet covering 193 m^2 of internal floors	183.4	No tool	1	One person	1	Reusable 3 times	0.9
Vinyl covering floors in wet areas	714	Hand tool	0.9	One person	1	Reusable once	0.7
Salvaged timber composing the stairway steps	164	Power tool	0.8	Forklift	0.4	Reusable 3 times	0.9
Plywood covering internal walls and first-floor ceiling	3328.0	Power tool	0.8	Two people	0.9	Reusable 3 times	0.9
Magnetic felt ceiling	333.7	No tool	1	One person	1	Reusable 3 times	0.9
Plasterboard cladding used in kitchen/bathroom and ground-floor ceiling	140.2	Power tool	0.8	One person	1	Disposable	0
Pressed timber for ground-floor external cladding	1811.7	Power tool	0.8	One person	1	Reusable 3 times	0.9
Steel sheets for first-floor external cladding	652.1	Power tool	0.8	Two people	0.9	Infinitely reusable	1

Description	Mass (kg)	Tools needed	*DIt*	Transport tools	*DIm*	Resilience	*Ri*
Steel sheets used for roof covering	531.3	Power tool	0.8	Two people	0.9	Infinitely reusable	1
Aluminum windows and glazed doors	744.0	Hand tool	0.9	Two people	0.9	Reusable 3 times	0.9
Internal timber doors	138.0	Power tool	0.8	One person	1	Infinitely reusable	1

Note: DIt = the tool(s) required to disassemble components; DIm = equipment required to move components; Ri = resilience of components.

Table 3.
Building material analysis [33].

of construction materials, but Brazil can recover only 6% of the construction waste [26] (**Table 3**).

For oil-based materials, the most emission-intensive process is production, followed by the incineration of the material itself and then the incineration of the attached glue and plaster. For mineral insulation materials, the environmental impact of production surpasses the impacts caused by the oil-based materials (inert material landfill) [19] (**Figure 5**).

The main drawback of the circular economy process is the disassembly or demolishing process, material size, and further installation process may require

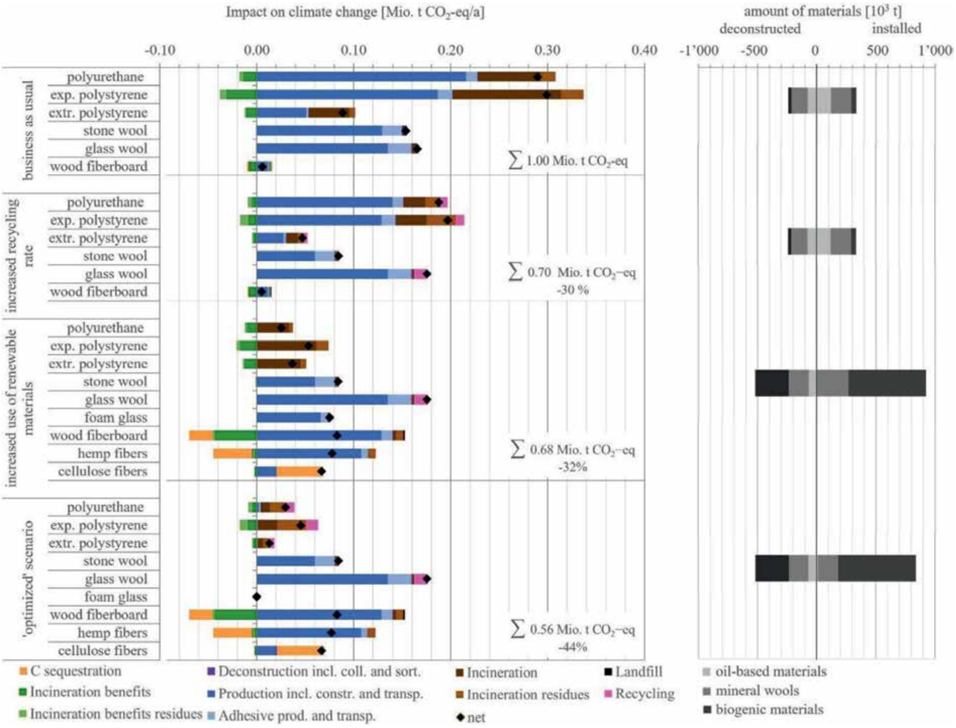


Figure 5.
Impact of different insulating materials [19].

Author	Research name	Research design	Study purpose	Key insights
Hopkinson et al. [34]	Recovery and reuse of structural products from end-of-life buildings.	Comprehensive literature review approach.	CE application to materials and building components.	• Recycling process can contribute to the environmental benefits • Research on environmental wellbeing and material reusability is not sufficient
Honic et al. [35]	Improving the recycling potential of buildings through material passports (MP): an Austrian case study	Creating a methodology to compile the Material Passport of the building, through the use of BIM.	Material matrix or passport for building materials. The authors tested the method with a case study of timber vs. concrete.	• Although concrete is recyclable, it produces more waste than timber. • Integration of a circular economy can be beneficial for the environment if it is started from the early design phase.
Jimenez-Rivero and Garcia-Navarro [36]	Best practices for the management of end-of-life gypsum in a circular economy.	Survey and literature review.	To collect sufficient information on recycling gypsum waste.	Many countries still do not have any proper regulations or policies for the recycling of gypsum. The following issues are also limiting the process- • On-site segregation. • Skilled workers • Lacking knowledge on disassembly
Verbinnen et al. [37]	Recycling of MSWI bottom ash: a review of chemical barriers, engineering applications and treatment technologies	General review.	Investigating the probabilities and limitations of using MSWI fly-ashes.	The combination of by-products with other materials can cause secondary consequences like heavy metal concentration.
Parron-Rubio et al. [38]	Concrete properties comparison when substituting a 25% cement with slag from different provenances.	Testing different types of slag as by-products To substitute concrete.	Reusability of concrete by integrating bioproducts.	• Reusing waste (Cross-Industry) is a new opportunity to develop a circular economy, • Combination of slag and concrete can be double beneficial.
Rose et al. [39]	Cross-Laminated secondary timber: experimental testing and modeling the effect of defects and reduced feedstock properties.	Research on used timber in cross-laminated secondary timber (CLST).	Comparison of the different structures of CLT with similar types of products.	• Conventionally, used-timber or similar products have the tendency to down-cycled before disposal. • In the EU, reusability of timber is not allowed. CLST is proven to have similar characteristics to CLT.

Table 4.
Focus on circular economy practices.

some additional time and cost in some cases [24]. However, when a good number of material and construction companies will start the recycling unit and maintain the supply chain regularly then the recycling products will be regular products which will reduce the demand for using materials from primary resources. Due to a lack of research on the circular economy, there are no proper databases or building material matrixes that can be followed by professionals to select the building materials with circular economy potentialities. There are few studies that were based on specific types of materials or properties, but they are not precise enough to take decisions when compared with other materials. As a consequence, a building material matrix is necessary where a wide range of building materials will be present and identified with their circular economy potentialities like recyclability, reusability, toxicity, wastages, assembly and disassembly.

The main drawback of the circular economy process is the disassembly or demolishing process, and further installation process may increase the required time to complete the project and cost in some cases Atkins [24]. Because the material recycling plant will need the time to recycle the materials after the demolishing of the building and prepare them to use or reuse in the new building. However, when a good number of material and construction companies will start the recycling unit and maintain the supply chain regularly then the recycling products will be a regular products which will reduce the demand for using materials from primary resources.

2.3 Summary of state of art of circular economy

This subsection summarizes the studies which are focused on circular economy in **Table 4**.

3. Embodied energy of tall buildings

This subsection presents the embodied energy of different building materials which can be reused in the process of circular economy and their relationship with the operational energy consumption of the building (**Table 5**).

3.1 Embodied energy of building materials

The embodied energy of building materials means all the energy which were expended during the production of that material, from the extraction of resources to the final manufacturing processes, transportation, and construction. Embodied energy (EE) difference among the different tall buildings is significant not only for the thermal performance or specific construction types but also for the material selection process. Maintaining the circularity principles of building materials is also responsible for the difference in EE in tall buildings. The combination of a conscious material selection process and durable design decisions can also help to achieve 50% embodied energy saving in the building.

3.1.1 Building structure, floor and walls

The embodied energy of the building rises according to the floor level of the building as the tall building requires more structural materials. Azari and

Author	Research name	Research design	Study purpose	Key insights
Eberhardt et al. [40]	Life cycle assessment of a Danish office building designed for disassembly.	LCA of a building designed for disassembly, a case study in Denmark. Four different structural materials are compared to traditional buildings.	To identify the potentialities of environmental savings, the authors investigated the LCA and reusability of concrete, steel, and timber structure.	• Components of building service systems are very significant and • influence the LCA of buildings. • By reusing the building components three times, Up to 60% of savings can be achieved.
Brambilla et al. [41]	Environmental benefits arising from demountable steel-concrete composite floor systems in buildings	LCA of different concrete/steel floor structure technologies designed for disassembling (case studies).	Evaluating the impact of structural components and technologies on the environment.	Reusing the structural components multiple times can reduce the negative impacts on the environment.
Tingley et al. [42]	Understanding and overcoming the barriers to structural steel reuse, a UK perspective.	Semi-structured interviews and literature study.	Identify the limitations and barriers of steel components in the UK and prepare a framework to overcome them overcome these barriers.	• Demand for reused steel components is not still popular in the market and their reintegration in the market is unachievable. • Disassembling and reusing steel the structure can be more expensive • Government can create pressure to reuse and recycle building materials by implementing new regulations.
Akanbi et al. [2]	Salvaging building materials in a circular economy: a BIM-based whole-life performance estimator.	BIM and case study evaluation.	Use of BIM and calculate the reusability and recyclability of building materials accurately.	Buildings designed with the BIM tools have the potentialities to provide 93% reusable components.

Table 5.
Focus on design for disassembly.

Abbasabadi [11, 34] compared embodied energy of building materials on different floor levels in **Table 6**.

3.1.2 Windows and window frames

Giordano [44] investigated the operational energy (OE) and embodied energy (EE) of different types of façades in 5 climatic zones. Although, in terms of OE,

Source	**Method**	**Number**	**Structural System & Material**	**EE of Structure**	**Total**	**CED**
		of floors		(GJ/m^2)	EE(GJ/m^2)	(GJ/m^2)
Treloar, et al. [26]	Economic Input–output	3	Precast concrete walls, floors and columns	—	10.7	—
		7	Reinforced concrete	—	11.9	—
		15	Reinforced concrete frame	—	16.1	—
		42	Reinforced concrete core with composite columns	—	18	—
		52	Steel frame with reinforced concrete core and floor slabs	—	18.4	—
Foraboschi et al. [2]	Process-based	20	Steel frames and steel-concrete floor	3.3	—	—
		30		3.3	—	—
		70		5.6	—	—
		20	Reinforced concrete frames and slabs	2.2	—	—
		30		2.3	—	—
		20	Reinforced concrete frames and floors with the 3rd lightweight floor system	2.9	—	—
		30		3	—	—
		60		3.8	—	—
		70		3.8	—	—
Bawden and Williams [38]	Hybrid	3	Wood siding and wood frame	—	—	30
		3	Stucco on concrete block/wood joists	—	—	29.9
		4	Precast concrete panels/reinforced concrete	—	—	33.6
		4	Precast concrete panels/steel	—	—	33.7
		7	Precast concrete panels/reinforced concrete	—	—	33.8
		7	Precast concrete panels/steel	—	—	34
		11	Ribbed precast concrete/ reinforced concrete	—	—	39

Source	Method	Number	Structural System & Material	EE of Structure	Total	CED
		11	Ribbed precast concrete/steel	—	—	39.9
		21	Ribbed precast concrete/ reinforced concrete	—	—	38.6
		21	Ribbed precast concrete/steel	—	—	39.5

Table 6.
Embodied energy as a function of the number of the floors [44].

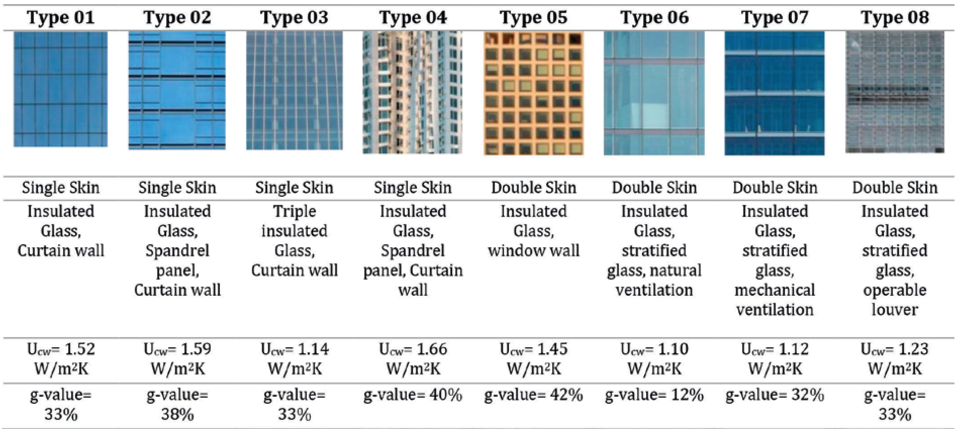
double skin systems involve lower operational energy requirements in all the climate zones, but consume higher embodied energy (**Figure 6**).

They have also experimented with the double-skin façade (U-1.10 W/m^{2}K) of "The Shard" in the UK and found that the embodied energy has increased almost double than the typical single-skin façades. Azari and Abbasabadi [11, 43] experimented with the embodied energy of different window systems from cradle to grave and found that wood has the lowest embodied carbon emission. The performance of PVC is completely opposite to the wooden window systems and Aluminum has a high operational and embodied carbon emission rate (**Figure 7**, **Table 7**).

3.1.3 Fabric insulation

In Europe, inorganic fibrous insulations like glass wool and stone wool are dominating the market of insulation materials (almost 60% of the market), and organic foamy materials like polystyrene and polyurethane account are almost 27% of the market. Different glass types, window-to-wall ratio, size, number of glass panes, and frame types are responsible for the embodied carbon emission of windows (**Table 8**).

Therefore, EE studies of tall buildings should be facilitated by comparing available materials and developing inventory databases of building materials and tools that represent tall building construction practices [43] Designer's choice made on all



Type 01	Type 02	Type 03	Type 04	Type 05	Type 06	Type 07	Type 08
Single Skin	Single Skin	Single Skin	Single Skin	Double Skin	Double Skin	Double Skin	Double Skin
Insulated Glass, Curtain wall	Insulated Glass, Spandrel panel, Curtain wall	Triple insulated Glass, Curtain wall	Insulated Glass, Spandrel panel, Curtain wall	Insulated Glass, window wall	Insulated Glass, stratified glass, natural ventilation	Insulated Glass, stratified glass, mechanical ventilation	Insulated Glass, stratified glass, operable louver
U_{cw}= 1.52 W/m^{2}K	U_{cw}= 1.59 W/m^{2}K	U_{cw}= 1.14 W/m^{2}K	U_{cw}= 1.66 W/m^{2}K	U_{cw}= 1.45 W/m^{2}K	U_{cw}= 1.10 W/m^{2}K	U_{cw}= 1.12 W/m^{2}K	U_{cw}= 1.23 W/m^{2}K
g-value= 33%	g-value= 38%	g-value= 33%	g-value= 40%	g-value= 42%	g-value= 12%	g-value= 32%	g-value= 33%

Figure 6.
Embodied energy analysis of glazed façade typologies [44].

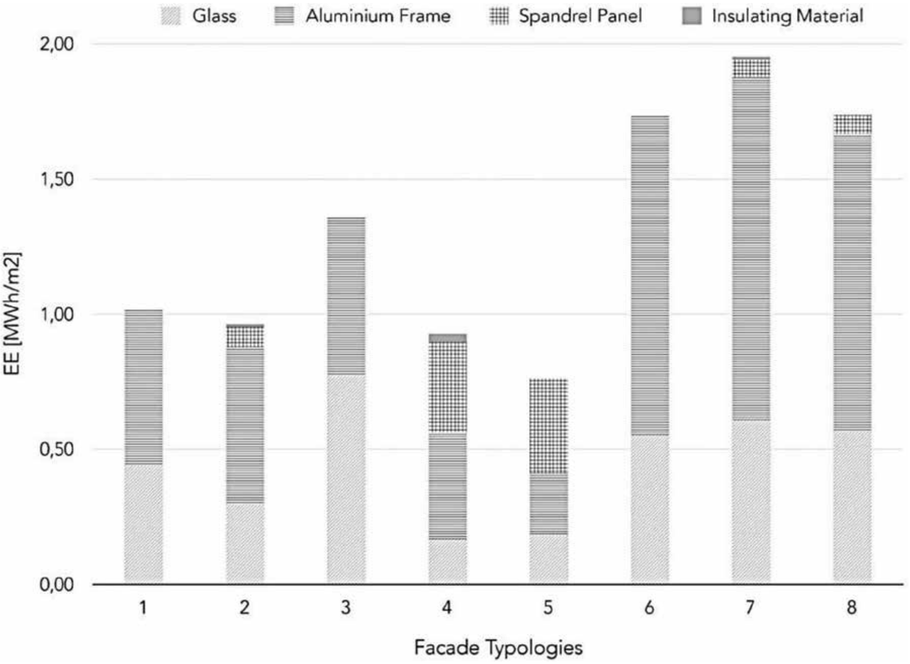


Figure 7.
Embodied energy analysis of glazed façade typologies chart [44].

Frame		Glazing	Conductivity of window (W/m^2/°C)	EE of window (kWh)	OE ∗ 50 yrs. (kWh)
Material	**Recycled content**				
PVC	0	double	0.65	352.6	1427.4
PVC	30%	double	0.65	312.6	1427.4
Aluminum without thermal break	0	double	0.89	2218.5	2194.5
Aluminum without thermal break	30%	double	0.89	1643.5	2194.5
Aluminum with thermal break	0	double	0.77	2219	1600
Aluminum with thermal break	30%	double	0.77	1644	1600
wood	—	double	0.68	138.2	1906.8
wood	—	single	1.14	84.1	2548.9

Table 7.
Cradle-to-grave embodied energy and operational energy of different windows [43].

the materials in the building construction can introduce reductions of 50% of non-renewable life cycle EE in the buildings (Himpe E et al. 2013). Comparing the embodied energy emission of steel, concrete, and wood, the following results were found.

For the non-zero-energy buildings, the impact of the building services was about 5% of the life cycle EE which is negligible but the impact of the building services

	Density	**Embodied Energy**	**Conductivity**	**Embodied Energy**
	(kg/m^3)	**MJ/kg**	**(W/m/K)**	**(MJ/m^2/RSI)**
Cellulose	40–70	0.9	0.045	1.6–2.8
Fiberboard (Enginering Wood)	190–240	11.2–11.8	0.053–0.45	113–127
Polystyrene	15–30	127	0.032–0.30	61–113
Polyurethane	30–35	137	0.035–0.020	144–96
Mineral Wool	20–140	18	0.045–0.035	16–88
Fiberglass	35	22.2	0.04	31.1

Table 8.
Embodied energy of insulation panels [43].

of zero-energy tall buildings rose to 18 and 48%. The area of research on building embodied energy is still a largely unexplored area. Many of the existing studies on EE are subject to inconsistently reported methodologies, poor data quality, lack of technological and geographical representativeness, limitations in the generalizability of results and repeatability of research, etc. [11]. While there exist strong quantitative methodologies for EE estimation in the built environment, the lack of standardized protocols is still a major problem. To reduce the embodied energy of tall buildings and increase material circularity, BIM can assist construction and demolition by providing an accurate number of materials. So that contractors are aware of valuable components which can be used in the process of circular economy.

The embodied energy of building materials is an essential component for calculating the potentialities of the circular economy of building materials. Building materials that have higher embodied energy can be recycled or reused more than materials with lower embodied energy. As a consequence, it is important to investigate and select the building materials which have lower embodied energy and high potential to reuse or recycle several times.

4. Circular economy building materials matrix

O'Grady [33] introduced the 3DR method (design, disassemblability and deconstructability) which was used to prepare a circular economy index by considering the design stage, disassembly, deconstruction, resilience of the buildings' structural fabric and finishing components. The potential second life of building materials, reuse, recycling, downcycling or disposal and the difficulty of separating materials from each other was the main influence in preparing the index [33].

The necessity of circular economy building material matrix is significantly rising as there is no specific matrix yet which can be followed by the designers to select the potential building materials. Designers and users are being more conscious of the need for recyclability and reusability of different materials to ensure holistic sustainability. But this is very challenging for them when they want to select materials for construction due to the lack of material database and tables. They need to study and research the materials to figure out the most potential materials which have the maximum value of reusability and recyclability. Due to this reason, many designers often ignore the considerations of the circular economy of building materials.

Consequently, the building construction and demolition industries are contributing the largest portion of wastage globally.

To prepare that matrix, building materials need to be selected by assessing their quality to follow the principles of circular economy. Extensive literature reviews will be studied to identify the potentialities of recyclability, reusability, toxicity, tolerance of assembly and disassembly, amount of wastage and finishing requirements of the building materials which have been being used in different types of buildings. Collected data will be used to prepare the circular economy building matrix which can be used to select the building materials that satisfy the principles of circular economy.

5. Circular economy barriers and mitigations

According to the study by [43, 45], there are 16 barriers if the circular economy in developing countries' supply chains. Among them, "lack of sufficient environmental regulations" and "lack of policies for promoting circular economy" were the main barriers. Their survey also found that only 65.33% of professionals were aware of the circular economy.

Out of 25 barriers identified from the literature, 12 barriers were shortlisted by building sector experts [45]. The MICMAC technique and CE barriers-indicator matrix were used by Bilal et al. [46] to identify key barriers to CE. According to their study, the key barriers were "lack of environmental laws and regulations", "lack of customer/public awareness", "lack of support/public awareness" and "inadequate financial resources". They also recommended further CE assessment by collecting

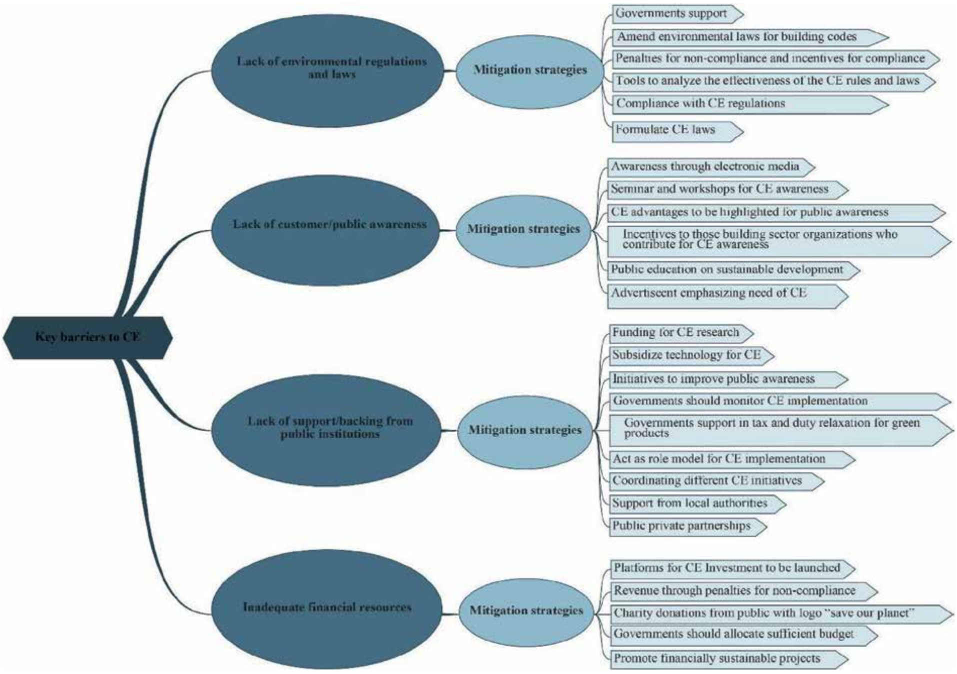


Figure 8.
Circular economy barriers mitigation framework [46].

quantitative data, the round of expert's opinions, testing building materials, and preparing database (**Figure 8**).

Inadequate knowledge and certified professionals on circular economy strategies are also significant construction problems of circular economy for a new generation and refurbished buildings. In many cases, the designers are selecting the building materials without being aware of the whole life cycle scenario of the materials. Sometimes the strategies are based on so many assumptions which may lead the strategy to failure which.

Additional detailed information should be included in the "Circular Economy Statement" which is prepared to submit to the Greater London Authority (GLA). So that, the strengths and weaknesses of the proposed strategies can be identified properly to ensure the presence of adequate measures.

6. Conclusion

Circular economy of building materials can significantly preserve the embodied carbon which is not properly defined in building regulations yet. Therefore, further improvements to the building regulations are recommended to achieve the reduction target of building energy consumption. The relationship between operational carbon and embodied carbon should be considered from the early design stage as there is always a possibility of higher embodied energy during the optimization process of the operational energy. The properties of the building materials play a vital part in resource and energy efficiency in buildings. Hence, building material matrices are also recommended to develop continuously with new materials and follow regularly to select the building materials. This process will help to enhance the potentialities of circular economy in our building construction industries and reduce the consumption of primary resources and overall project cost as well.

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References

[1] Ajayi SO et al. Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements. Resources, Conservation and Recycling. 2015;**102**:101-112. Available at. DOI: 10.1016/j.resconrec.2015.06.001 Accessed: November 2021

[2] Akanbi AL et al. Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. Resources, Conservation & Recycling. 2018;**129**:175-186

[3] Kaza S et al. What a waste 2.0. In: A Global Snapshot of Solid Waste Management to 2050. Washington, DC: World Bank; 2018 Available at: https://openknowledge.worldbank.org/handle/10986/2174

[4] European Commission. 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives

[5] Niu Y et al. Prolonging life cycles of construction materials and combating climate change by cascading: The case of reusing timber in Finland. Resources, Conservation and Recycling. 2021;**170**:1-4

[6] Ellen MacArthur Foundation. 2017. What is a circular economy? Available at: https://www.ellenmacarthurfoundation.org/circular-economy/concept. [Accessed: October 2021]

[7] Addis B. Building with Reclaimed Components and Materials: A Design Handbook for Reuse and Recycling. London: Earthscan; 2006

[8] Coelho A, de Brito J. Economic analysis of conventional versus selective demolition – A case study. Resources, Conservation and Recycling. 2011;**55**:382-392

[9] European Energy Performance of Buildings Directive (EPBD). Directive 2002/91/CE of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings. 2002

[10] Cao X et al. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. Energy and Buildings. 2016;**128**:198-213

[11] Azari R, Abbasabadi N. Embodied energy of buildings: A review of data, methods, challenges, and research trends. Energy and Buildings. 2018;**168**:225-235. DOI: 10.1016/j.enbuild.2018.03.003

[12] Petrides D et al. Dematerialisation of products and manufacturing-generated knowledge content: relationship through paradigms. Procedia CIRP. 2018;**56**:86-96. Available at. DOI: 10.1016/j.procir.2018.03.131 Accessed: November 2021

[13] Kirchherr J, Van Santen R. Research on the circular economy: A critique of the field. Resources, Conservation and Recycling. 2019;**151**:1-2. DOI: 10.1016/j.resconrec.2019.104480 [Accessed: November 2021]

[14] Ellen MacArthur Foundation. 2013. Circular economy towards the Economic and business rationale for an accelerated transition

[15] Minunno R et al. Strategies for applying the circular economy to prefabricated buildings. Buildings. 2018;**8**(9):125. DOI: 10.3390/buildings8090125

[16] Tazi N. Towards achieving circularity in residential building materials: Potential stock, locks and opportunities. Journal of Cleaner Production. 2021;**281**:3-7

[17] Kirchherr J et al. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation & Recycling. 2017;**127**:221-232. Available at. DOI: 10.1016/j.resconrec.2017.09.005

[18] Brunner PH, Rechberger H. Waste to energy – Key element for sustainable waste management. Waste Management. 2015;**37**:3-9. DOI: 10.1016/j.wasman.2014.02.003

[19] Wiprächtiger M. A framework for sustainable and circular system design: Development and application on thermal insulation materials. Resources, Conservation & Recycling. 2020;**154**:5-8

[20] Gopalraj SK, Karki T. A study to investigate the mechanical properties o frecycled carbon fiber/glass fiber reinforced epoxy composites using a novel thermal recycling process. Publishers of Open Access Journal. 2020;**8**(8):2-16. DOI: 10.3390/PR8080954

[21] Potting J et al. Circular Economy: Measuring Innovation in Product Chains. The Hague: PBL Netherlands Environmental Assessment Agency; 2016

[22] Ganon M, Dupla F. Glass-ceramic and their applications. In: Encyclopedia of Materials: Technical Ceramics and Glasses. Vol. 2. 2021. pp. 709-727. DOI: 10.1016/B978-0-12-818542-1.00008-4

[23] Khalid MY et al. Natural fiber reinforced composites: Sustainable materials for emerging application. Results in Engineering. 2021;**11**:1-8. DOI: 10.1016/J.RINENG.2021.100263

[24] Atkins C. Sustainability of glass in construction. In: Sustainability of Construction Materials. 2009. pp. 171-183. DOI: 10.1533/9781845695842.171

[25] Hanon S. Testing Biomaterials. Biomaterials Science1996. pp. 215-242. DOI: doi.org/10.1016/B978-0-08-050014-0.50010-9

[26] Noor T et al. Types sources and management of urban wastes. In: Urban Ecology. 2020. pp. 239-263. DOI: 10.1016/B978-0-12-820730-7.00014-8

[27] Asakura H. Removing gypsum from construction and demolition waste (c&dw). In: Handbook of Recycled Concrete and Demolition Waste. Elsevier; 2013:479-499

[28] GtoG. Gypsum is Indefinitely Recyclable. 2016. Available from: http://gypsumtogypsum.org/gtog/gtog-project/

[29] Tam VW, Tam CM. A review on the viable technology for construction waste recycling. Resources, Conservation and Recycling. 2006;**47**:209-221

[30] BRE/Eurobond. Recycling of Mineral Wool Composite Panels into New Raw Materials. 2008. Available from: http://www.wrap.org.uk/sites/files/wrap/xxEurobond_WRAP.pdf

[31] Hevner AR et al. Design science in information systems research. MIS Quarterly. 2004;**28**:75-105. DOI: 10.2307/25148625

[32] Tokazhanov G et al. Circularity assessment tool development for construction projects in emerging economies. Journal of Cleaner Production. 2022:3-6

[33] O'Grady T et al. Design for disassembly, deconstruction, and resilience: A circular economy index for the built environment. Resources, Conservation & Recycling. 2021;**175**:5-9

[34] Hopkinson P, Chen H-M, Zhou K et al. Recovery and reuse of structural products from end-of-life buildings. Proceedings of the Institution of Civil Engineers - Engineering Sustainability. 2019;**172**(3):119-128

[35] Honic et al. Improving the recycling potential of buildings through material passports (MP): An Austrian case study. Journal of Cleaner Production. 2019;**217**: 2-6. DOI: 10.1016/j.jclepro.2019.01.212

[36] Jimenez-Rivero and Garcia-Navarro. Best practices for the management of end of-life gypsum in a circular economy. Journal of Cleaner Production. 2017;**167**:2-7. DOI: 10.1016/j.jclepro.2017.05.068

[37] Verbinnen et al. Recycling of MSWI bottom ash: A review of chemical barriers, engineering applications and treatment technologies. Waste and Biomass Valorization. 2017:**8**(5):2-5. DOI: 10.1007/s12649-016-9704-0

[38] Parron-Rubio ME et al. Concrete properties comparison when substituting a 25% cement with slag from different provenances. Materials. 2018;**2018**:3-10. Available at: https://www.mdpi.com/1996-1944/11/6/1029/htm

[39] Rose et al. Cross-Laminated Secondary Timber: Experimental Testing and Modeling the Effect of Defects and Reduced Feedstock Properties. UCL Discovery. 2018:3-8. Available from: https://discovery.ucl.ac.uk/id/eprint/10061947

[40] Eberhardt et al. Life cycle assessment of a Danish office building designed for disassembly. Building Research and Information. 2019;**47**(6):2-10. DOI: 10.1080/09613218.2018.1517458

[41] Brambilla et al. Environmental benefits arising from demountable steel-concrete composite floor systems in buildings. Resource Conservation and Recycling. 2019;**141**:2-8 DOI: 10.1016/j.resconrec.2018.10.014

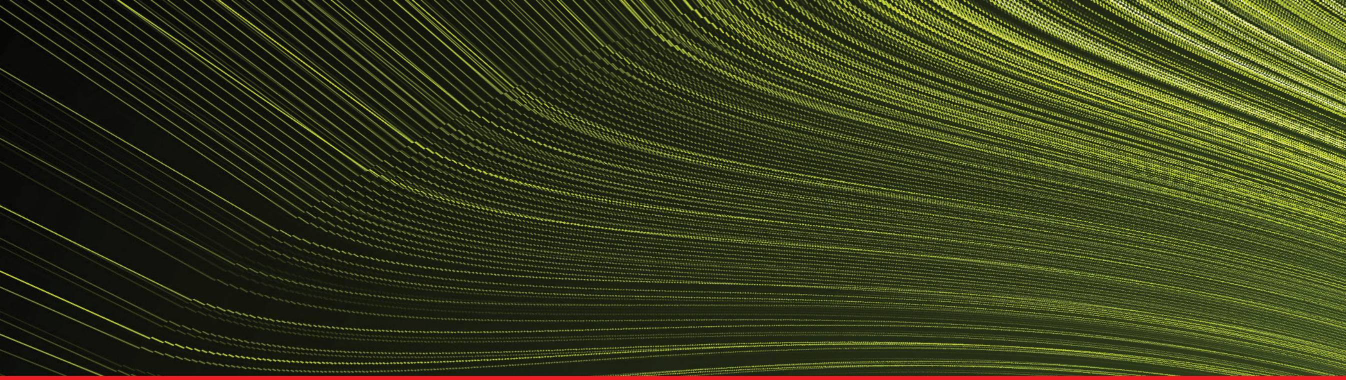
[42] Tingley et al. Understanding and overcoming the barriers to structural steel reuse, a UK perspective. Journal of Cleaner Production. 2017;**148**:2-6. DOI: 10.1016/j.jclepro.2017.02.006

[43] Azari R. Embodied energy of buildings: A review of data, methods, challenges, and research trends. Energy and Building. 2018;**168**:226-234

[44] Giordano, R. 2017. Embodied energy and operational energy evaluation in tall buildings according to different typologies of façade. Ninth International Conference on Sustainability in Energy and Buildings 134. pp. 224-233.

[45] Mangla SK et al. Barriers to effective circular supply chain management in a developing country context. Production Planning & Control. 2018;**29**:551e569. DOI: 10.1080/09537287.2018.1449265

[46] Bilal M. Current state and barriers to the circular economy in the building sector: Towards a mitigation framework. Journal of Cleaner Production. 2020;**276**:13-16



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The treatment of waste is highly relevant to human life and is receiving increasing attention from researchers. This volume contains a number of innovative and cutting-edge approaches to waste treatment, which hopefully will provide authors with new ideas for research in the area of waste treatment to contribute to the development of circular economy models.

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