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REVIEW

Circular economy strategies for combating climate change and other environmental issues

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Abstract

Global industrialization and excessive dependence on nonrenewable energy sources have led to an increase in solid waste and climate change, calling for strategies to implement a circular economy in all sectors to reduce carbon emissions by 45% by 2030, and to achieve carbon neutrality by 2050. Here we review circular economy strategies with focus on waste management, climate change, energy, air and water quality, land use, industry, food production, life cycle assessment, and cost-effective routes. We observed that increasing the use of bio-based materials is a challenge in terms of land use and land cover. Carbon removal technologies are actually prohibitively expensive, ranging from 100 to 1200 dollars per ton of carbon dioxide. Politically, only few companies worldwide have set climate change goals. While circular economy strategies can be implemented in various sectors such as industry, waste, energy, buildings, and transportation, life cycle assessment is required to optimize new systems. Overall, we provide a theoretical foundation for a sustainable industrial, agricultural, and commercial future by constructing cost-effective routes to a circular economy.

Keywords Circular economy strategies · Climate change · Waste management · Circular economy applications and opportunities · Life cycle assessment · Cost-effective route

Introduction

Reducing greenhouse gas emissions, addressing resource depletion and environmental pollution, and optimizing waste management have become global hot topics (Dantas et al. 2021; Sadhukhan et al. 2020; Zhang et al. 2019). Countries worldwide have identified efforts to mitigate climate change as establishing commitments to reduce emissions or using advanced technologies to limit greenhouse gas emissions (Peña et al. 2021; Serrano et al. 2021). However, only the governments of 55% of the world's greenhouse gas emitters have announced specific targets for increased carbon emission reductions by 2030, and the majority of countries still plan to achieve net-zero carbon emissions by 2050–2070 (Chen et al. 2022; Wyns and Beagley 2021). In the meantime, energy systems in developing nations continue to rely heavily on fossil fuels, and the high consumption of coal and oil in industry and transportation contributes to climate change and environmental pollution issues (Su and Urban 2021). Moreover, as the global population and standard of living rise, manufacturing automation has led to mass production and consumption, resulting in increased solid waste production. The growing volume and complexity of waste pose a significant threat to the environment and public health (Chioatto and Sospiro 2022; Kurniawan et al. 2022).

In this review, implementing circular economy strategies is a useful tool for enhancing the world's sustainability. Figure 1 shows the three main approaches of linear, recycling, and circular economy and their relationship to waste management. The principle of the circular economy is illustrated in Fig. 2. From the perspective of human economic sustainability, numerous scholars have repeatedly referred to the natural ecosystem model of matter and energy flow, and the circular economy is the

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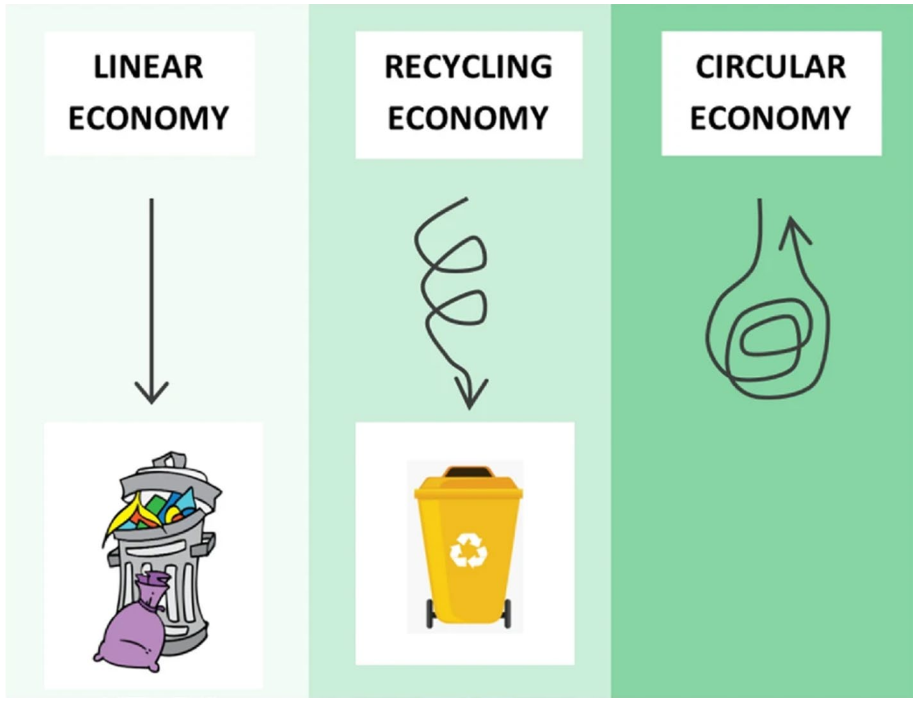

Fig. 1 Transition from linear, recycling to circular economy approach and their relationship to waste management. To achieve this, the entire production system must be taken into account, including waste generation, collection, transportation, recycling and treatment, use of recovered resources, and disposal of waste. In this instance, the circular method reduces resource market dependence and lowers disposal costs. This figure is reprinted with permission from Gorrasi et al. (2021)

Fig. 2 Circular economy begins with the consumption of natural resources and concludes with the production of non-recyclable waste. The fundamental principle of the circular economy is the recycling of manufactured products after their daily consumption and use

model of this approach that adheres to the laws of nature (Korhonen et al. 2018). It is becoming increasingly apparent that structural optimization of sustainable development measures cannot be accomplished without circular economy strategies (Alhawari et al. 2021). National governments seek to decouple economic growth from natural resource consumption and environmental pollution while preserving economic resources for as long as possible (Almagtome et al. 2020; Atabaki et al. 2020). The application of the circular economy is primarily concerned with preventing the consumption of resources and optimizing the structure of the energy and material cycle at its various levels: enterprises and consumers at the micro-level, economic agents integrated in a symbiotic manner at the meso level, and cities, regions, and governments at the macro-level (Rincón-Moreno et al. 2021).

Due to the vast differences between scientific fields and schools of thought, Nikolaou et al. (2021) found that circular economy definitions emphasize both material preservation and economic growth. As a new economic development model, circular economy need to restructure and modernize the economic system under the laws governing material circulation and energy flow in the natural ecological system (Shen et al. 2020). Under the increasing acceptance of circular economy principles by national and local governments and within the context of the Paris Agreement, implementing circular strategies at the city scale becomes essential for managing climate change issues (Christis et al. 2019). The circular economy is not limited to modifying waste management systems to increase resource efficiency, decrease resource inputs, and increase economic benefits. Increasingly, the circular economy is recognized as a highly effective strategy for both policy development and the reduction of environmental pollution and greenhouse gas emissions (De Pascale et al. 2021; Durán-Romero et al. 2020).

This review systematically illustrates how the circular economy can be used as an effective waste management strategy based on three aspects: eliminating waste, recirculating materials, and regenerating ecosystems. The novelty of this review focuses primarily on clarifying the circular economy strategy as an effective measure to combat climate change, as well as the investigation of how well the circular economy meets the climate change goals and how the circular economy strategy addresses the climate change issue. In the meantime, research will be conducted into the specific effects of circular economy strategies on air and water pollution, energy consumption, natural resources, solid toxic waste, and land use. In addition, the opportunities presented by the circular economy will be investigated in the industrial and food systems context. Eventually, a critical analysis of the full life cycle analysis of the circular economy will be conducted, and a cost-effective path will be developed.

Circular economy for waste management

There are many concepts of circular economy, dating back as far as 1966 (Adami and Schiavon 2021). In addition, in 1991, researchers analyzed the approach to economic recycling (Leontief 1991). However, the concept of a circular economy was not defined until 2013. The circular economy aims to reduce waste from production and distribution processes as one of its components. The Waste Framework Directive (European Union 2008) further strengthened the connection between the circular economy and waste management. Consequently, the circular economy can be an efficient means of reducing waste recovery and recycling.

Eliminating waste

Rapid economic and population growth and increased urbanization have resulted in a rise in solid waste in the majority of the world's nations, particularly in developing countries (Guerrero et al. 2013). Europe and North America generate between 1.6 and 2.2 tons per person per year of solid waste, which can be recycled or reused progressively (Aguilar-Hernandez et al. 2011). The Environmental Protection Agency estimates that the United States generated approximately 238.5 million tons of municipal solid waste in 2015, a significant increase from previous years (United states Environmental Protection Agency 2015). China's average daily amount of municipal solid waste is 0.73 kilogram (Zhu et al. 2021). In India, the per capita generation of municipal solid waste is approximately 91.01 ± 45.5 gram per day, while the per capita generation of organic waste is 74 ± 35 gram per person per day (Ramachandra et al. 2018). The global per capita generation of solid waste is estimated at around 1.74 tons per year (Song et al. 2015). With the production of large quantities of solid waste, there will be a correspondingly large consumption of natural resources. Any generation of solid waste consumes natural resources, necessitating recycling and reuse, which not only facilitates the reuse of waste but also reduces the economic costs associated with waste management.

Global governments are under immense pressure to reduce waste generation by implementing various sustainable approaches to effective waste management due to the massive quantity of waste (Cheng and Hu 2010). Solid waste treatment methods are engineering techniques that recover and repurpose solid waste resources. Environmental engineering plays a crucial role in developing solid waste disposal, recycling, and utilization technologies, depending on its source, nature, characteristics, and environmental hazards. Solid waste is typically disposed of through stockpiling, containment piles, landfills, incineration, and biodegradation. However, researchers have proposed zero-waste strategies to reduce the growing amount of solid waste (Bartl 2011; Phillips et al. 2011; Song et al. 2015). A zero-waste strategy is redesigning a resource's life cycle to ensure that all products are recycled and that no waste is sent to landfills, incineration, or other traditional disposal methods, allowing waste to be recycled and reused (Zaman 2014; Zaman and Lehmann 2011). In essence, recycling waste into new materials is a method of reusing resources, thereby achieving the goal of sustainability.

This section focuses on how to solve the increasing amount of solid waste due to rapid economic and population growth. The Environmental Protection Agency estimates that the United States generated 238.5 million tons of municipal solid waste in 2015, a substantial increase over previous years. As a result, governments worldwide are under tremendous pressure to reduce waste generation by implementing various sustainable approaches such as circular economy strategies to manage waste effectively.

Circular materials

The rising volume of solid waste has caused a shortage of landfill space (Li et al. 2019; Silva et al. 2017). Conventional methods of waste disposal not only waste land resources but also pollute the environment. Natural materials are also in short supply due to the extensive use of natural resources and nonrenewable energy sources; therefore, recycling and reusing solid waste solves the problem of natural resource scarcity, protects the environment, and ultimately leads to a circular economy development model. At the end of a product's life cycle, the circular economy development model provides greater social and environmental benefits by demonstrating waste management benefits at multiple spatial levels and facilitating the transformation of waste into circulating materials.

There are currently five primary aspects of recycling solid waste into circulating materials (Abdel-Shafy and Mansour 2018; Chen et al. 2019; Ibrahim and Mohamed 2016; Li et al. 2019): (1) extraction of valuable metals such as copper, iron, gold and silver from metal smelting slag; extraction of glass beads from fly ash; recovery of sulfur iron ore from coal gangue; (2) recycling of solid waste such as paper, glass, metal and plastic; (3) the production of construction materials from blast furnace slag, fly ash, coal gangue, waste plastics, sludge, tailings and construction waste, which include lightweight aggregates, heat insulation and thermal insulation materials, decorative panels, waterproofing rolls and coatings, biochemical fiberboard, recycled concrete and other materials; (4) the production of cement from fly ash, coal gangue and red mud; the use of chrome slag instead of limestone as a fusion agent for iron making and other alternative materials; (5) solid waste with high calorific value through incineration for heat and power generation; the use of kitchen waste, plant straw, human and animal manure and sludge can be fermented to produce combustible biogas. Thus, solid waste is first sorted to recover useful resources such as plastics, rubber, paper, glass, and metal; it is then crushed to appropriate particle size and further sorted using magnetic separation and other techniques to recover useful resources. After separation, the various fractions may be utilized for composting, biogas production, production of derived fuels, or incineration to recover heat energy. The waste gas and wastewater generated during the process of resource utilization must be treated to the applicable standards before being released. The waste residues can be utilized as building and road materials. Those that cannot be reused are discarded in landfills, achieving a circular ecosystem in the end.

This section focuses on the shortage of landfill space due to the rising volume of solid waste. In addition, conventional waste disposal methods not only wasteland resources but also pollute the environment. Therefore, recycling and reusing solid waste can facilitate the conversion of waste into circulating materials, thus providing greater social and environmental benefits.

Regenerating nature using ecosystems

Due to the consumption of nonrenewable resources by traditional industries and the high level of environmental pollution, the transformation of waste into circulating materials is an example of the ecological transformation of traditional economic systems (Ghisellini et al. 2016). The eco-dynamic system is the fundamental driving force behind developing a regional circular economy, which promotes the improvement and upgrading of the organizational structure and operational mechanisms of regional production, circulation, and consumption, and ultimately achieves maximum economic benefits while simultaneously reducing resource consumption and preventing environmental pollution. In other words, transforming waste into circulating materials is a way for humanity to pursue ecological and human advancement while pursuing economic sustainability at the ecological civilization stage.

The most representative model for the development of circular economy is the new production method in which humans live in harmony with the ecosystem. The intuitive expression of the dynamics of ecological productivity, also known as eco-dynamics, is that ecological productivity promotes the harmonious exchange of information, energy, and materials between humans and nature. Constantly promoted are the integration and eco-legislation of natural ecosystems, in conjunction with the development of ecological civilization in human society. Eventually, in accordance with ecological laws, a composite ecological system is formed.

This section examines the circular economy as an approach to waste management, beginning with the current pressures on individual nations to dispose of waste and convert it into circulating materials through various means, and ultimately creating ecosystems that maximize economic efficiency, reduce resource consumption, and prevent environmental pollution.

Circular economy and climate change

Meeting the targets of climate change

Countries worldwide have agreed to meet climate change mitigation targets (Fawzy et al. 2021). One of the goals is to reduce global warming below 1.5 °C compared to pre-industrial levels. Additionally, reduce carbon emissions by 45% by 2030, and reach carbon neutrality by 2050, as stipulated in the Paris Agreement, which was adopted by 196 parties in the 21st conference of the parties. In addition, the Paris agreement encourages developed nations to provide developing nations with financial and technological support for climate change mitigation and adaptation. The zero-carbon implementation has been competitive, concerning approximately 25% of emissions from economic sectors, particularly the energy and transportation sectors. Nevertheless, countries are apparently leaving the 2030 plan to reduce carbon emissions by 45%, as the current forecast predicts a 14% increase in global greenhouse gas emissions by 2030 (United Nations Framework Convention on Climate Change 2021). In addition, the majority of emissions come from a small number of countries, as the top ten emitters account for over 68% of global greenhouse gas emissions. In contrast, less than one hundred countries account for 3% of global greenhouse gas emissions. The top ten emitters are China, the United States, the European Union, India, the Russian Federation, Japan, Brazil, Indonesia, Iran, and Canada. The summarization of the nationally determined contributions of 2020/2021 of the top ten emitters can be found in Table 1.

Apart from national climate change targets, firms around the world have set their climate change targets. 1495 firms were studied worldwide, and about 1099 (73.5%) firms adopted climate change targets (Wang and Sueyoshi 2018). The countries leading in firms' climate change adoption are Japan, European Union, and the United States at 97.35%, 76.76%, and 73.91% rates, while developed countries with the lowest climate change adoption are Australia and Canada at 56% and 47.87% rate. Firms in Canada and Australia lag in climate change adoption due to weak national climate policies and resource-driven economies. The materials sector, particularly the metal and mining industries, has the lowest climate change adoption in Canada and Australia at 43.48% and 26.67%, respectively. On the other hand, the Japanese firms' high climate change target percentage is outstanding, which is attributed to resource scarcity, government concentration on clean developments and emphasis on lean operations.

Apart from global firms, the retail sectors have also set their climate change targets. The United Kingdom supermarkets' emissions account for 0.9% of total greenhouse gas emissions; the United States retail sector accounts for the highest energy use and the second-highest greenhouse gas emissions compared to all the commercial sectors (Sullivan and Gouldson 2016). Some of the United Kingdom supermarkets' targets include Tesco's target of being a net zero carbon business by 2050 and reducing supply chain greenhouse gas emissions by 30% in 2020 compared to 2008. Other supermarkets are Sainsbury's, with a target of reducing 50% greenhouse gas emissions by 2030 and Morrisons, with a target of reducing operational greenhouse gas emissions by 30% in 2020 compared to 2005 levels. On the other hand, United States supermarkets like Best Buy had a target of reducing carbon footprint by 20% in 2020 compared to 2009 levels. Walmart had a target of eliminating 20 million tons of greenhouse gas emissions from products' lifecycles by 2015, and Home Depot had a target of reducing greenhouse gas emissions from upstream transportation and distribution by 20% in 2015 compared to 2009 levels. From the few supermarkets highlighted, the data shows that the United Kingdom retailers have absolute emissions targets, with a focus on supply chains and longer timeframes. In contrast, United States retailers have a narrow focus on transport and operational-related emissions and shorter timeframes. The retail sector observation showed that if all United Kingdom retailers' targets are achieved, the reduction of greenhouse gas emissions will be higher compared to the United States retailers' targets achievements.

In conclusion, achieving the climate change targets is still behind schedule, and governments, particularly the top emitters, should take immediate action to reduce emissions and enhance their nationally determined contributions.

Countries adopt economic and social reforms to meet their climate change objectives. One of the sectors undergoing change is the energy sector, as countries shift their attention to energy technologies such as biomass, solar, wind, nuclear energy, hydrogen, and waste-to-energy to meet their climate change targets (Kang et al. 2020; Osman et al. 2022b). In addition, other technologies adopted to decarbonize the energy sector include bioenergy carbon capture and storage, electric vehicles, smart grids, storage and energy-saving technologies (Osman et al. 2021a). Creating social awareness, implementing climate-friendly policies, implementing sustainable urban planning, shifting from a linear to a circular economy, facilitating resilience in agriculture, promoting clean transportation, and conducting climate research are additional measures taken to meet the climate change objectives (Moore et al. 2021). Furthermore, carbon removal options like afforestation which costs

Table 1 Climate change targets and accomplishments by 2020–2021

Country	Targets	Achievements by 2020/2021	Source URL (Nationally determined contributions 2021)
China	Achieve carbon dioxide emissions peak by 2030 and carbon neutrality by 2060 Reduce carbon dioxide emissions per unit gross domestic product by 65% from 2005 levels. Increase non-fossil fuel share in energy to 25% and increase solar and wind capacity to 1.2 billion kilowatts by 2030	Carbon dioxide emissions per unit gross domestic product in 2019 decreased by 48.1% compared to 2005, which is better than the 2020 goal of reducing carbon dioxide emissions per unit gross domestic product by 40–45% In 2019, the share of non-fossil fuel energy was 15.3% which increased from 7.9% in 2005	https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/China%20First/China%E2%80%99s%20Achievements,%20New%20Goals%20and%20New%20Measures%20for%20Nationally%20Determined%20Contributions.pdf
United States	Reduce greenhouse gas emissions by 50–52% in 2030 compared to 2005 levels Achieve 100% carbon emissions-free electricity by 2035 Achieve net-zero emissions economy-wide before 2050	In 2020, the greenhouse gas emissions were 17% below compared to 2005 levels In 2020, renewable energy sources reached 761 million megawatt-hours, about 19% of total electricity use	https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/United%20States%20of%20America%20First/United%20States%20NDC%20April%2021%202021%20Final.pdf
European Union	Achieve climate neutrality by 2050 Increase renewable energy consumption to 32% by 2030, which is double the 2017 percentage Reduce carbon emissions per kilometer for passenger and vans cars by 37.5% and 31% in 2030 compared to 2021 levels Reduce greenhouse gas emissions by 55% in 2030 compared to 1990 levels	By 2019, the European Union had reduced their emissions by 26% compared to 1990 levels The average per capita emissions have fallen from 12 tons of carbon dioxide equivalent in 1990 to 8.3 tons of carbon dioxide equivalent in 2019	https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/European%20Union%20First/EU_NDC_Submission_December%202020.pdf
India	Reduce emissions intensity of its gross domestic product by 20–25% and 33–35% in 2020 and 2030 compared to 2005 levels Achieve 40% of electric power installed capacity from non-fossil fuels Achieve 60 gigawatts and 100 gigawatts of installed wind and solar capacity in 2022	The emissions intensity of gross domestic product decreased by 12% between 2005 and 2010 Increased renewable energy from 2% (3.9 gigawatts) to 13% (36 gigawatts) between 2002 and 2015	https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/India%20First/INDIA%20INDC%20TO%20UNFCCC.pdf
Russian Federation	Reduce greenhouse emissions by 70% in 2030 compared to 1990 levels Reduce more than 55 billion tons of carbon dioxide equivalent cumulative by 2030 since 1990	Not indicated	https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Russian%20Federation%20First/NDC_RF_eng.pdf
Japan	Reduce greenhouse emissions by 46% (760 million tons of carbon dioxide) in 2030 compared to 2013 levels Achieve net-zero carbon emissions by 2050	Not indicated	https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Japan%20First/JAPAN_FIRST%20NDC%20(UPDATED%20SUBMISSION).pdf
Brazil	Reduce greenhouse gas emissions by 37% and 50% in 2025 and 2030 compared to 2005 levels Achieve climate neutrality by 2050	Renewable energies accounted for 48.4% of total energy demand in 2020	https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Brazil%20First/Updated%20-%20First%20NDC%20-%20%20FINAL%20-%20PDF.pdf
Indonesia	From 2020 to 2030, reduce emissions by 29% unconditional and up to 41% conditional of the business as usual Increase renewable energy share to at least 23% and 31% in 2025 and 2050	Not indicated	https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Indonesia%20First/Updated%20NDC%20Indonesia%202021%20-%20corrected%20version.pdf

Table 1 (continued)

Country	Targets	Achievements by 2020/2021	Source URL (Nationally determined contributions 2021)
Iran	Unconditional emissions reduction pledge of 4% and conditional emissions reduction pledge of 12% in 2030. Both pledges are subject to the removal of current sanctions Decrease industries' energy consumption by 1% annually Expand wind and hydropower installation to 6 gigawatts and 18.7 gigawatts by 2030	Not indicated	https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-11-30_climate-change_29-2018_country-report-iran.pdf
Canada	Reduce emissions by 40–45% in 2030 compared to 2005 levels Achieve net-zero emissions by 2050	Generates 82% of total electricity from clean sources	https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Canada%20First/Canada%27s%20Enhanced%20NDC%20Submission1_FINAL%20EN.pdf

The summary is based on the nationally determined contributions submitted to the United Nations by the world's top ten emitting countries and unions. Most nations aim to achieve net-zero carbon emissions by 2050, but their accomplishments have lagged behind their targets and goals by 2020/21. Lagging behind means countries must step up and take immediate actions to lower carbon emissions toward net-zero economies

3–30 dollars per ton of carbon dioxide, and is commercially ready for implementation, can be used to meet the carbon emissions targets (Princiotta 2021). However, other carbon removal options like direct air capture, biochar, and accelerated weathering have issues such as high costs of 100–1200 dollars per ton of carbon dioxide and are not commercially ready as they are in the development stage; apart from biochar which is technologically ready for immediate deployment. No single action can achieve the climate change targets; meeting the targets requires multiple climate actions and technology advancements in all sectors.

In summary, countries use a variety of strategies to meet their climate change goals. One of the strategies is the transition from a linear to a circular economy, which is discussed in detail in the following sections of this review.

Circular economy to tackle climate change

The circular economy approach improves resource efficiency while decreasing inputs and emissions and can therefore be used to combat climate change. As discussed in this section, the circular economy can be implemented in various sectors, including industry, waste, energy, buildings, and transportation.

Industry

As industrialization progresses, the problem of climate change caused by industry grows gradually. Circular economy strategies reduce carbon emissions and provide a profitable business model for the industry with improved quality, efficiency, and working conditions via a traceable carbon footprint throughout the product's life cycle (Khan et al. 2021). Utilizing blockchain technology in supply chains can provide accurate real-time data of circular economy processes like circular design, production efficiency and recycling, thereby reducing the carbon footprint of supply chain operations by a significant amount. Converting carbon dioxide, which contributes to global warming issues, into products with high added value has become an important area of study. The authors estimated that 5–10% of carbon dioxide emissions could be used to produce fuels and chemicals in a circular economy (Cucciniello and Cespi 2018). Wang et al. (2019) discovered that resource recovery measures would reduce the overall carbon emissions of industrial parks by substituting carbon-intensive energy sources through a quantitative analysis of the impact of a circular economy. In summary, using industrial by-products in the circular economy can reduce carbon emissions while adding value to the industrial processes.

Other industries that can adopt circular economy measures are the consumer goods industries. Household washing machines are not fully utilized as most time; they are idle. The washing machine industry can be transformed into a circular economy through ways like sharing among households, designing for disassembly and reassembling, and using technologies of the internet of things and big data (Bressanelli et al. 2017). The usage of circular economy strategies can save 30% of washing costs while reducing the country’s electricity generation and water consumption by 0.6% and 1% hence tackling climate change. The food industry's transformation to a circular economy can also help tackle climate change. A life cycle assessment study of canned tuna in Galicia, Spain, showed that the inclusion of valorization of bio-waste and production of tuna pate, fish meal and oil in the canned tuna process decreases the environmental impacts by 0.03 kilogram carbon dioxide equivalent per can (Cortés et al. 2021). In summary, achieving a circular economy in industries requires efforts such as a change in goods design and introducing new processes in the production chain, which can be expensive at first but will benefit the industries and tackle climate change in the long term.

Overall, the circular economy strategy can effectively reduce carbon emissions from industrial processes and mitigate the global climate change problem.

Waste

Population growth causes an increase in waste, whose disposal becomes difficult and contributes to climate change, while circular economy of recycling waste can help tackle climate change (Osman et al. 2022a). The effectiveness of two household organic waste management systems, anaerobic digestion and incineration, was studied in Trondheim, Norway (De Sadeleer et al. 2020). The results demonstrated that recycling through anaerobic digestion produced lower emissions than incineration, provided biogas is used in place of diesel. In addition, reducing food waste by 15% to 30% resulted in large amounts of avoided emissions; therefore, preventing food waste outweighs recycling and incineration. In the circular economy context, another study examined the technologies used for carbon dioxide capture from wastewater treatment plants' emissions. Biochar production from sludge, constructed wetlands, and microbial electrochemical processes are among the technologies examined (Pahunang et al. 2021). The results showed that sludge and constructed wetland biochar were the most cost-effective technologies. Furthermore, the microbial electrochemical processes were the most effective at producing valuable by-products from the treated wastewater. Here, the authors suggest that waste production should be avoided as much as possible. If waste is produced, circular economy strategies should be applied to maximize resource utilization and lower carbon emissions.

In the European Union, strategies to achieve a circular waste economy, such as increasing the recycling of municipal wastes by 65% and recycling all plastic packaging by 2030, are implemented (Aceleanu et al. 2019). By 2018, out of 2.2 billion tons of waste, 0.6 billion tons (27%) were recycled in the European Union. Shifting to a waste circular economy has the advantages of reducing carbon dioxide emissions, reducing waste management expenses and creating jobs. Other circular economy techniques include the usage of organic food waste and treated effluents to produce recycled water and fertilizers (Oliveira et al. 2021). The straw from wheat farming can be used as fertilizer, animal feed or energy recovery. In addition, the pineapple leaves residues in farms can be used to recover nanocellulose fiber that can be used in wound healing and drug delivery. Furthermore, waste vegetable and cooking oil can be processed into biodegradable detergents, and wheat bran can be processed into biodegradable tableware.

In conclusion, recycling and the transformation of wastes into useful raw materials for the production of other value-added goods results in the efficient use of resources and a smaller carbon footprint than harmful waste disposal methods such as landfilling and incineration. Therefore, more research should be conducted on large-scale recycling and waste technology utilization to achieve a circular economy and tackle climate change.

Energy

Global energy consumption is increasing due to the improvement in the quality of human life. However, the increase in energy consumption is accompanied by an increase in greenhouse gas emissions, resulting in climate change concerns. Applying circular economy strategies and digital technologies related to artificial intelligence can improve energy efficiency and facilitate carbon trading to help countries meet their climate change mitigation objectives (Jose et al. 2020). Using a standard greenhouse gas emission quantification model and scenario analysis, Islam et al. (2021) determined that a combination of circular economy principles and the use of renewable energy could lead to a 37.5% reduction in greenhouse gas emissions from the livestock sector in Bangladesh. To reduce the environmental impacts of wind energy turbines, after their end of life, they can be repurposed or the fibers recovered and used in manufacturing new wind turbines. However, carbon fibers degrade after multiple thermal treatments; hence research is required on the long-term sustainability of the fiber recovery process (Hao et al. 2020). Here, the authors suggest developing circular economy technologies from lab scale to large scale so that the technologies can be applied in the current energy sector and tackle climate change.

Using Aland islands in Finland as a case study energy data shows that using excess electricity to power electric vehicles and circular economy processes that increase the value of waste is more profitable than exporting the excess energy produced (Kiviranta et al. 2020). From analysis, the energy system involving a circular economy had an annual net profit of 0.72 million euros higher than exporting exceeded energy produced (-0.43 million euros). However, the circular economy system faced issues with the local feedstock availability for biogas production. Energy and materials circularity acts such as using scrap steel, recycling and reusing plastics, papers and cement can reduce energy consumption and dependence on expensive technologies like carbon capture (Fragkos 2022). All the circular economy measures require societal behavioural changes, capital investments, new business models and policies. In Meili town in China, the transformation to clean energy by using circular economy strategies like using excess industrial heat in symbiosis with other industries, electrifying transportation and reusing batteries positively impacts tackling climate change (Su and Urban 2021). The modelling results from 2020 to 2040 show an energy saving of 7.1 Mega tons of oil equivalent (34%) and a reduction of 14.5 Mega tons of carbon dioxide. In conclusion, the circular economy is profitable and tackles climate change by utilizing waste in energy production. However, depending on energy from waste can lead to shortage of waste availability such as in biogas production which can trigger production of more waste hence infeasibility.

Therefore, circular economy strategies can mitigate global climate change by increasing the use of renewable energy and transforming the energy structure to become more sustainable.

Buildings

Construction and buildings contribute to climate change; therefore, using circular economy practices, such as recycled aggregates, can aid in combating climate change. A life cycle assessment study was performed on a case study of a Town Hall building in the German city of Korbach that was demolished and rebuilt using recycled building materials (Mostert et al. 2021). Compared to conventional concrete, the use of concrete with recycled aggregates of up to 43% can save up to 37% of raw materials, according to the study's findings. The study also revealed that using recycled aggregates in concrete does not contribute much to climate mitigation because recycled aggregates concrete still contains cement, which has a substantial carbon footprint. In addition, the study revealed that processing recycled concrete in a mobile plant has a smaller carbon footprint than processing recycled concrete in a stationary plant due to reduced transport distance, low energy consumption, and low water consumption. Another study was conducted on using recycled wood shavings to produce wood bio-concrete utilizing life cycle assessment and considering the transport distance from various waste generation sites (Caldas et al. 2021). Regardless of the scenario, the results indicated that an increase in wood shaving content in wood bio-concrete contributed to climate mitigation when biogenic carbon was considered. In addition, transportation plays a crucial role in the wood bio-concrete lifecycle, as long distances result in greater carbon emissions. The emissions of the wood bio-concrete can be as low as 15 kilogram carbon dioxide equivalent per cubic meter if carbon dioxide capture during eucalypt growth is considered.

Utilization of information modeling in buildings is critical in attaining waste-efficient buildings and a circular economy (Ganiyu et al. 2020). Building information modeling has the ability to minimize design changes, generate waste information from the design model, and provide information on reusable materials in construction and modular construction techniques, which promote circular economy in tackling climate change. A life cycle assessment study was done on three structural methods of business-as-usual concrete, design for disassembly concrete and wooden structure in one building. The results revealed that in two 50 years of service life, the single-use wooden structure would achieve 13% emissions savings, and design for disassembly structure would achieve 16% emissions savings compared to the business as usual structure (Joensuu et al. 2022). Here, the authors advise architects and engineers to continuously learn the building information modelling and life cycle assessment tools, which are essential to achieving a circular economy in the construction industry.

In conclusion, there are opportunities to recycle construction waste and apply it to new construction sites, thus conserving resources and reducing carbon emissions, thereby combating climate change. Instead of dumping wastes that contribute to climate change, greater emphasis should be placed on reusing construction debris.

Transportation

A shift to electric vehicles is necessary for the transportation sector to meet climate change objectives. However, the whole life cycle of electric vehicles must be comprehended to prevent resource depletion. Motor technologies and batteries for electric vehicles are composed of rare earth metals such as lithium, cobalt, and graphite. Circular economy strategies, such as reusing, repairing, and refurbishing, are essential for achieving optimal resource utilization (Richter 2022). Batteries can be repurposed as energy storage systems and reused to extend their lifespan. Another circular economy strategy to combat climate change for road transport is for vehicle manufacturers to ensure that 85% of the weight of their vehicles is reusable or recyclable (Paradowska 2017). In addition, the vehicles should not be manufactured with toxic materials such as mercury or lead. Systems should be in place to collect end-of-life vehicles, with the possibility of collecting used parts from repaired vehicles. The costs of collecting end-of-life vehicles should not be incurred by vehicle owners, and the waste treatment facility should prioritize reuse, recovery, and recycling.

Circular economy can be used in extending ports' life and reducing environmental impacts, such as in Gavle Sweden, where contaminated dredged materials were used to expand ports' land. The expansion of Gavle port required the removal of 4 million cubic meters of dredged sediments, of which 1 million cubic meters would be contaminated by heavy metals (Carpenter et al. 2018). The disposal of the contaminated dredged sediments was a challenge as there was no vacant land near the port; hence, the disposal would require thousands of lorries transporting the sediments over long distances, emitting greenhouse gases and incurring large costs. The solution was to combine the dredged sediments with other materials like fly ash, slag and cement and use the sediment in the port's expansion. The circular economy approach saved the port from extinction while reducing the carbon footprint and costs. Apart from ports, the rail industry can also utilize a circular economy by recovering the end-of-life components of trains. The train bogie components can be recovered in different ways such as repair of compressors, exhauster, and block brake or recycling of bogie frame and wheel axle (Phuluwa et al. 2020). However, the cost of recovering the railcar components should be checked against the cost of manufacturing new components to ensure feasible circular operations.

In conclusion, combatting climate change in the transportation sector is difficult without considering the end of life of vehicles, which consume resources and rare earth metals. Transitioning to a circular economy based on reuse and recycling is essential for ensuring proper resource utilization and effective climate change mitigation. Circular economy strategies are essential for combating climate change in all sectors, as they ensure proper resource utilization and reduce carbon emissions. A focus should be placed on the whole life cycle, particularly the end-of-life stage, which is crucial for reuse, recovery, and recycling.

Impact of the circular economy on pollution, energy, waste, natural resources and land use

As the circular economy principles are implemented globally, circular economy strategies will play a more significant role on the international stage and have a greater impact on the world. This section analyzes the effects of circular economy strategies on various applications, including air and water quality, energy consumption, natural resources, solid and toxic waste, land use, and land cover.

Air and water quality

Deteriorating air and water quality have become one of the most widespread issues globally, as global economic and population growth has led to concerns about air quality and water resources that have become limited in quantity and quality. The discussion of air and water quality cannot be separated from the development of circular economy strategies. Su and Urban (2021) conclude from a scenario analysis of a circular economy strategy for a town of 140,000 people in eastern China that it is possible to reduce fine particulate matter emissions by 47% in 2040 compared to the past, but the total emissions in 2040 are almost the same as the levels in 2019, indicating that the circular economy strategy does not actually improve air quality, but merely prevents air quality from deteriorating. In contrast, if the circular economy is expanded by electrifying the transportation sector, fine particulate matter emissions will be reduced by 22%, and air quality will significantly improve. Meanwhile, Sgroi et al. (2018) suggest that new policies based on the concept of a circular economy may lead to a "paradigm shift" toward a more sustainable model of wastewater management beginning with the principle of source segregation and enhancing resource recovery to improve the water system's quality. Adopting a circular economy strategy can create significant synergies with reused water as an alternative water supply, and the circular economy strategy should ensure that water reuse is safe and that the applicable water quality standards are applied (Voulvoulis 2018). Consequently, circular economy practices can adjust and monitor wastewater pollutant levels to improve water supply quality via optimal wastewater management.

This section examines the potential effects of circular economy strategies on air and water quality. Overall, the effect of effective circular economy measures on air quality and water quality is positive due to the synergy between the circular economy and the deep electrification of transport, which can effectively reduce air pollutants, and the "paradigm shift" in wastewater management, which improves water quality as a result of the circular economy strategy.

Energy consumption

The issue of energy consumption is one of the global challenges. To achieve sustainable development, many nations and multinational corporations are focusing on reducing energy consumption through the circular economy perspective. Padmanabhan et al. (2022) utilized energy recovery from waste plastics as an alternative fuel source through a circular economy strategy. The pyrolysis-generated waste plastic fuel was evaluated as an alternative fuel, and the pyrolysis-generated waste plastic fuel increased brake thermal efficiency by 4.7% and decreased fuel consumption by 7.8% compared to diesel. The anaerobic degradation of organic fractions during waste treatment utilizing a circular economy strategy results in biogas production for use in power plants. In addition, the sorted dry waste can be burned in power plants to replace the grid's electricity supply. Non-recyclable, high-calorie fractions can be used as refuse-derived fuel in cement plants to replace fossil fuels and reduce energy consumption (Berechet et al. 2019). Using case studies, Laskurain-Iturbe et al. (2021) examined circular economy strategies and found that technologies such as additive manufacturing, big data and advanced analytics, artificial intelligence, artificial vision, cybersecurity, the Internet of Things, robotics, and virtual reality can effectively reduce energy consumption in the transportation phase, manufacturing phase, and utilization phase.

In this section, we analyze the effect of circular economy strategies on energy consumption, which can be effectively reduced by alternative fuels generated from the pyrolysis of recycled plastics or the anaerobic decomposition of recycled organic components to produce biogas. Combined with circular economy strategies, additive manufacturing, big data and advanced analytics, artificial intelligence, artificial vision, cybersecurity, the Internet of Things, and robotics can reduce energy consumption throughout the product life cycle.

Natural resources

Population growth and economic development have added to the problem of diminishing natural resources. Utilizing the circular economy concept can promote economic growth while conserving natural resources (Sverko Grdic et al. 2020). Circular economy measures can positively impact continuously degrading industries that rely heavily on natural resources, thereby reducing and optimizing the consumption of natural resources (Chiappetta Jabbour et al. 2020). Pavolová et al. (2020) demonstrate that the circular economy strategy can be a significant conceptual model for guiding the optimal use of natural resources and that the circular model is based on the partial substitution of secondary raw materials for primary raw materials, allowing for a significant reduction in the consumption of natural resources. A dual systematic and bibliometric survey of published scientific results by Abad-Segura et al. (2021) found that the efficiency of natural resource utilization can be enhanced through a systematic approach if the circular economy and the bioeconomy are implemented in conjunction. The circular economy production model is being pushed by policymakers as an alternative to the linear "take, make, discard" model of large natural resource inputs. In a circular economy model, natural resource consumption would continue to decline (Centobelli et al. 2020). It was realized that the circular economy strategy is advantageous for natural resource conservation.

This section examines the effect that circular economy strategies have on natural resources. By partially substituting secondary raw materials for primary raw materials, the circular economy model can limit the use of natural resources; for instance, industries that rely heavily on metals as a natural resource can adopt circular economy strategies to reduce natural resource inputs. Simultaneously, the efficiency of natural resource utilization can be enhanced via a systemic approach by combining the circular economy and bioeconomy.

Solid and toxic wastes

Solid wastes containing potentially toxic elements, such as municipal sludge, waste incineration fly ash, tailings, metallurgical and chemical solid wastes, and electronic wastes, are widely produced worldwide (Ge et al. 2022; Xiong et al. 2019). Circular economy strategies positively impact solid waste management and have been implemented successfully and comprehensively in some developed regions, where policy has also been developed (Ezeudu and Ezeudu 2019). Product design and business models based on circular economy strategies emphasize multifunctional products, prolonged life of products and components, and intelligent manufacturing to maximize product utility, thereby reducing waste generation in public and private sectors (Sharma et al. 2021). Al-Wahaibi et al. (2020) conducted a techno-economic study on the potential of biogas production from food waste. The experimental results show a cumulative gas production value of 1550 milliliter per 1 gram of dry matter for a sample of food solid waste, with a net present value of 3108 dollars if calculated at 0.39 dollars per cubic meter and a discount period of 6 years. Meanwhile, Rolewicz-Kalinska et al. (2020) analyzed the correlation between waste collection and circular economy strategies and estimated that the amount of biogas generated from solid waste could increase to nearly 9 million cubic meters per year by 2030, bringing the annual production of renewable energy to almost 17 kilowatt hour.

The investigation reveals that the circular economy strategy positively affects solid and toxic waste. The circular economy strategy presents favorable application prospects for solid waste management. The circular economy strategy will maximize product utility by extending product and components' life, reducing public and private sector waste generation. Moreover, circular economy strategies can reduce total waste by converting solid waste into biogas and using it as fuel.

Land use and land cover

Land serves a multitude of essential functions in our daily lives, including the production of food and other biomass products, as well as the storage, filtration, and conversion of substances such as carbon, nitrogen, and water. A circular economy strategy is an economic system that prioritizes the reuse and minimal depreciation of resources and products, which substantially affects land use (Breure et al. 2018). Wiprächtiger et al. (2020) evaluated the specific effects of a circular economy by developing circular strategy scenarios. According to the findings, increasing the use of biomaterials or recycling combined with increasing the use of biomaterials would have a greater negative impact on land use and land cover. Furthermore, the need for a larger area to cultivate bio-based materials places pressure on land use concerns (Jerome et al. 2022). Similarly, Fidelis et al. (2021) found in their survey of policy narratives on the circular economy in the European Union that proposals for land-related circular economy strategies are based on a bioeconomy context with potential land-use pressures from the renewability, degradability, or compostability of bio-based materials.

However, the potential problem of land use and cover from a circular economy also has solutions. The use of plants growing on marginal land and the production of climate change mitigation biochar from waste avoids competition with fertile land and food needs. Leppäkoski et al. (2021) found that biochar from willow trees on marginal land in Finland could compensate for 7.7% of annual agricultural greenhouse gas emissions. At the same time, energy crops grown on marginal land also allow cellulosic biomass without competing with food crops and help reclaim marginal land, significantly reducing greenhouse gases without posing any risk to food security (Mehmood et al. 2017). Regardless, implementing circular economy strategies remains a powerful challenge for both land use and land cover.

In this section, we find through our investigation that the proposed land-based circular economy strategies are bioeconomy-based. Therefore, increasing the use of bio-based materials poses significant challenges for land use and land cover due to the larger land area required to cultivate bio-based materials and their renewable, degradable, or compostable characteristics.

Summary

We examined the specific effects of circular economy strategies on air and water quality, energy consumption, natural resources, solid and toxic waste, and land use and cover. The findings revealed that the effects of circular economy strategies vary depending on the application. Table 2 illustrates the specific effects of the circular economy strategy on a variety of applications, as well as the most significant findings.

According to the survey results, the impact of the circular economy strategy is generally positive for most applications, except for land use and land cover, which may experience negative effects. Strategies for a circular economy can improve air and water quality, lower energy consumption, and reduce the use of natural resources. Simultaneously, solid and toxic waste will be reduced due to a circular economy strategy. However, the use of bio-based materials in the circular economy strategy will necessitate more land to cultivate bio-based materials, and the bio-based materials' recyclability, degradability, and compostability must also be considered in terms of land use.

Opportunities of the circular economy for the industry

The advancement of the circular economy presents risks and opportunities for various stakeholders in the context of ethical and sustainable industry development. Anttonen et al. (2018) empirically examined the concept of the circular economy as a triple helix innovation system within three institutional domains: industry, government, and university. The consensus space of industry, government, and university focuses on materials and products and views the circular economy as a method for creating new resources and products from waste. A triple-helix innovative circular economy strategy can facilitate sufficient consensus among industry, government, and university to enable global business opportunities to be realized by industry. In particular, the government's circular economy strategy can support the industry's sustainable development, while innovative university research on circular economy strategies can create more opportunities for the industry.

Under the assumption that the government and universities promote the spiral of industrial sustainability, the industrial production process based on the circular economy strategy will be directly accountable to consumers. The circular economy strategy can create advantageous resource input and output opportunities throughout the product life cycle (Osman et al. 2021b). The circular economy strategies are implemented throughout the entire product lifecycle, from product design to product use to business transition. Visualizing existing innovative business models based on the circular economy improves the monitoring of circular efficiency and enables a more thorough and effective evaluation of materials, products, and assets in industrial production (Rossi et al. 2020).

Table 2 The specific impact of the circular economy strategy on air and water quality, energy consumption, natural resources, solid and toxic waste, and land use and cover is different

Various applications	Impacts from circular economy	Key findings	References
Air and water quality	◆	The synergy between the circular economy and deep electrification of transport can effectively reduce air pollutants The circular economy concept can lead to a "paradigm shift" in wastewater management systems to improve water quality systems Circular economy strategies can ensure that water recycling is safe and applicable to the water quality standards for a specific use	Sgroi et al. (2018), Su and Urban (2021) and Voulvoulis (2018)
Energy consumption	◆	The circular economy strategy improves the brake thermal efficiency by 4.7% and reduces fuel consumption by 7.8% compared to diesel fuel through alternative fuels generated by pyrolysis of recycled plastics The circular economy strategy produces biogas by anaerobic decomposition of recovered organic fractions for energy production and uses in power plants Additive manufacturing, big data and advanced analytics, artificial intelligence, artificial vision, cybersecurity, Internet of Things, and robotics combined with circular economy strategies can reduce energy consumption throughout the product life cycle	Berechet et al. (2019), Laskurain-Iturbe et al. (2021) and Padmanabhan et al. (2022)
Natural resources	◆	The circular economy strategy limits the use of natural resources through partial substitution of primarily natural materials by secondary raw materials The efficiency of natural resource utilization can be improved through a systemic approach using the circular economy combined with the bio-economy	Abad-Segura et al. (2021) and Pavolova et al. (2020)
Solid and toxic wastes	◆	Product design and business models based on circular economy strategies can maximize product utility and thus reduce solid waste generation by extending the life of products and components The cumulative gas yield of the food solid waste sample is 1550 milliliter per 1 gram of dry matter, with a net present value of 3108 dollars It is expected that by 2030, almost 17 kilowatt hours of additional energy will be produced due to the treatment of solid waste, generating biogas volume that can grow to almost 9 million cubic meters per year	Al-Wahaibi et al. (2020), Rolewicz-Kalińska et al. (2020) and Sharma et al. (2021)
Land use and land cover	◇	The increased use of bio-based materials will require larger areas to grow bio-based materials, which will increase land use The potential pressure on land use and land cover will arise from whether bio-based materials are renewable, degradable, or compostable	Fidélis et al., (2021), Jerome et al. (2022) and Wiprächtiger et al. (2020)

◆ Means that the impacts coming from circular economy strategies are overall positive

◇ Means that the implementation of circular economy strategies may have negative impacts

Throughout the life cycle of industrial products, circular economy strategies can facilitate using renewable resources and energy. Patil et al. (2022) significantly enhanced the sustainability of industrial production by generating purified biogas that can replace crude oil and natural gas via anaerobic consumption and purification of recycled sucrose waste. The production of biofertilizers and the recycling of digestate are typical industrial applications of circular economy, reducing raw materials and energy inputs by utilizing waste as a raw material. In the meantime, Aguilar Esteva et al. (2020) developed the first circular economy vehicle manufacturing schematic within the framework of the Ellen MacArthur Foundation, with experimental results indicating that electric vehicles use approximately 47% less non-renewable energy than internal combustion engine vehicles throughout their life cycle. It is evident that a circular economy strategy can effectively reduce energy input.

Similarly, circular economy strategies can provide opportunities for waste and emissions throughout the product life cycle. By increasing overall system efficiency and promoting greener, safer industries, circular economy strategies help reduce waste (Cucciniello and Cespi 2018). A new plastics economy based on the core principles of the circular economy can improve the socio-economic performance of the entire supply chain and significantly reduce plastic waste and the negative environmental impacts associated with plastic waste in industrial production processes (Payne et al. 2019). The application of circular economy principles to mine waste treatment represents a significant opportunity to reduce the negative impact of mine waste and increase its value. Circular economy strategies enable the mining industry and managers to participate in the entire life cycle of a project, including the final residual waste and promote the use of natural cycles in the metallurgical industry of metals and conversion of the environment and, most importantly, the development of adaptive capacity resource cycles, thereby responding to global changes in the supply and demand for various resources (Tayebi-Khorami et al. 2019). Khan et al. (2021) demonstrated in his study that adopting circular economy practices improves productivity and, consequently, financial performance as a result of circular design, circular procurement, and, most significantly, waste recycling and remanufacturing. As a result, we can conclude that the circular economy aids businesses in improving their environmental and financial performance, which translates to a greater organizational performance by reducing waste and emissions.

This section explores the industrial development opportunities presented by the circular economy. Using the opportunities presented by a circular economy strategy, industrial companies can manufacture products responsibly through government and university collaboration. Effective circular economy strategies provide numerous opportunities for industry to reduce natural resource and energy inputs and waste and emission outputs throughout the product life cycle.

Circular economy for food systems

As shown in Fig. 3, this section will examine the circular economy opportunities in the food system from three aspects: food production, food consumption and food waste management.

Food production

The circular economy model tries to change the unsustainability of the traditional linear production mode and applies recycled materials to food production to reduce the use of external resources (Borrello et al. 2017). The recovery and recycling of the waste in the system can reduce the consumption and waste of external resources and the environmental impact (Diaz-Elsayed et al. 2020; Toop et al. 2017). There are numerous opportunities for a circular economy in food

Fig. 3 Food system production, consumption, and waste management can all benefit from the circular economy. In food production, the circular economy will promote the recycling of internal waste resources and reduce the use of external resources; a diverse and healthy diet will promote a circular economy in food consumption; and in food waste management, there will be a greater diversity of waste treatment options and a shift toward the use of waste to produce byproducts with high added value

production. In agricultural production, for instance, in Almería, southeast Spain, it has been developed to convert plant wastes into compost, bioethanol and other biological products (Aznar-Sánchez et al. 2020). The products obtained by utilizing plant wastes can be put into new food production links, which is the embodiment of circular economy opportunities in agricultural production.

In addition, a significant amount of water resources is used for grain production. Consider agricultural production as an example of the food system. Agriculture accounts for 70% of the world's freshwater consumption and is the largest consumer of freshwater resources (Alexandratos and Bruinsma 2012; Dubois 2011). According to research, the food processing industry is the second largest water consumer in the world after agriculture (Hoekstra and Chapagain 2007). Therefore, there are potential circular economy opportunities in water use in food production. Water recovery and recycling is an approach to water resource management based on a circular economy (Smol et al. 2020). Rainwater is typically collected for agricultural irrigation as part of water recovery, reducing surface water consumption and groundwater (Yannopoulos et al. 2019). In the context of the water cycle, municipal, agricultural, and industrial wastewater can be used for agricultural irrigation after undergoing multiple stages of filtration and nontoxic treatment (Pedrero et al. 2020). Many studies indicate that treated wastewater still contains trace elements, including nitrogen, phosphorus, and potassium. After wastewater is used for agricultural irrigation, chemical fertilizers can be reduced, which has positive environmental and economic effects and demonstrates the sustainability of water resource utilization (Chojnacka et al. 2020; Rossi et al. 2021).

Local food production is another important area where the circular economy can be effective, mainly because food is wasted due to damage or spoilage caused by long supply chains, and longer transportation processes consume more external resources. For example, the "Nordic Diet" is a way of eating that embodies the concept of a circular economy, placing as little emphasis as possible on meat from industrially farmed animals imported from other countries and highlighting locally produced terrestrial and aquatic foods (Bere and Brug 2009). This dietary approach can reduce transportation costs and waste caused by food spoilage during transport, promoting local economic growth. The shorter production chain also ensures that the entire food production process can be monitored locally for food safety, which can positively impact consumers (Jurgilevich et al. 2016).

Food consumption

Reducing meat consumption is one of the critical opportunities for the circular economy in the food consumption system (Jurgilevich et al. 2016), mainly because meat production has a more significant impact on the environment than vegetarian food. Most directly, by reducing the consumption of meat products, the energy, land and water consumption used in producing meat products will be directly reduced. Jurgilevich et al. (2016) put forward that raising consumers' awareness of a sustainable diet will promote the transformation of food consumption into a circular economy. For example, food suppliers, supermarkets and caterers can change people's "food environment" by increasing the quantity and attractiveness of plant foods. De Boer et al. (2014) found that "Meatless days", "less but better", and other strategies have specific effects on reducing meat consumption in different groups.

Families are the primary food waste consumers (Priefer et al. 2016). There are numerous causes of food waste in the home, including impulse purchases, excessive purchases, insufficient quantities of favorite foods, a lack of food preparation skills, poor storage management, and an inability to repurpose leftovers (Priefer et al. 2016). In this regard, case-by-case strategies should be proposed following the circular economy concept. For instance, the standard conditions for storage should be clearly stated on food packaging in the event of poor storage management (Müller and Schmid 2019). Consideration should also be given to storage conditions at home, such as refrigeration and protection from light (Bajželj et al. 2020). The supervision of policy food suppliers and the advocacy of consumers' healthy diet are conducive to building a more sustainable food environment.

Food waste management

It is beneficial to consider organic food waste in its entirety. Often, organic food waste is biologically fermented to produce methane, which is then burned to generate electricity; the fermented waste is also frequently used as compost. Methane combustion for electricity reduces the use of coal in thermal power generation, thereby reducing carbon dioxide emissions, and the use of compost on land can also contribute to carbon sequestration in organic waste (Kaur et al. 2019; Pramanik et al. 2019). Methane, compost, and digestate are typically regarded as low-value by-products of the biological treatment of organic waste throughout the chain. In addition, some biogas is released into the atmosphere during biodegradation, which can also cause environmental problems (Bouaita et al. 2022).

However, there is a more incredible opportunity and potential to utilize fruit and vegetable waste from food waste. In recent years, there has also been a growing demand for organic waste as an alternative to nonrenewable natural resources to produce high-value or eco-friendly goods. For example, more than 100 million tons of citrus fruits are made globally (Werede et al. 2021). However, the peel of citrus fruits is typically discarded during processing (Li et al. 2014). Several studies have utilized soluble dietary fiber prepared from orange peel (Khanpit et al. 2022; Tejada-Ortigoza et al. 2018; Wang et al. 2015). For instance, Khanpit et al. (2022) found that the concentration of soluble dietary fibers increased about 5.16 times after the dried orange peel was extruded at 135 ℃. Dietary fiber from orange peel positively affects human health by lowering blood lipid and glucose levels, reducing the risk of cardiovascular disease, and boosting intestinal immunity (Gunness and Gidley 2010). In addition, extracting essential oil from orange peel is necessary to produce additional high-value goods (Gavahian et al. 2019). Several studies have reported orange peel essential oil extraction (Aboudaou et al. 2019; Ciriminna et al. 2018; Franco-Vega et al. 2016).

Additionally, the skins or pomace of other fruit and vegetable products can be employed to develop products with a high added value. Baaka et al. (2017), for instance, reported the extraction of natural colorants from grape pomace. For fruit pomace, Osman et al. (2020b) found that pomace biomass waste had a calorific value of 21 megajoules per kilogram compared to other biomass energy crops such as miscanthus (16.58 megajoules per kilogram) and potato peel (15.73 megajoules per kilogram), so it can be used as a good solid biofuel; for the ash from the burning of pomace biomass waste, Osman et al. (2020b) found a high potassium content of 28.5 weight percentage, which can be used as a good agricultural fertilizer.

On the other hand, biodegradable films containing nanocellulose extracted from agricultural waste have started to be used in food packaging products in recent years. Biodegradable films are usually prepared by the following method: firstly, the cellulose is converted into nanoparticles by acidic, alkaline, mechanical and biological methods; the nanoparticles can be prepared into cellulose nanocomposites by methods or technologies such as melt intercalation, solvent casting, in situ polymerization, composite extrusion, and casting (Qasim et al. 2021). The mechanical properties of the prepared cellulose nanocomposites were improved by 87% compared to pure polypropylene (Yakkan et al. 2018), and the barrier properties were also improved to some extent (Dufresne 2017; Plackett et al. 2010; Qasim et al. 2021).

In addition, through more literature review, there are many examples of using biological wastes to prepare higher value-added products. For example, brewer's spent grain can be used to prepare highly activated carbon and carbon nanotubes, and the specific surface area of activated carbon can reach 692.3 square meters per gram; the synthesized activated carbon also showed 77% lead removal capacity after the first hour of testing in wastewater treatment (Osman et al. 2020a). Waste from various fruits and vegetables can be incorporated into microbial media to reduce the expense of conventional microbial media (Deivanayaki and Antony 2012; Tijani et al. 2012). Osman et al. (2019) proposed transforming waste lignocellulose biomass into high surface area activated carbon and, subsequently, multi-walled carbon nanotubes to promote a circular economy.

In conclusion, the use of biological waste to develop products with high added value or environmentally friendly products demonstrates the contribution of the circular economy to the development of food systems.

Life cycle assessment and circular economy

The conceptual model of the circular economy is utilized globally and in numerous research fields (Peña et al. 2021). It is based on the principle that waste from one system can be used as an input in another, thereby increasing resource use efficiency and reducing environmental impact (Tóth Szita 2017). However, the circular economy development model is not only environmentally beneficial but also requires consideration of its economic and social benefits. In addition, there is no uniform method for determining whether a particular circular economy development model contributes to sustainable consumption and production. Therefore, when introducing the circular economy concept, the environmental, economic, and social benefits of its technological solutions should be considered from a life cycle perspective, such as examining the positive and negative environmental, economic and social impacts of the waste-to-treasure life cycle. Thus, life cycle assessment is ideal for evaluating the effects of circular economy development strategies on the environment. Table 3 provides a summary of studies utilizing life cycle assessment to implement circular economy strategies in various countries, as well as a description of how life cycle assessment supports the circular economy.

Many nations and governments around the world, including the European Union, have adopted circular economy development strategies (European Union 2020), Sweden (Swedish Research and Innovation Strategy for a Bio-based Economy 2012), Denmark (Ministry of Environment and Food and Ministry of Industry 2018), and the Netherlands (The Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs 2016). Many companies have also adopted circular economy business development strategies. Theoretically, a triple evaluation of products or materials in terms of environmental, economic, and social aspects using a model that combines circular economy and life cycle assessment could aid in promoting their sustainability. However, according to Table 3, which analyzes studies conducted in various countries and sectors using circular economy life cycle assessment models for projects, we find that despite the application of circular economy life cycle assessment models in the fields of business, biomaterials, food, metal materials, construction, water, environment,

Table 3 The circular economy is supported by life cycle assessment analysis

Country	Year	Sector	Project description	Key findings	References
Netherlands	2016	Business	Analysis and design of complex (regional) circular economy systems using two life cycle assessment-based methodologies through a case study of water tourism	The study demonstrates that life cycle assessment is useful for analyzing, designing, and implementing sustainable water recreation systems, but that adding water navigation services has positive economic effects but negative environmental impacts. Consequently, the incorporation of life cycle assessment into a circular economy framework can contribute to the enhancement of regional business models for sustainable products	Scheepens et al. (2016)
India	2020	Biomaterials	Life cycle assessment of bio-based products in the context of a circular economy	The study demonstrates that there is some potential for assessing the sustainability of bio-based products within the framework of the circular economy during their life cycle, but that their practice, application, evaluation, and output have certain implications. In addition, producing bio-based products within a circular economy strategy necessitates measuring sustainability by overcoming limitations and obstacles	Dahiya et al. (2020)
Italy	2015	Food	Life cycle assessment from food to food: A case study of circular economy from cruise ships to aquaculture	The study employs a life cycle assessment to demonstrate the benefits of a case study circular economy strategy in terms of carbon footprint, energy accounting, and water footprint. However, such circular solutions remain unspecified in practice; therefore, the perspectives of stakeholders and regulators on the study must be gathered	Strazza et al. (2015)
Denmark	2016	Metal materials	Life cycle assessment of aluminum cans containing alloying elements using a circular economy strategy	The findings suggest that in order to improve the environmental performance of the beverage can industry and achieve a circular economy, efficient recycling systems must be developed. The ability of the aluminum can supply chain to be closed must be considered from an economic, environmental, and consumer standpoint	Niero and Olsen (2016)
Australia	2020	Food	Research into the relationship between food systems and diet utilizes life cycle assessment and circular economy strategies	The study highlights the limitations of the circular economy framework and life cycle assessment for evaluating the sustainability of its food systems	Lu and Halog (2020)
Netherlands	2021	Building	Circular economy life cycle assessment of building components	According to the study, circular economy and life cycle assessment models can theoretically support the recycling of building components	van Stijn et al. (2021)
Kuwait	2021	Water	Life cycle assessment of a circular economy for recycling treated sewage sludge for agricultural use	The study evaluated the environmental benefits of recycling the useful material from treated sewage sludge for plant growth but did not evaluate the cost implications of its native fertilizer production and transport	Aleisa et al. (2021)
Denmark	2020	Environment	Development of a life cycle assessment Allocation Approach for Circular Economy in the Built Environment	Utilizing circular economy and life cycle assessment in the built environment has significantly reduced waste, resource use, and environmental impact generated by the building sector, but no economic benefits have been identified	Malabi Eberhardt et al. (2020)

Table 3 (continued)

Country	Year	Sector	Project description	Key findings	References
Switzerland	2021	Materials	Regional circular economy of building materials: environmental and economic assessment combining material flow analysis, input–output analyses, and life cycle assessment	A circular economic life cycle assessment of construction materials is conducted to inform business decisions in the construction industry. However, these references are region-specific	Meglin et al. (2022)
Mexico	2020	Chemical	Life cycle assessment of intensified processes towards a circular economy: omega-3 production from waste fish oil	This case study evaluates the economic, environmental, and social aspects of Omega-3 production from waste fish oil in order to determine the model's viability. Various alternatives have a greater environmental impact, so several approaches were chosen to improve the circular economy model, but the natural environment influenced the study	Monsiváis-Alonso et al. (2020)

Research on the implementation of circular economy strategies in various fields can be statistically assessed through life cycle assessment, and the main findings of the research can be summarized

building materials, and chemistry, the results of their studies are unsatisfactory. Most studies demonstrate significant environmental sustainability potential, but economic and social sustainability considerations are still lacking.

In addition, research has demonstrated that assessing the sustainability of their products or materials using circular economy life cycle assessment models can be instructive for stakeholders and investment decision-makers. However, additional research is required in terms of practice, references, and outputs. In addition, the studied materials may be affected by the climate of the natural environment. Studies on the production of Omega-3 from waste fish oil have shown, for instance, that seasonal and fishing area conditions also play a role (Monsiváis-Alonso et al. 2020). Although the circular economy strategy is widely spread, there is a lack of research on its social context, as well as on its economic sustainability assessment and translation into practical application. Therefore, in the future, it will be necessary to strengthen its life cycle assessment methods and other assessment methods such as practice theory and actor-network theory to improve our understanding and implementation of circular economy strategies in a variety of contexts (Niero et al. 2021).

This section examines studies evaluating the life cycle models of the circular economy for research projects in various countries, regions, and times. The results indicate that their theoretical findings serve as a guide for relevant stakeholders but that their application in practice need to be strengthened in the future.

Cost-effective routes for the circular economy

This section will look at three potential circular economy routes for the current period to establish circular economy parks, promote the recycling of bulk commodity waste and municipal solid waste utilization system.

Establishing circular economy in an industrial park

As shown in Fig. 4, the construction of an eco-industrial park based on a circular economy, particularly a single circular economy industrial park for a particular industry, will concentrate waste recovery, treatment, production, packaging, and marketing on each company in a park, which will have numerous positive effects. Fan et al. (2017), for instance, believe that establishing industrial parks can improve industrial optimization, environmental protection, and economic benefits. According to Van Bueren et al. (2012), industrial parks can reduce environmental impact and associated costs.

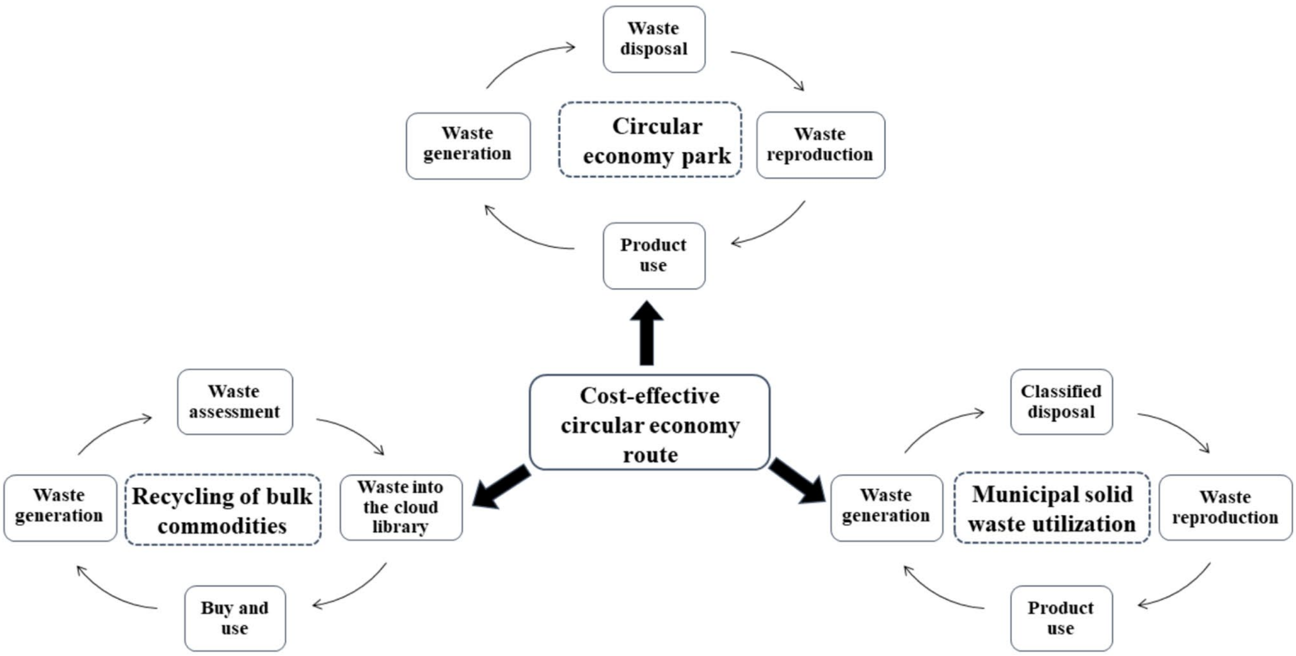

Fig. 4 Cost-effective circular economy route map based on a circular economy industrial park, the recycling of bulk commodities, and a municipal solid waste utilization system. As for the circular economy park, the recycling route includes waste generation, waste disposal, waste reproduction and waste reuse; the recycling route for the recycling of bulk commodities includes waste generation, assessment of waste quality, entry of waste information into the cloud and trading; the application of municipal solid waste is also a very critical aspect, encompassing waste generation, waste classification, waste reproduction and waste reuse

Dong et al. (2013) applied life cycle analysis and input–output analysis to China's Shenyang Economic and Technological Development Zone and found that eco-industrial parks can reduce overall carbon emissions and increase resource utilization efficiency. This deeply bound industrial park can be regarded as industrial symbiosis. The establishment of centralized industrial parks will give all stakeholders in the eco-industrial park a collective competitive advantage in energy procurement, raw materials, waste treatment and other by-products exchange, thus making the whole circular economy more cost-effective.

Increase the recycling of bulk commodity waste

Construction waste is currently one of the largest sources of waste (Bilal et al. 2020); approximately 40% of the world's total waste is generated by the construction industry (Nasir et al. 2017). The current construction industry is unsustainable due to its "obtain, manufacture, and dispose" linear economic model (Bilal et al. 2020). The construction waste generated in the end-of-life stage accounts for 50% of the total waste generated by the construction industry (Kibert 2016); this is primarily since most building materials are discarded directly at the end of their service life (Akanbi et al. 2018b). Circular economy is currently widely advocated in the construction industry, aiming to improve the efficiency of building resources and minimize waste during construction and at the end of a building's service life (Tserng et al. 2021).

Promoting the circular economy in the construction industry is more cost-effective by evaluating construction waste. For instance, Akanbi et al. (2018a) proposed and developed methods for determining the level of reusability of building materials at the end of their useful lives; the primary way to achieve this is to first develop a mathematical model that can simulate the residual value estimator of buildings or building materials. Based on this mathematical model, a reusable analysis tool is developed, which can be used to simulate the quantity and quality of materials that can be obtained from buildings at the end of their life. According to the evaluation level, construction waste should be categorized and utilized to achieve maximum reusability. In addition, the combination of the building reusability analysis tool and building information model will improve the acceptability and usability of this tool among industry practitioners. Akanbi et al. (2018b) proposed a building salvage performance estimate based on building information modeling, which can simulate the recyclability of buildings from the design stage and objectively evaluate the potential of buildings to meet the circular economy goal.

Issuing material passports for construction waste materials, which also contain much important information about construction materials stored on the internet or in the cloud, will facilitate the flow or exchange of construction waste and promote a more cost-efficient circular economy in the construction sector (Honic et al. 2019). For instance, Sauter et al. (2019) developed the procedure for recyclable building materials to encourage the sharing of construction waste data among industry personnel and the circulation of building materials, particularly waste. In addition, the construction materials passport will aid in analyzing the circulation of construction waste. For instance, Honic et al. (2019) discovered that concrete has greater potential for recycling than wood.

As shown in Fig. 4, for waste generated by bulk commodities such as construction waste, the waste's quality and performance should be evaluated prior to transmitting the waste's data information to the cloud for the convenience of buyers. This route encourages the trade of bulk product waste and is the most cost-effective circular economy path.

Municipal solid waste utilization system

Compared to all municipal wastes that are not recyclable, they are incinerated or dumped directly after recycling. Classified recycling at the end of the garbage recycling process is very efficient and can be used for various types of waste. Take China as an example; the per capita garbage productivity in China is 0.8 kilogram per day (Guerrero et al. 2013), but the landfill rate in China is higher than that in developed countries (Mian et al. 2017), which causes not only waste of garbage resources but also causes three-quarters of China's waste (Xin-Gang et al. 2016). China's national development and reform commission has published a "plan for the mandatory waste classification system" since 2016. By the end of 2020, 46 Chinese cities will have implemented a pilot waste classification and management system (Liu et al. 2022). Implementing waste sorting at the recycling source is certain to yield long-term benefits and is consistent with the contemporary concept of sustainable development. Municipal solid waste classification will undoubtedly increase waste reproduction efficiency and prevent more garbage from being directly landfilled (Zhang et al. 2021). From Fig. 4, recyclable municipal solid waste usually enters the reproduction stage and is transformed into new products, thus improving the utilization efficiency of municipal solid waste and helping the development of a circular economy.

Conclusion

This literature review provides a comprehensive analysis of the implications of effective circular economy strategies for climate change mitigation and other applications. This review article first analyzes the circular economy as an approach to waste management in three ways: waste elimination, recycling materials, and natural regeneration via ecosystems. Circular economy strategies can construct ecological waste management systems that maximize economic efficiency, reduce resource consumption, and prevent environmental pollution, thereby mitigating the pressures faced by individual countries.

In addition, the circular economy strategy aligns well with the climate change objective and is a means of addressing the climate change issue. A circular economy strategy can reduce carbon emissions from industry, waste disposal, energy use, building construction, and transportation, thereby mitigating global climate change. Moreover, circular economy strategies have various effects on air and water quality, energy consumption, natural resources, solid toxic waste, and land use cover. Specifically, a circular economy strategy can improve air and water quality, reduce energy and natural resource consumption, and dispose of solid and toxic waste effectively and reasonably. However, using bio-based materials in the circular economy strategy may increase land use and land cover pressure.

The circular economy will create numerous industrial growth opportunities and provide food system optimization opportunities. By collaborating with governments and universities, industrial companies can recycle to manufacture consumer-friendly products. Effective circular economy strategies can reduce natural resource and energy inputs as well as waste and emissions outputs throughout the entire product life cycle. The circular economy can provide opportunities for the food system's food production, food consumption, and food waste management. Through circular economy strategies, it is possible to reduce the use of nonrenewable resources in food production, increase externally recyclable resources, and recover internally generated waste. A circular economy strategy can shorten the supply chain and reduce the scale of food consumption by rationalizing the supply chain. At the same time, a circular economy strategy will provide additional waste treatment methods for food waste management and boost the value of by-products.

Theoretically, environmental, economic, and social evaluation of products or materials through a combined circular economy and life cycle assessment model can promote the sustainability of products and materials. The study revealed that although the circular economy life cycle assessment model has been applied to various sectors, the evaluation model lacks economic and social sustainability considerations. The life cycle assessment model can provide information to stakeholders and investment decision-makers. It will be necessary for the future to strengthen the combination of life cycle assessment methods with practical theory or actor-network theory to promote the implementation of circular economy strategies.

Finally, we propose a circular economy path that can provide a theoretical foundation for the future sustainability of industry, agriculture, and commerce. By concentrating the recycling, treatment, production, packaging, and marketing of waste within the park's individual businesses, developing an eco-industrial park based on a circular economy can bring several benefits. For waste generated from bulk products such as construction waste, the quality and performance of the waste are assessed, and data on the waste is uploaded to the cloud, thereby facilitating the trade of bulk product waste. Simultaneously, implementing waste separation at the recycling source will undoubtedly result in long-term sustainability benefits.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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