

# CircAI – Artificial Intelligence and the Circular Economy

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Lead organisation: Maynooth University



# Environmental Protection Agency

The EPA is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

## The work of the EPA can be divided into three main areas:

**Regulation:** Implementing regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.

**Knowledge:** Providing high quality, targeted and timely environmental data, information and assessment to inform decision making.

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- > Large-scale industrial, waste and petrol storage activities;
- > Urban waste water discharges;
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- > Monitor air quality and implement the EU Clean Air for Europe Directive, the Convention on Long Range Transboundary Air Pollution, and the National Emissions Ceiling Directive;
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- > Coordinate and fund national environmental research activity to identify pressures, inform policy and provide solutions;
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1. Office of Environmental Sustainability
2. Office of Environmental Enforcement
3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

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## What did the research aim to address?

The Artificial Intelligence and the Circular Economy (CircAI) project aimed to address the understanding of how artificial intelligence (AI) is currently used in the circular economy (CE) in Ireland. Despite increased levels of research and attention on AI and the CE, there is currently not enough familiarity with this topic for most of its stakeholders to understand the overall benefits. The innovation in this research arises from considering current state-of-the-art international best practice on AI within the CE and providing best practice guidance for future implementation and integration of AI into CE processes. Our research is of particular importance and relevance to Irish small and medium-sized enterprises (SMEs) that are considering the integration of AI into their existing CE processes. Indeed, the CircAI project can inspire stakeholders to explore relevant opportunities for AI applications for the CE, based on a strong understanding of both what AI can do and its limitations, as well as an appreciation of how CE principles could apply to their domain of interest or industry.

## What did the research find?

The CircAI project used structured interviews, literature reviews, technical analysis and engagement workshops with stakeholders from across the AI and CE sectors as well as members of the public. The adoption of AI within the CE in Ireland, as identified and highlighted by these stakeholders, is hampered by the lack of opportunities for education and training on AI. Education and training, for all stakeholder groups, is urgently required on AI applications, the societal and economic benefits of AI and the limitations of AI. In a similar way, AI developers and experts also require an increased understanding of the challenges faced by industry within the CE, which require specialized and nuanced solutions. Increased funding support for research and development in AI-driven CE models is needed at this time to stimulate innovation and ensure that technological advancements align with sustainability goals. Governments, not just in Ireland, must also provide financial incentives to SMEs to help them adopt AI for CE practices, given that SMEs often face higher barriers to entry to these technological domains due to cost constraints.

## How can the research findings be used?

There are several ways that the research findings of CircAI can be implemented. First, as the development of AI continues at pace, it is necessary for governments and industry to develop expert-led taskforces or advisory groups that bring together AI and CE experts to advise policymakers and others on the integration of AI into sustainability practices. This is required to ensure that the policy and implementation timeline remains aligned with the fast pace of constant progress, evolution and development of AI. Furthermore, from a CE perspective, collaborative efforts among businesses, policymakers and academia are crucial to ensure that regulatory frameworks support the adoption of CE practices and foster innovation. Despite increased levels of research on AI and the CE, there is still a gap in the knowledge of most stakeholders, including the public, on these topics. Policymakers themselves can face significant challenges due to their lack of understanding and proper education in this area, which prevents the development of effective policies that encourage industrial adoption of AI for the CE. Research funding agencies are encouraged to provide funding programmes that support development of educational and training platforms for both AI and the CE going forward.

**EPA RESEARCH PROGRAMME 2021–2030**

# **CircAI – Artificial Intelligence and the Circular Economy**

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## **EPA Research Report**

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Prepared by

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This report is based on research carried out/data from 2022 to 2024. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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# Contents

<b>Acknowledgements</b>	<b>ii</b>
<b>Disclaimer</b>	<b>ii</b>
<b>Project Partners</b>	<b>iii</b>
<b>List of Figures and Tables</b>	<b>vii</b>
<b>Executive Summary</b>	<b>ix</b>
<b>1 Introduction and Background</b>	<b>1</b>
1.1 CircAI – Aims and Objectives	1
1.2 Background to AI in the Circular Economy	2
1.3 Research Aims and Policy Relevance	2
1.4 Structure of the Report	4
<b>2 What is Artificial Intelligence?</b>	<b>5</b>
2.1 Examples of AI	5
2.2 Types of AI	5
2.3 AI in Sustainable Development	6
<b>3 What is the Circular Economy?</b>	<b>8</b>
3.1 The Circular Economy	8
3.2 Circular Economy in Ireland	8
<b>4 How Can Artificial Intelligence Be Used in the Circular Economy?</b>	<b>11</b>
4.1 AI for a Circular Economy	11
4.2 AI for a Circular Economy Case Studies	12
4.3 Obstacles in Using AI for a CE	13
<b>5 Summary and Recommendations</b>	<b>15</b>
5.1 Literature Reviews	15
5.2 Case Studies	15
5.3 Stakeholder Engagement	16
<b>6 Recommendations</b>	<b>17</b>
6.1 Societal Recommendations	17
6.2 Governance Recommendations	17
6.3 Technological Recommendations	18

6.4	Political Recommendations	19
6.5	Legal Recommendations	19
	<b>References</b>	<b>20</b>
	<b>Abbreviations</b>	<b>23</b>

# List of Figures and Tables

## Figures

Figure 3.1.	Comparison of LE and CE models	9
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## Tables

Table 2.1.	Common examples of AI usage, companies and techniques	5
Table 3.1.	Comparison of key parameters of LE and CE models	9
Table 3.2.	Initiatives related to the CE in Ireland	10



# Executive Summary

The Artificial Intelligence and the Circular Economy (CircAI) project considered how artificial intelligence (AI) can be used within the circular economy (CE) both in Ireland and beyond. AI is rapidly evolving and impacting our lives in many ways: how we socialise and interact, how we learn, and how we solve difficult science, engineering, socioeconomic and environmental challenges. The rapid pace of AI advancement is difficult to comprehend, yet AI can provide solutions to problems that exist in almost every domain in society today. One such area where AI is predicted to have a major positive impact is the CE. Unlike the traditional linear economy, which follows a “take–make–waste” pattern, the CE encourages the continual use of resources to create a “closed-loop” system. The CE approach ultimately results in reduced waste production, limits the consumption of new resources and greatly reduces negative environmental impacts. A CE is one in which we can protect the environment and also enable innovation and economic growth that is more sustainable in character. AI-driven systems have been shown to have significant potential to enhance CE processes and systems. Examples include automating waste sorting and management, analysing data and making predictions for supply chain management, optimising the design and manufacturing stage of products to ensure that they are easier to repair and recycle, and helping to optimise resource usage across different industries.

Despite these many advantages and positive environmental outcomes, it is necessary to carefully assess the positive and negative aspects of using AI within the CE before implementing AI-based systems, revising policy to adopt AI approaches or investing in AI-driven circular processes. The CircAI project reviewed international best practice on using AI within the CE in Ireland and other parts of the world. The project also comprehensively reviewed a large collection of case studies where AI was used within circular processes. Finally, the project findings informed the development of best practice on the role of AI in CE innovation and development of circular economic practices for Ireland.

There are several key outcomes from this project that will inform future research and policy development in this area.

First, there is a lack of specialised education and training around the topic of AI and how it could be adopted for use by businesses and industry. AI proficiency among industry is lacking, and new partnerships between industry and academia will be needed to provide education around AI.

Second, using AI for the CE involves extensive collaboration and data sharing between multiple stakeholders. Such data sharing across organisations introduces additional privacy, ethical and security risks. Organisations must consider how to understand and audit AI systems to ensure fairness, accountability and compliance with ethical guidelines. Achieving this will require substantial effort, coordination and attention to detail.

Third, governments and policymakers will be key facilitators in ensuring that AI is adopted where appropriate to achieve maximum impact within the CE. In addition, governments must ensure that financial support, educational programmes, etc., are available to industry in order to help it adopt sustainable digital CE business models, which often require costly infrastructure changes and additional resources. In addition, governments can engage with key stakeholders, including industry, academia and the public, in the policymaking process to ensure that policies are inclusive, equitable and reflective of diverse perspectives and needs.

Finally, overall, there is a requirement for more awareness around AI and the CE as individual concepts and as integrated features of sustainability initiatives. There needs to be a broader awareness and understanding of how AI works and a better general awareness of what circularity and the CE means beyond simply “recycling”. Combining proactive knowledge transfer with real-world examples can inspire stakeholders to explore relevant opportunities for AI applications in the CE, based on a sound understanding of what AI can do, as well as an appreciation of how CE principles could apply to their area of interest or industry.



# 1 Introduction and Background

Artificial intelligence (AI) is influencing and shaping many aspects of society today. It is used in industrial settings and sectors that affect everyday life, whether in healthcare, fashion, manufacturing, education, entertainment, tourism or other areas of society. AI is an area of computer science, and refers to the development of intelligent entities such as machines and computer programs that can perform tasks that are commonly associated with human intelligence (Joiner, 2018). Building such machines includes processes such as learning (the acquisition of rules from the data they are provided with), reasoning (using those rules in the data to reach approximation) and self-correction. AI applications range from expert systems and natural language processing to computer vision (CV) and robotics (Gollapudi, 2019).

Enabling more sustainable production and consumption processes is of major importance due to the rapidly increasing climate change patterns linked to our current economic model founded on the linear economy (LE) principles of “take–make–waste”. The take–make–waste strategy involves extracting raw materials from the earth, manufacturing products from those materials, and, once the products reach their end-of-life, discarding these products as waste (Pathan *et al.*, 2023). LE models lead to unsustainable waste management practices, excessive natural resource consumption, and major health, biodiversity and climate issues (Zahoor *et al.*, 2022). The circular economy (CE) offers a more sustainable alternative to address the varying negative aspects of the LE. The CE is an economic model based on restorative principles, aiming to minimise material consumption and eliminate waste, all while still promoting economic growth (Priyadarshini and Abhilash, 2020; Sverko Grdić *et al.*, 2020).

During the last decade, researchers and industry experts have agreed on the fact that AI can be used as a potential tool to facilitate a meaningful transition from the LE to the CE (Roberts *et al.*, 2022). Using AI within the CE serves the goal of optimising processes and generating solutions to complex problems. Across industries and sectors, AI technologies can unlock three high-potential CE opportunities: (1) design

circular products, components and materials; (2) operate circular business models; and (3) optimise infrastructure to ensure circular product and material flow (MacArthur, 2019). Although AI approaches work effectively in complex processes such as CE practices, it is not entirely clear to users of computer systems how AI can be used, in a practical sense, to advance the CE. It is now timely and necessary to understand what is “state of the art” in terms of international best practices on the use and implementation of AI approaches within the digitisation of the CE.

## 1.1 CircAI – Aims and Objectives

The Artificial Intelligence and the Circular Economy (CircAI) project is dedicated to exploring and explaining how AI can be effectively integrated into the CE. The project explored sustainable practices across various sectors with three primary objectives:

- objective 1 – reviewing international best practice on AI within the CE;
- objective 2 – developing best practice guidance on sectoral challenges of AI integration into the CE;
- objective 3 – creating a collection of case studies of usage of AI within the CE.

The primary objective of the CircAI project was to investigate the current usage of AI for CE practices around the globe, especially in Ireland. To achieve this goal, CircAI has generated several knowledge outputs, including comprehensive reviews (Pathan *et al.*, 2023; Ali *et al.*, 2024) of international best practices for integrating AI into the CE, compiled from stakeholder interviews, industry workshops and web-based surveys. The reviews showcase some successful real-world case studies, where innovative AI technologies are utilised for the CE, illustrating how the combination of AI and the CE can lead to sustainability and efficiency across diverse sectors. Additionally, by collaborating with industry partners, CircAI has considered what types of sector-specific guidelines are needed to address the challenges of integrating AI into CE practices. Overall, CircAI has been successful in considering how best to communicate the integration

of AI into the CE, fostering sustainability and efficiency in various sectors.

## 1.2 Background to AI in the Circular Economy

Researchers have started exploring a range of strategies and opportunities to effectively achieve the Sustainable Development Goals (SDGs) as quickly as possible (Govindan, 2023). Among various strategies, the CE has garnered increased attention recently, particularly after the documented benefits of its adoption in various organisations, as highlighted by the Ellen MacArthur Foundation (Kirchherr *et al.*, 2023). Experts have concluded that the CE has a strong positive correlation with the SDGs and that the transition to a CE is now crucial amid the climate crises<sup>1</sup> (Letta, 2024). However, the transition to a CE cannot be achieved without innovations. Various AI techniques have shown the potential to leverage the CE and help address sustainability issues (Fraga-Lamas *et al.*, 2021). The integration of AI into the CE is an emerging field that holds immense promise for sustainable development.<sup>2</sup> It is now evident that AI can significantly enhance the efficiency and effectiveness of circular processes in many diverse ways, including hidden pattern identification, data analysis, predictive analysis, improved process optimisation, and enhancing responsiveness and supporting closed-loop systems (Sánchez-García *et al.*, 2024).

Researchers have investigated the use of AI in the CE; for example, machine learning (ML) models can analyse and classify waste materials with more accuracy and speed than traditional methods (Platon *et al.*, 2024). By processing and learning from large datasets, ML models can accurately distinguish between various materials, even in mixed and complex waste streams (Li and Chen, 2023). This results in increased recycling rates and reduces the number of materials that end up in landfills. Additionally, AI is being used for predictive maintenance to extend the service life of machines and products (Fontana *et al.*, 2021). Techniques such as time series analysis, anomaly detection and advanced ML algorithms, involving recurrent neural networks, are being

employed to analyse historical and real-time data from sensors embedded in equipment. By predicting potential failures and identifying wear patterns, these models can predict when components are likely to fail, thereby reducing the need for new equipment and ultimately saving natural resources.

Several businesses have already started integrating AI into CE practices. In manufacturing, AI-based automation and robotics are improving production efficiency and reducing waste (Javaid *et al.*, 2022). For example, AI systems can optimise raw materials usage, reducing excess and ensuring that products are produced with minimal environmental impact. In agriculture, AI is used to develop precision farming techniques that optimise the use of resources like water and fertilisers, thereby supporting sustainable agricultural practices (Kuusi and Heinonen, 2022).

Globally, initiatives like the Ellen MacArthur Foundation's Artificial intelligence and the Circular Economy Project<sup>3</sup> underscore the increasing interest in utilising AI for sustainability. These efforts accumulate evidence and case studies that showcase the practical benefits of AI in promoting circularity for sustainability.

## 1.3 Research Aims and Policy Relevance

The CircAI research project has ensured a comprehensive understanding of how AI can be effectively integrated into CE practices across various sectors by adopting the following systematic research approach.

### 1.3.1 Workshops and interviews

Engaging with stakeholders from different sectors was a core component of CircAI. Several workshops were conducted, involving stakeholders from various sectors in Ireland and abroad to gather insights. These workshops yielded valuable outcomes, such as the identification of CE practices in different sectors, research trends, key CE practices and integration of AI methods. The findings informed enhanced awareness and highlighted future AI opportunities. Participants gained practical insights through sector-specific

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1 [https://environment.ec.europa.eu/topics/circular-economy/first-circular-economy-action-plan\\_en](https://environment.ec.europa.eu/topics/circular-economy/first-circular-economy-action-plan_en).

2 <https://www.circuire.ie/post/revolutionizing-circular-economy-and-business-success-with-industry-5-0>.

3 <https://www.ellenmacarthurfoundation.org/artificial-intelligence-and-the-circular-economy>.

guidance and hands-on sessions, while also sharing knowledge with and learning from others. Furthermore, several interviews were conducted with professionals who are currently working in or managing companies in Ireland and abroad that are actively utilising AI for the CE. The interviews helped the project team to understand the potential challenges facing the industry in implementing AI for the CE. Valuable suggestions were also collected on what industry believe governments, industry and academia must do to raise awareness of this topic and to support and increase the adoption of CE principles.

### 1.3.2 Details of workshops organised

**Workshop 1.** This workshop was jointly organised with Irish Manufacturing Research and its AI4CE project team. Participants at this workshop were predominantly drawn from the manufacturing sectors and more general small and medium-sized enterprises (SMEs). Representatives of relevant government departments as well as state bodies such as ESB Networks and Uisce Éireann were in attendance. The key outcomes of this workshop were establishing networks and introducing both the CircAI and AI4CE projects.

**Workshop 2.** This was an online webinar hosted by the CircAI project. There were four speakers who provided practical examples of AI and CE from Ireland and beyond. The overall theme of the webinar was the opportunities that digitalisation and AI offer the CE, and participants discussed how these technologies will be core components in the transition towards a CE. The speakers were drawn from academic research, SMEs, consultancy and industry research.

**Workshop 3.** This was the closing workshop for the CircAI project, and it attracted over 30 participants. Participants were drawn from academic research, SMEs involved in CE activities and interested in learning about AI for the CE, and environmental consultancy. They included academic experts in AI and members of the public. The main outcome of this workshop was the dissemination of the results from the CircAI project to a wide range of stakeholders. The workshop also provided opportunities for further networking and knowledge exchange among participants.

### 1.3.3 Details of interviews conducted

Due to the private nature of the interview process, we cannot provide details of the participants in the CircAI interview process. However, we believe that our 11 interviewees, detailed as follows, provided a good overall sample of stakeholders in AI and the CE:

- one European Commission expert on sustainability;
- five chief executive officers (CEOs) of Irish SMEs;
- three academic researchers (one AI expert, one expert on CE and one expert on sustainability business models);
- one non-governmental organisation (NGO) professional;
- one technical enterprise laboratory professional (construction sector).

### 1.3.4 Literature reviews

Extensive literature reviews were conducted to map the current landscape of AI applications in the CE. Various review techniques, such as structured search and predefined inclusion criteria, helped in identifying and categorising key themes, trends and patterns within the literature. The reviews assisted in identifying existing knowledge gaps and informed a more comprehensive understanding of AI applications and their implementation for the CE. The reviews also provided a theoretical foundation for developing new AI-driven circular solutions. The reviews were compiled into review papers (Pathan *et al.*, 2023; Ali *et al.*, 2024) that present detailed analyses and real-world case studies. Finally, the reviews also offer recommendations and policy implications for stakeholders. The outputs from this research contribute to academic discourse and serve as valuable resources for practitioners and policymakers seeking to leverage AI for sustainable economic practices.

### 1.3.5 Case studies

Real-world case studies are crucial for demonstrating the practical benefits of AI in the CE. These cases<sup>4</sup> are documented and provide stakeholders and the public with concrete examples of AI integration into the CE, showcasing how AI can enhance efficiency,

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4 <https://www.cs.nuim.ie/~pmooney/circai/>.

reduce waste and promote sustainability. The project team conducted a critical analysis of the workings/operations of various case study subjects around the world to understand their AI-driven circular practices and studied their methods and outcomes in detail. Additionally, in-depth interviews with stakeholders who are actively engaged in applying AI to CE initiatives provided key learning about the barriers they are facing in implementing AI for the CE. The findings from these interviews also provided learnings about the CE goals that these stakeholders are focused on and what supports they believe are needed from governments and the public to advance progress towards them. These case studies will serve as valuable resources for spreading knowledge and inspiring further innovation in the field.

### ***1.3.6 Policy and public service impacts***

The relevance of the CircAI project to policy, particularly in Ireland, is significant. The project aligns with national and international sustainability goals, including the European Green Deal<sup>5</sup> and the Whole of Government Circular Economy Strategy 2022–2023.<sup>6</sup> By providing best practice guidelines and policy recommendations, CircAI supports the development of frameworks that encourage AI adoption in CE practices in Ireland. Furthermore, some impactful reviews of AI integration into CE approaches have been published (Pathan *et al.*, 2023; Ali *et al.*, 2024) and made open access. Making all knowledge

outputs open access maximises the opportunities for policymakers and industry experts to understand the concepts explained in the outputs.

## **1.4 Structure of the Report**

This report is structured into five comprehensive chapters.

Chapter 2 explores the potential of AI and its impact across various sectors. It further details key AI techniques and their inner workings. Finally, it discusses the important role of AI in achieving environmental sustainability.

Chapter 3 introduces the CE and the urgency of transitioning from the LE. It further highlights some steps taken by the Irish government in implementing CE at the national level.

Chapter 4 explores AI's transformative potential in advancing the CE, focusing on high-priority areas. It presents real-world case studies of AI applications in advancing the CE and addresses significant obstacles in the usage of AI for the CE.

Finally, Chapter 5 discusses the knowledge outputs produced during the CircAI project. It also provides some recommendations that might be helpful for governments, policymakers, industry experts and the public in realising the potential of AI for the CE, as well as some clear guidelines for its effective implementation.

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5 [https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal\\_en](https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en).

6 <https://www.gov.ie/en/publication/b542d-whole-of-government-circular-economy-strategy-2022-2023-living-more-using-less/>.

## 2 What is Artificial Intelligence?

This chapter explores the potential of AI and its influence across various sectors. It explains how AI operates using data-driven algorithms and key techniques such as ML, deep learning, natural language processing and CV. It further explores the potential for AI in promoting sustainable development, with its applications in environmental monitoring, smart city development, sustainable agriculture and waste management poised to drive substantial economic benefits and environmental sustainability.

### 2.1 Examples of AI

AI refers to computer systems that can perform tasks that typically require human intelligence, for example object identification, predictions, speech translation and generating natural languages (Joiner, 2018). AI systems possess the ability to improve their performance on tasks, adapt to new conditions and provide decisions without explicit programming.<sup>7</sup> Nowadays, AI is increasingly used in almost every field of life, from marketing and finance to healthcare, education and manufacturing, on account of its ability to aid informed decision-making and perform computationally intensive operations.<sup>8</sup> Various companies use AI to improve the capabilities of their existing technologies. This is evident in

smartphones with AI assistants, smart home devices with automation features, and driverless vehicles.

Table 2.1 shows some examples of where AI is used in everyday life.

### 2.2 Types of AI

There are two major types of AI:

- Weak AI (or narrow AI).** Weak AI refers to highly specialised systems that focus on a single or limited range of activities within a narrowly defined context (Kuusi and Heinonen, 2022). This type of AI is the one that is most frequently encountered with AI systems today. In general, these systems process large amounts of data quickly and accurately. The systems lack higher general intelligence, which means that they cannot apply their capabilities beyond their programmed functions. For example, a CV system for detecting faults in a manufacturing process does not possess the vision capabilities to be used in a vehicle for autonomous driving. Currently, all AI systems exemplify weak AI, from recommendation engines and email inbox spam filters to chatbots and many of the applications mentioned in Table 2.1.

**Table 2.1. Common examples of AI usage, companies and techniques**

Application area	Specific examples	Description	Companies
Entertainment	Netflix recommendations	AI algorithms analyse user behaviour to suggest personalised content.	Netflix
Healthcare	Medical diagnosis	AI assists in diagnosing diseases by analysing medical images and patient data.	IBM Watson Health, Zebra Medical
Retail	E-commerce recommendations	AI analyses purchase history and browsing patterns to recommend products.	Amazon, Alibaba
Customer service	Chatbots and virtual assistants	AI-powered chatbots handle customer inquiries and provide support.	Microsoft (Cortana), Google (Google Assistant)
Finance	Fraud detection	AI detects fraudulent transactions by analysing patterns and anomalies in financial data.	PayPal, Mastercard
Education	Personalised learning	AI tailors educational content and pace to individual student needs.	Coursera, Duolingo
Marketing	Targeted advertising	AI analyses user data to deliver personalised advertisements.	Facebook, Google Ads

<sup>7</sup> <https://www.linkedin.com/pulse/artificial-intelligence-ai-type-rajoo-jha/>.

<sup>8</sup> <https://online.york.ac.uk/artificial-intelligence-and-its-impact-on-everyday-life/>.

- **Strong AI.** Strong AI, often referred to as artificial general intelligence (AGI), represents a hypothetical level of AI that possesses human-like cognitive abilities (Omran and Schwarz-Herion, 2018) and capacity to understand, learn and apply knowledge across a wide range of tasks and environments. This enables AGI to solve problems it has never been explicitly trained to address. While AGI remains a theoretical concept, it is a significant area of interest within the research community.

## 2.3 AI in Sustainable Development

As we continue to learn more about the effects of climate change, it is now clear that environmental sustainability should be a high priority (Omran and Schwarz-Herion, 2018). Sustainability is a well-established concept usually recognised as having three dimensions: environmental, economic and social (Moldan *et al.*, 2012). It is not feasible to have a sustainable economy and social well-being with such an environmental crisis, as climate change affects economic, social and environmental systems worldwide, and its consequences are expected to persist. As per the reports of the World Meteorological Organization, it is estimated that within the next 5 years there is a 50/50 chance that the global average temperature could rise more than 1.5°C above pre-industrial levels (Marques, 2020). Furthermore, it is reported that 85,000 to 145,000 human fatalities have been registered annually across Europe due to extreme weather events such as floods, storms and extensive heatwaves.<sup>9</sup> With such mounting environmental concerns, the call to accelerate our path to sustainable development becomes more urgent. Here, AI is considered to have a potential role in tackling the problems of achieving environmental sustainability. AI has the potential to significantly analyse the complex environment, transforming data into actionable insights, improving predictions and accelerating scientific modelling and discovery, thereby enabling better-informed decision-making (Chen *et al.*,

2023). Research has shown that AI techniques and strategies have had a significant impact on sustainability across the following sectors.

### 2.3.1 Environmental monitoring and protection

AI plays a crucial role in environmental monitoring and protection by analysing vast amounts of climate data to predict and monitor climate change impacts, aiding policymakers and scientists in developing effective mitigation and adaptation strategies (Jones, 2017). For instance, AI can process satellite imagery to monitor deforestation, land use changes and natural resource exploitation.<sup>10</sup> AI systems also enhance pollution control by monitoring air and water quality in real time, identifying pollution sources and predicting pollution levels (Fu *et al.*, 2023). Through timely intervention, real-time monitoring can aid in the reduction of air pollution by up to 30%. In terms of water quality management, AI-driven surveillance systems can efficiently detect pollutants and ensure a safe supply of water, thereby safeguarding public health (Yaroshenko *et al.*, 2020).

### 2.3.2 Smart cities

AI has made a significant contribution to the development of smart cities by analysing data on traffic, population density, energy consumption and environmental conditions, aiding urban planning. Additionally, AI can be applied to optimise public transport routes and reduce traffic congestion by up to 25%, thus reducing the emissions that result from traffic jams.<sup>11</sup> AI can efficiently predict waste generation patterns, increasing recycling rates by up to 30% and improving the overall waste management of cities (Olawade *et al.*, 2024). Additionally, AI-powered emergency response systems can significantly reduce response times by analysing and predicting incident patterns, thus improving the overall safety and sustainability of cities.

9 <https://www.eea.europa.eu/en/topics/in-depth/climate-change-impacts-risks-and-adaptation>.

10 <https://icpac.medium.com/integrating-earth-observation-and-artificial-intelligence-to-combat-climate-change-impacts-and-93388a6d8b29>.

11 <https://syndelltech.com/ai-in-transportation/#:~:text=A%20study%20by%20McKinsey%20%26%20Company,significant%20economic%20and%20environmental%20benefits>.

### 2.3.3 *Agriculture*

To maintain a healthy environment and guarantee food security for generations, it is now necessary to implement sustainable agriculture practices.<sup>12</sup> AI has proved successful in precision farming, where ML algorithms can be used to analyse massive amounts of data from various sources, including satellite imagery, weather data and soil sensor data, to optimise the use of water, fertilisers and pesticides.<sup>13</sup> This strategy

has been shown to increase crop yields while having minimal environmental impact. CV algorithms can help predict plant disease efficiently, helping farmers to take timely preventive measures and thus reducing the need for chemical interventions (Shaikh *et al.*, 2022). Additionally, AI-driven resource management techniques can help in conserving water resources at large by analysing weather patterns and soil moisture levels, ensuring that crops receive the right amount of water at the right time (Srivastava *et al.*, 2022).

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12 <https://www.plugandplaytechcenter.com/insights/importance-sustainable-agriculture>.

13 <https://thedata scientist.com/ai-in-precision-agriculture-optimizing-crop-yield-through-data-driven-insights/>.

# 3 What is the Circular Economy?

This chapter provides a comprehensive introduction to the CE, emphasising its critical importance in transitioning from the traditional LE model, which poses severe environmental threats. The chapter highlights the significant benefits of the CE, such as optimising resource use, reducing waste generation and minimising environmental impacts. The chapter also delves into Ireland's proactive steps towards CE adoption, detailing government strategies such as the Whole of Government Circular Economy Strategy 2022–2023, the National Circular Economy Strategy and the Local Government (Miscellaneous Provisions) Act 1982, and initiatives such as the Circular Economy Programme (2021–2027) and CIRCULÉIRE, which aim to enhance regulatory frameworks, foster innovation and achieve substantial reductions in carbon dioxide (CO<sub>2</sub>) emissions, showcasing Ireland's commitment to sustainable economic growth.

## 3.1 The Circular Economy

The global economy largely relies on linear economic principles characterised by a take–make–waste approach. This approach involves extracting natural resources from the earth, manufacturing them into products and discarding them as waste at their end-of-life stage (Ivanova *et al.*, 2022). This economic model promotes excessive natural resource consumption, leading to unsustainable waste management practices. Consequently, it creates serious issues related to climate, biodiversity and health (Rashid and Malik, 2023). It is estimated that the amount of resource consumption will double from 90 gigatonnes in 2020 to 167 gigatonnes by 2060 (Marín-Beltrán *et al.*, 2022). Such excessive consumption patterns heighten the demand for resource extraction, resulting in increased greenhouse gas emissions from extraction and mining activities, which ultimately degrades air quality and accelerates habitat destruction (Woydt, 2022). Furthermore, the rapid production and consumption cycles contribute significantly to the accumulation of waste, creating substantial environmental issues.

It is estimated that over 2 billion tonnes of municipal solid waste is generated each year, a figure expected to rise given current patterns.<sup>14</sup> Given these trends, there emerges an urgent need to transition towards more sustainable economic practices, to ensure economic, social and environmental sustainability.

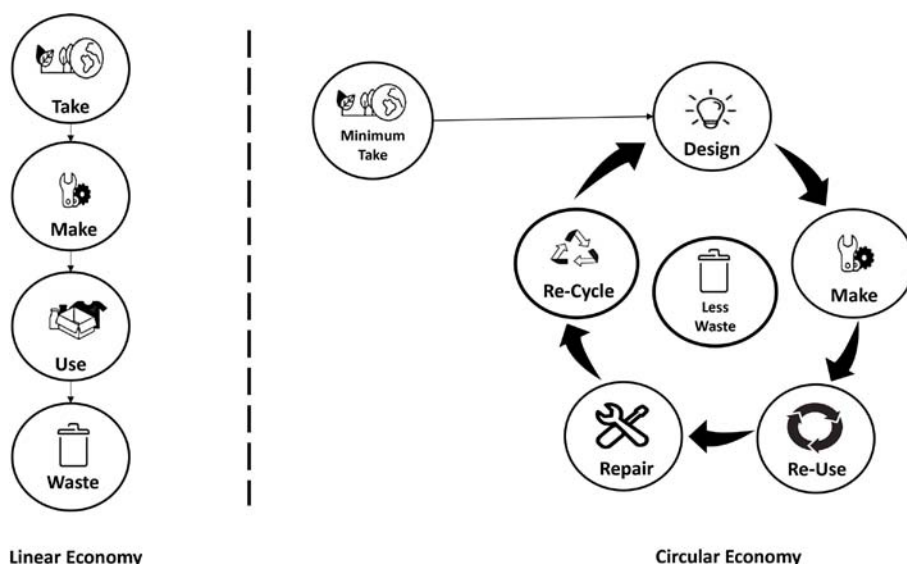
At this critical juncture, the idea of a CE has surfaced as a key strategy for fostering sustainable economic practices. A CE is defined as “an economic system that adopts business models focused on minimising waste and replacing the end-of-life concept by reducing, reusing, recycling and recovering materials at every stage of the production, distribution and consumption processes” (Xiong *et al.*, 2023). Figure 3.1 clearly illustrates the distinct working models of the LE and CE. Furthermore, in an ideal CE, waste no longer exists, since the production cycles would be fully closed. As a result, adopting CE practices has the potential for reducing raw material and energy consumption by 80–90% compared with the traditional linear model (Allacker *et al.*, 2014). From an economic perspective, CE practices can lower product costs by 25–30%, offering substantial financial benefits alongside their environmental advantages (Tolio *et al.*, 2017). To further illustrate the differences between the LE and CE, Table 3.1 provides a comparative overview of their key parameters. The CE model aims to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations, and has received a lot of attention in recent years. The move from an LE to a CE has been emphasised by the European Commission as a crucial contribution to the European Union's efforts to establish a sustainable, low-carbon, resource-efficient and competitive economy.<sup>15</sup>

## 3.2 Circular Economy in Ireland

The adoption of the CE model is more critical than ever, and the urgency of this approach is evident in

<sup>14</sup> [https://datatopics.worldbank.org/what-a-waste/trends\\_in\\_solid\\_waste\\_management.html](https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html).

<sup>15</sup> <https://www.ellenmacarthurfoundation.org/completing-the-picture>.



**Figure 3.1. Comparison of LE and CE models. Source: reproduced from Pathan *et al.* (2023); licensed under CC BY 4.0 (<https://creativecommons.org/licenses/by/4.0/>).**

**Table 3.1. Comparison of key parameters of LE and CE models**

Parameter	LE	CE
Resource use	High (up to 100% of raw materials)	Optimised (can save 80–90% of raw materials)
Waste generation	High (up to 90% of materials become waste)	Low (can reduce waste by 70–90%)
Economic impact	Short-term gains, long-term resource depletion	Sustainable growth (product costs can be cut by 25–30%)
Environmental impact	High (significant pollution and resource depletion)	Low (can reduce environmental footprint by 40–60%)

the growing global interest in CE practices (Ghosh, 2020). Aligning with the global trend, Ireland is actively working to integrate CE principles through national strategies. The government has started initiating several measures for integrating a CE approach into various sectors, demonstrating a strong commitment towards sustainable development. The Whole of Government Circular Economy Strategy 2022–2023<sup>16</sup> is the first national strategy to establish the CE. This comprehensive plan underscores the critical need to transition to a CE framework to address climate change, minimise greenhouse gas emissions and promote sustainable economic development. This strategy is an integral part of the government’s broader objectives of reducing overall greenhouse gases by 51% by 2030 and achieving a net-zero

economy by 2050. This strategy was mentioned as an explicit commitment in the Waste Action Plan for a Circular Economy (WAPCE) (2020–2025).<sup>17</sup> The WAPCE aims to position Ireland as a leader in sustainable waste management by promoting CE principles, enhancing regulatory frameworks and fostering innovation. The Environmental Protection Agency’s (EPA’s) Circular Economy Programme (2021–2027)<sup>18</sup> is designed to support Ireland’s shift towards a CE by offering seed funding, innovation grants and sponsorships. The programme’s objectives are to provide leadership, maintain competitive support programmes, build a knowledge base and realise enterprise opportunities through circular business models and regulatory frameworks.

16 <https://www.gov.ie/en/publication/b542d-whole-of-government-circular-economy-strategy-2022-2023-living-more-using-less/>.

17 <https://repak.ie/news-room/blog/the-waste-action-plan-for-a-circular-economy/>.

18 <https://www.epa.ie/publications/circular-economy/resources/the-circular-economy-programme-2021-2027.php>.

**Table 3.2. Initiatives related to the CE in Ireland**

Initiative	Type of activities	Characteristics and objectives
Landfill levy	Prevention	Encourages recycling and reduces the amount of waste that goes to landfill and incineration
Circular Economy Innovation Grant Scheme	Prevention Reuse Recycling	Financially supports CE-based projects in order to raise awareness of the need for transition to a CE
CIRCULÉIRE Innovation Fund	Prevention Reuse Recycling	Financially supports large-scale systems-level innovation for circularity in the manufacturing sector
MyWaste.ie	Prevention Reuse Recycling Disposal	Provides information and advises households and businesses on options for reusing, recovering and disposing of a wide range of materials
ReMark	Reuse	Aims to give consumers the confidence to buy from reuse organisations via labelling
Government Climate Toolkit 4 Business	Prevention Reuse Recycling Disposal of materials	Supports businesses in analysing, understanding and taking action on their carbon footprint
Rediscovery Centre	Prevention Reuse Recycling	Ireland's National Centre for the CE organises workshops for students and thematic workshops to citizens and provides policymakers with data and information on the non-waste reuse sector in Ireland
National Waste Prevention Programme	Prevention Reuse Recycling	Seeks to prevent waste and drive the CE by delivering national-level strategic programmes with high visibility, impact and influence

Source: Reproduced from Pathan *et al.* (2023); licensed under CC BY 4.0 (<https://creativecommons.org/licenses/by/4.0/>).

In addition to these high-level strategies and plans, the Irish government has rolled out several key initiatives (Table 3.2) to promote circularity, such as the following.

- Extended producer responsibility<sup>19</sup> schemes mandate that manufacturers and importers bear a level of responsibility for the environmental impact of the products they circulate on the market.
- MyWaste.ie,<sup>20</sup> Ireland's official guide to managing waste, supports households and communities in actions to reduce, reuse and recycle.
- The Rediscovery Centre<sup>21</sup> is Ireland's national centre for the CE. The centre promotes sustainability through various initiatives such as educational programmes, workshops and research opportunities to foster environmental awareness and sustainable practices.
- The National Waste Prevention Programme<sup>22</sup> is a Government of Ireland initiative, led by the EPA,

which has supported national-level programmes to prevent waste and drive the CE in Ireland since 2004. These funding programmes aim to develop novel solutions for the CE in priority areas such as food waste, construction and demolition, plastics, agriculture, resources and raw materials, and local waste prevention.

- CIRCULÉIRE<sup>23</sup> is Ireland's national platform for circular manufacturing, aiming to support the transition from linear to circular business models. It is a €4.5 million public–private partnership formed by Irish Manufacturing Research, the Department of Climate, Energy and the Environment, EPA and Climate-KIC, along with 25 founding industry members. CIRCULÉIRE aims to identify, test, fund and scale circular manufacturing systems that contribute to reducing both CO<sub>2</sub> emissions and waste.

<sup>19</sup> <https://www.gov.ie/en/department-of-climate-energy-and-the-environment/publications/extended-producer-responsibility-epr/>.

<sup>20</sup> <https://mywaste.ie/>.

<sup>21</sup> <https://www.rediscoverycentre.ie/>.

<sup>22</sup> [https://www.epa.ie/publications/circular-economy/resources/Circular\\_Economy\\_8PP\\_fa\\_v9\\_digital.pdf](https://www.epa.ie/publications/circular-economy/resources/Circular_Economy_8PP_fa_v9_digital.pdf).

<sup>23</sup> <https://circuleire.ie/>.

## 4 How Can Artificial Intelligence Be Used in the Circular Economy?

This chapter discusses the transformative potential of AI in advancing the CE. It discusses a few high-priority areas where AI can be valuable to help implement circular practices in the real world, such as circular product designs, optimising circular business models and enhancing circular infrastructures. This chapter further presents several real-world case studies where AI is being successfully used to achieve circular ambitions, illustrating the practical usage of AI in promoting sustainability across various sectors. However, the chapter also addresses significant obstacles in using AI in the transition to a CE, such as data availability, ethical concerns, funding challenges, regulatory barriers and the need for education and awareness. By overcoming these hurdles, AI can play a crucial role in driving a sustainable and efficient CE.

### 4.1 AI for a Circular Economy

AI holds significant transformational potential for a CE through several applications, including enhanced circular product design, data analysis, predictive analysis, reverse logistics, automated material sorting and improved process optimisation.<sup>24</sup> This section explores, in a practical sense, the important role that AI can play in the transition to a CE and how it can be further used to optimise a circular infrastructure. The findings from this research suggest that AI can unlock three high-potential CE opportunities:

- **Designing new circular products.** A CE prioritises innovative design principles to ensure that materials, components and products retain their utility and value throughout their life cycle (Ghoreishi and Happonen, 2020). Such designs extend the lifespan and also promote increased cycles of reuse, repair and recycling of products and their constituent materials. AI can assist product designers in managing such complex tasks by facilitating iterative, assisted design generation processes (MacArthur and Ellen MacArthur Foundation, 2019). These AI-driven approaches enable rapid prototyping and testing, allowing designers to quickly render and refine their product designs for optimal performance within a shorter time frame. Consequently, new products can be created with circularity in mind, which are then maintained and preserved within the economy for an extended time (Pregowska *et al.*, 2022). This approach significantly reduces resource extraction and waste production.
- **Operating circular business models.** To develop sustainable business models, organisations must integrate CE principles into various business operations, including manufacturing, marketing, sales and logistics. AI is currently being effectively used in developing or enhancing business models that are underpinned by the principles of a CE (Di Vaio *et al.*, 2020). For example, AI can be used to accurately predict demand by analysing large volumes of real-time consumer data (Aktepe *et al.*, 2021). This can help businesses avoid wasteful purchasing practices or over-manufacturing of products based on poor insight into consumer behaviour and consumer demands. Additionally, AI supports predictive maintenance of products and machinery by providing timely alerts for maintenance, thereby extending equipment lifespans and minimising the need for and cost of new equipment (Carvalho *et al.*, 2019). AI-assisted circular business models, including product-as-a-service, dynamic pricing and asset sharing, open new avenues for enhancing circularity, which in turn increases economic benefits and conserves resources (Chen *et al.*, 2022; Fallahi *et al.*, 2023).
- **Optimising circular infrastructure.** The key principle of a CE is the continuous reuse of materials and products, avoiding the traditional cycle of consumption and disposal. This requires a robust circular infrastructure for the collection, sorting and separation of materials (Julianelli *et al.*, 2020). AI offers numerous solutions for optimising the infrastructure needed to circulate

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<sup>24</sup> <https://www.ellenmacarthurfoundation.org/artificial-intelligence-and-the-circular-economy>.

products and materials within the economy. A prominent example is the use of AI-driven image recognition techniques combined with robotics for sorting mixed-material streams (i.e. optical sorting) (Schmidt *et al.*, 2021). Using large databases of images of materials for sorting, robotic machinery can be developed to perform this task automatically and, in many cases, faster than human operators. Another innovative approach is the automated disassembly of multi-part products using AI-embedded cameras and sensors to assess the condition of each product (Yu *et al.*, 2023). This technology improves the efficiency and precision of disassembly processes.

## 4.2 AI for a Circular Economy Case Studies

### 4.2.1 Circular product design case study

**General Motors and Autodesk.** General Motors (GM)<sup>25</sup> has partnered with Autodesk to leverage generative design and additive manufacturing in the development of electric vehicles (EVs). This collaboration is aligned with the principles of circular product design and sustainability through the optimisation of vehicle components for performance, cost and material utilisation.

**AI-powered innovation.** GM and Autodesk utilised generative design AI software to explore various design permutations for EV components. Generative design involves setting parameters such as strength, mass and required connection points. The software then uses AI to generate various feasible working design options. This approach is coupled with additive manufacturing (3D printing), which provides greater geometric flexibility than traditional methods such as injection moulding or, in the case of subtractive manufacturing, where materials are removed from a workpiece to create a desired product.

**Contribution to the CE.** The collaboration<sup>26</sup> between GM and Autodesk has showcased a substantial advancement in circular product design.

One significant outcome is the creation of a seat bracket that is 40% lighter and 20% stronger than its traditionally manufactured counterpart, achieved using generative design and additive manufacturing. The integration of AI and 3D printing enables rapid design iterations and refinement, reducing waste by a significant amount and thereby promoting beneficial resource utilisation.

### 4.2.2 Circular business model case study

**Tailr.** Tailr<sup>27</sup> is an innovative Irish software company that aims to revolutionise the garment industry by addressing production inefficiencies and sustainability challenges. Recently, Tailr raised €700,000 in investment from Delta Partners, Haatch, Enterprise Ireland and angel investors to scale up its operations and expand its market reach.<sup>28</sup>

**AI-powered innovation.** Tailr's cloud-based software-as-a-service platform utilises AI to optimise garment production, ensuring consistent sizing and reducing waste. The platform enables real-time data flow between design teams, fabric mills and factories, enhancing efficiency and sustainability. Tailr's technology automates the creation of tech packs and improves quality control, significantly reducing the need for multiple samples and speeding up production cycles.

**Contribution to the CE.** Tailr addresses the fashion industry's sustainability issues by minimising sampling errors, reducing overproduction and decreasing size-related returns. The platform's ability to ensure consistent sizing and streamline production processes supports clothing brands in achieving their sustainability goals, contributing to a more CE approach within the industry.

### 4.2.3 Optimising circular infrastructure case study

**Sensi.** Sensi<sup>29</sup> is an Irish start-up specialising in developing reverse vending machines (RVMs). These smart RVMs accept a variety of recyclable materials,

25 <https://www.autodesk.com/customer-stories/general-motors-generative-design>.

26 <https://www.additivemanufacturing.media/news/gm-seat-bracket-made-with-autodesk-generative-design-software>.

27 <https://tailr.ai/>.

28 <https://www.enterprise-ireland.com/en/news/irish-tech-platform-tailr-announces-700-000-investment-further-cementing-their-role-in-revolutionising-the-garment-industry-and-advancing-sustainable-fashion>.

29 <https://www.envipco.com/reverse-vending-machines/compact>.

such as paper cups, plastic bottles and aluminium cans, rewarding users with digital vouchers and promoting efficient recycling.

**AI-powered innovation.** Sensi's RVMs make use of Internet of Things (IoT) sensors and CV algorithms to detect recyclables based on their appearance and materials, to perform improved sorting. This technology is efficient in identifying and segregating recyclables, improving overall recycling processes. These machines can continuously learn and adapt, refining their identification capabilities over time.

**Contribution to the CE.** By increasing recycling rates, Sensi's RVMs help increase recovery rates for the target materials, divert waste from landfills, reduce greenhouse gas emissions and preserve natural resources. The incentives provided for recycling encourage more sustainable consumer behaviour, promoting a more efficient use of resources and minimising waste.

### 4.3 Obstacles in Using AI for a CE

It is clearly understood that AI can be a crucial factor in enabling a CE. However, there are some challenges that need to be addressed to enable AI to be utilised to its full potential in this context. The CircAI project identified what it considers to be the most pressing challenges facing companies and practitioners when using AI in CE processes. Some of these challenges are outlined below.

#### 4.3.1 Data availability

Data availability is a significant barrier to implementing AI for CE practices. Reliable, comparable and comprehensive data are essential for developing effective AI models for advancing the CE. However, many businesses face difficulties in accessing high-quality data due to the lack of standardised data collection methods, collaborations between stakeholders for data sharing and transparency across industries. While the General Data Protection Regulation imposes regulations to protect personal data, it should not be viewed as a barrier to collaboration. The regulation's intent is to safeguard personal data, not to prevent businesses from sharing non-personal or anonymised data, which is often critical for AI and CE initiatives. It is very challenging to implement AI CE initiatives without robust data. Improved availability of data can empower businesses

to take full advantage of the potential of AI to drive the CE, leading to more efficient and sustainable business practices.

#### 4.3.2 Technological and implementation barriers

Businesses, particularly those that operate with limited capital and tight profit margins, often face challenges in adopting advanced technologies such as AI, IoT and digital manufacturing tools in their operations due to the high costs attached and the complexities of integration. Although these technologies are critical for advancing CE practices such as resource optimisation, enhanced waste management practices and circular product design, their adoption is hindered by a lack of substantial investments and the necessary expertise for effective integration. Moreover, the legacy systems are not designed to be used for circular practices, making the integration of new technology more difficult and resource intensive. Additionally, there is a lack of available resources tailored to the implementation of CE infrastructure, compelling businesses to innovate from scratch.

#### 4.3.3 Ethical and algorithmic challenges

When developing and deploying AI or other advanced systems for the CE, several concerns may arise related to algorithmic bias, transparency and accountability. AI systems can inherit biases from their historical training data and are likely to replicate these biases in decision-making processes. This can result in skewed outcomes that may enforce some socioeconomic disparities. For instance, an AI system trained predominantly on data from urban areas with advanced infrastructure may become ineffective in identifying recyclable materials in rural or underdeveloped areas. This could lead to a disparity in recycling efficiency between regions, impacting communities with fewer resources. Moreover, the lack of transparency and interpretability in AI decision-making processes can result in a lack of trust and broader acceptance among stakeholders. Ethical considerations also extend to handling sensitive information responsibly by keeping data privacy and security parameters in mind. Robust frameworks and assessment tools are required to mitigate potential risks and protect data, to ensure an ethically sound and transparent digital circular infrastructure for the CE.

#### **4.3.4 Funding**

To develop and scale up sustainable business projects using AI, securing adequate funding support from relevant sources is essential. Many businesses face financial challenges due to the higher costs related to the adoption of new and innovative circular business models, such as predictive maintenance, automated recycling and closed-loop manufacturing. Moreover, the time-consuming and complex application process (extensive documentation, detailed project proposals and rigorous compliance with regulations) for government grants deters businesses from pursuing these funding opportunities. To address this funding gap, governments and institutions need to develop more accessible financial resources, simplified application procedures and targeted incentives to make sustainable practices economically viable and attractive for businesses of all sizes.

#### **4.3.5 Regulatory and policy issues**

The current regulatory frameworks are generally designed to support LE models that prioritise production and disposal over reuse and recycling. This misalignment creates significant obstacles, leading to fragmented and inconsistent policies that hinder implementation of sustainable practices. There is also the issue of inconsistencies in existing policies across different regions and industries and a lack of harmonised standards, which leads to confusion and reduces the effectiveness of circular initiatives. To address these challenges, governments at national and regional levels should lead in developing regulatory frameworks. International bodies like the European Union and the United Nations can create unified standards, while industry associations and organisations like the International Organization for Standardization can develop sector-specific guidelines. Collaborative efforts among businesses, policymakers and academia are crucial to ensure that these frameworks support the adoption of CE practices and foster innovation.

#### **4.3.6 Stakeholder engagement challenges**

To create a cohesive and functioning CE, it is essential to engage a diverse group of stakeholders, including businesses, consumers, policymakers and communities; however, several significant barriers impede this process. The stakeholders and the ecosystem settings in which they collaborate are diverse, which might affect stakeholders' engagement with CE goals. Furthermore, many businesses are reluctant to adopt or embrace CE processes due to a lack of proper technology, financial resources, expertise and resources, and a lack of consumer interest in environmental sustainability when making purchasing decisions. Additionally, building collaborative networks among stakeholders is difficult due to differing interests and priorities. To overcome these challenges, clear communication channels and platforms for dialogue need to be established to align stakeholder goals. Neutral facilitators like government bodies or industry associations can play a role in mediating discussions, ensuring that common objectives are prioritised over conflicting interests.

#### **4.3.7 Education and awareness**

There is a significant gap in the understanding and awareness of the CE among businesses, consumers and the public, which creates several hurdles in the usage of AI for the CE. Given the evolutionary field of AI and the plethora of AI applications that exist today, businesses need guidance and expertise on the capabilities of AI and how to implement AI into their operations, which they lack. Furthermore, consumers, even if they are environmentally conscious, do not fully recognise the benefits of circular product purchasing and remain unaware of ecological problems associated with their consumption patterns. There is an important role for education institutes in bridging this gap, by including curricula that adequately cover CE concepts. Collaboration between government and industry is integral to how we create and develop educational programmes and campaigns to raise awareness of the CE.

## 5 Summary and Recommendations

The main objective of CircAI was to demonstrate how AI can effectively be utilised for CE practices across various sectors to promote sustainability. Several knowledge outputs were produced during this project, including detailed review papers, research posters, compilations of real-world case studies, interview summaries and stakeholder workshops. To ensure that all stakeholders benefit from the findings of this project, these outputs are stored in an open-access and extendible repository, improving ease of access. A summary of these outputs is provided below.

### 5.1 Literature Reviews

To analyse and observe the practical applications of AI for the CE in depth and across various sectors, CircAI conducted extensive literature reviews. The reviews helped us to gain a thorough understanding of the topic and the existing knowledge gaps. The reviews are compiled and produced in the form of published review papers, presenting a detailed analysis and showcasing some real-world case studies.

- ***The Role of Artificial Intelligence within Circular Economy Activities – A View from Ireland*** (Pathan *et al.*, 2023). This review paper examines the intersection of AI and the CE, specifically focusing on the initiatives undertaken by the Irish government. This paper discusses how AI can help in transitioning to a CE by improving circular product design, developing new innovative circular business models and optimising circular infrastructure in organisations. This paper further discusses some real-world case studies where AI has been successfully used to enhance circular practices. Furthermore, this paper also discusses the role of Industry 4.0 technologies, including IoT, big data, cloud computing and blockchain, in supporting CE advancement. The paper also highlights the importance of robust data collection, standardisation and regulatory frameworks to maximise the potential of AI in driving circularity.

- ***Contributions of Artificial Intelligence for Circular Economy Transition Leading Toward Sustainability: An Explorative Study in Agriculture and Food Industries of Pakistan*** (Ali *et al.*, 2024). This paper focuses on the agriculture and food sectors in Pakistan. It examines how AI can address sustainability challenges by optimising waste management and supporting the CE transition in agriculture. The study provides a theoretical framework for AI-driven CE, highlights the current waste situation in Pakistan and proposes a multi-purpose framework for integrating AI capabilities into CE practices. It concludes with recommendations for boosting AI-driven CE practices in Pakistan, suggesting that crucial measures must be taken to achieve sustainable development.

### 5.2 Case Studies

A set of case studies were compiled to demonstrate how AI is being used for the CE in the real world. These case studies show the practical implementation of AI for various circular ambitions, such as circular product design, waste management, predictive maintenance and supply chain optimisation. Each case study highlights the tangible environmental benefits achieved through AI-driven CE initiatives and provides a roadmap for implementing similar initiatives across various sectors. Furthermore, these case studies can help guide policymakers, industry experts and researchers in understanding the potential of AI for the CE. The demonstrated successes can attract further investment in AI technologies aimed at promoting a CE. To gather a representative set of case studies, we followed a structured and multi-step approach, as follows:

- **Literature review and desk research.** We conducted an extensive literature review using academic databases, industry reports and publications from leading sustainability organisations such as the Ellen MacArthur Foundation.

- **Stakeholder interviews and workshops.** We held several stakeholder workshops and interviews with industry experts and academia to gather insights on organisations that are successfully integrating AI into their circular practices.
- **Broad representation.** To ensure a broad perspective, we selected case studies from a variety of geographical locations, which helped us compare different technological advancements and business models.

### **5.3 Stakeholder Engagement**

To attract stakeholders and raise awareness of the topic, two on-site<sup>30,31</sup> workshops and one online<sup>32</sup> webinar were held. The primary motivation for these sessions was to discuss current ideas, solutions and policies regarding the integration of AI into the CE ambitions of companies, governments and countries. These events provided an opportunity to highlight and discuss ongoing research, collaboration opportunities and the current state of AI and the CE around the globe. The workshops and webinar were targeted towards a diverse group of stakeholders with interests and roles in AI, sustainability and the CE. The attendees included representatives from various sectors, such as academia, industry, start-ups, government and NGOs. These groups were chosen for their potential influence in the implementation and regulation of AI and CE practices. At these events, speakers explored the intersection of AI and the CE

and the policies surrounding the implementation of CE principles using AI. They presented numerous practical examples of AI and the CE from Ireland and beyond. Some speakers shared how they are currently using AI for CE goals and what challenges they are facing.

#### **5.3.1 Stakeholder interviews**

We conducted a series of interviews with various stakeholders, particularly industry experts, CEOs and academicians, which provided deep insights into the multifaceted challenges and opportunities associated with integrating AI into CE practices. Key themes emerged, including the significant barriers posed by cost and financial constraints, data availability and quality, and the lack of standardised data collection and transparency, impeding effective AI implementation. The technological and implementation barriers that were highlighted were the difficulties in integrating advanced technologies within existing systems, coupled with a shortage of technical expertise. In addition, regulatory and policy issues were highlighted as significant hurdles that must be addressed. The interviews underscored the necessity of cultural and behavioural shifts to embrace circularity, requiring extensive education and awareness campaigns. These interviews collectively emphasised the need for comprehensive support systems, streamlined funding processes and robust educational and policy frameworks to drive the successful adoption of AI-driven CE practices.

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30 <https://www.maynoothuniversity.ie/news-events/how-can-ai-work-circular-economy>.

31 <https://www.cs.nuim.ie/~pmooney/CircAI2023/>.

32 <https://ivi.ie/webinars/ai-and-circular-economy-webinar/>.

## 6 Recommendations

The findings from the CircAI project suggest that AI has the potential to significantly enhance CE practices across various sectors. However, successful adoption is contingent on addressing several key challenges, including a lack of understanding of how AI can be used for the CE, the need for transparent and interpretable AI models, concerns around data privacy and algorithmic bias within AI-based tools, and the requirement for supportive government policies for both adoption of AI by businesses and adoption of CE practices by businesses and industry. Additionally, greater awareness and education on using AI for the CE are essential to drive widespread adoption. To address these challenges, the following recommendations are derived from the CircAI project findings and are categorised under societal, governance, technological, political and legal recommendations. In some cases we have provided a recommendation regarding general contemporary issues with AI, as well as the use of AI within CE practices.

### 6.1 Societal Recommendations

- **Education and awareness of AI and the CE.** Despite increasing research on the nexus of AI and the CE, there is not enough familiarity with this topic. Most of the time, policymakers face significant challenges due to a lack of understanding and proper education in this area, which prevents effective policies that encourage businesses to adopt AI for the CE. This is not surprising given the fast pace at which AI is moving. Education and technological innovations are key components in raising awareness, shaping attitudes and promoting sustainable behaviours. Schools could integrate environmental, technological and CE education into their curricula, providing students with learning on how AI can effectively be used for the CE. Higher education institutions can also equip students with the necessary knowledge and technical skills to support the transition to a CE and to pursue careers in the emerging field of digital CE. Furthermore, open courses related to

this topic can help faculty members elevate their standard of teaching and learning in this field, ensuring that our educators have knowledge of CE practices and their benefits. Additionally, more opportunities for industry–academia partnerships should be developed to transform research into practical CE solutions. These partnerships can foster innovation by combining academic research with real-world industry challenges. There is a need to provide opportunities for education and training for SMEs, for example around key AI technologies, and for developing a strong working understanding of these approaches. This will allow stakeholders such as SMEs to become more confident in and engaged with AI technologies.

- **Cultural and behavioural shifts for CE adoption.** Encouraging a societal shift towards circularity will require extensive awareness campaigns and educational efforts to foster sustainable behaviours and practices. AI cannot be directly used in this regard but could be employed to develop insights into the current practices and trends in society around issues of sustainability and circular activities.

### 6.2 Governance Recommendations

- **Government support.** There are various ways in which the government can play an impactful role in facilitating the use of AI for the CE. Research and development (R&D) is considered one of the critical areas where government intervention is necessary. By investing in R&D, governments can support the development of AI-based CE models, as it has been highlighted as a key area where R&D can drive advancements. Governments must provide financial support to SMEs to help them adopt sustainable digital CE business models, which often require costly infrastructure changes. Furthermore, effective data management and analytics are crucial for AI-driven models for the CE, necessitating the use of highly cost-effective data management platforms by SMEs for effective operations. Governments must provide adequate financial support for SMEs to enable them to

adopt such digital platforms to innovate digital circular business models. Policies that align with CE practices and AI integration should be introduced to CE practices such as renewable energy adoption, recycling and reducing carbon emissions. There are several potential opportunities for governments to lead in this area, with Ireland being no exception. Some potential opportunities include the following:

- The use of innovation voucher schemes to give incentives to SMEs to consider using AI in their processes.
- The development and deployment of a national platform or system to allow SMEs to match with other SMEs that have similar needs with regard to AI.
- The establishment of a government agency to facilitate training for specific SME sectors. This could be deployed by funding or hosting training programmes, certifications or workshops on AI and CE for SMEs and manufacturers. This could be enabled by partnering with universities and AI research centres to offer research support.
- **Stakeholder inclusion.** Stakeholder engagement and governance are crucial in policymaking. Governments must engage various stakeholders, including industry, academia and the public, in the policymaking process to ensure that policies are inclusive, equitable and reflective of diverse perspectives and needs.
- **Real-world case studies.** The showcasing of real-world case studies can inspire stakeholders to explore relevant opportunities for AI applications for the CE, based on a sound understanding of what AI can do, as well as an appreciation of how CE principles could apply to their area of interest or industry. Our showcase of real-world case studies is available online at <https://www.cs.nuim.ie/~pmooney/circai>.

### 6.3 Technological Recommendations

- **Model interpretability.** AI has immense potential to advance the CE in businesses. There are some obstacles that might hinder the implementation of AI for the CE, one of which is AI model interpretability. The results generated by AI models

can frequently be opaque, creating challenges for stakeholders to understand how the conclusions are made by the model. This opacity, often referred to as the black box problem, can cause a lack of trust and acceptability among stakeholders, especially in sectors where decision-making is crucial and must be well documented and understandable to all stakeholders. To get the most out of the benefits of AI, it is necessary to develop and implement some interpretability frameworks that enhance the transparency of AI models. This includes investing in further research on explainable AI. Explainable AI provides clear and understandable insights into an AI system's decision-making process. This clarity of decision-making enhances the collaboration and broader acceptance among stakeholders by communicating the visible benefits and limitations of AI models, even to non-technical stakeholders. There are already some well-known examples of interpretability frameworks, such as the following:

- The AI for Interoperability Framework (EU),<sup>33</sup> which is one of several interoperability frameworks being actively developed by the EU as part of its Digital Europe Programme and AI strategy.
- ONNX (Open Neural Network Exchange), which is a widely used open format to represent AI models. ONNX allows models to be trained in one framework (e.g. PyTorch) and run in another (e.g. TensorFlow, Caffe2).
- Model cards and datasheets for datasets, although not frameworks in a technical sense, are tools to promote semantic interoperability between systems. More specifically, model cards allow for standard documentation describing an AI model's purpose, risks and performance, while datasheets for datasets allow for the description of dataset provenance, structure, limitations and biases.
- **Data management and standardisation.** Standard reference architectures for data capture and analysis should be distributed to all stakeholders to describe a standard way of collecting data and building AI models on these data. These architectures should use interoperable data formats (e.g. JSON for exchange between systems) and databases

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<sup>33</sup> <https://interoperable-europe.ec.europa.eu/collection/semic-support-centre/ai-interoperability>.

to ensure strict data formatting and rule-based checking of data quality and consistency. Data architectures, which use non-interoperable data formats, should not be considered a standard way of collecting and storing data.

#### **6.4 Political Recommendations**

- **Policy development.** Governments should develop policies that support the integration of AI into CE practices. These policies should encourage AI usage in these situations, including providing investment opportunities for AI-driven innovation in CE practices.
- **R&D investment.** Political support for R&D in AI-driven CE models is crucial to stimulate innovation and ensure that technological advancements align with sustainability goals.

#### **6.5 Legal Recommendations**

- **Regulatory frameworks.** Regulatory frameworks must be established to address issues related to data privacy, algorithmic bias and ethical AI

usage. AI auditing practices should be enforced to ensure fairness, accountability and compliance with ethical guidelines. Such audits help in assessing whether the appropriate standards are followed when using AI systems, analyse the input datasets for any signs of bias and evaluate the outputs generated by the models as well. The EU Artificial Intelligence Act<sup>34</sup> is the world's first major law to comprehensively regulate AI. The act will strive to ensure that AI is safe, ethical and respects fundamental rights. It attempts to classify AI systems by risk level and ban unacceptable use cases. The European Data Governance Act<sup>35</sup> and Data Act promote secure, fair sharing of data between businesses, governments and citizens.

- **Data privacy and security.** To build trust and acceptance of AI-based solutions among customers who are reluctant to share data, transparency in regulations and ownership of data needs to be ensured. Regulations should be implemented to protect sensitive data and ensure transparency in data sharing between organisations involved in AI for the CE.

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<sup>34</sup> <https://artificialintelligenceact.eu/>.

<sup>35</sup> <https://www.european-data-governance-act.com/>.

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# Abbreviations

<b>AGI</b>	Artificial general intelligence
<b>AI</b>	Artificial intelligence
<b>CE</b>	Circular economy
<b>CEO</b>	Chief executive officer
<b>CircAI</b>	Artificial Intelligence and the Circular Economy
<b>CV</b>	Computer vision
<b>EPA</b>	Environmental Protection Agency
<b>EV</b>	Electric vehicle
<b>GM</b>	General Motors
<b>IoT</b>	Internet of Things
<b>LE</b>	Linear economy
<b>ML</b>	Machine learning
<b>NGO</b>	Non-governmental organisation
<b>ONNX</b>	Open Neural Network Exchange
<b>R&amp;D</b>	Research and development
<b>RVM</b>	Reverse vending machine
<b>SDG</b>	Sustainable Development Goal
<b>SMEs</b>	Small and medium-sized enterprises
<b>WAPCE</b>	Waste Action Plan for a Circular Economy

# An Gníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaoil a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaoil a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

## Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

**Rialáil:** Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

**Eolas:** Sonraí, eolas agus measúnú ardchaighdeán, spriocdhírthe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

**Abhcóideacht:** Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

## I measc ár gcuid freagrachtaí tá:

### Ceadúnú

- > Gníomhaíochtaí tionscail, dramhaíola agus stórála peitрил ar scála mór;
- > Sceitheadh fuíolluisce uirbhig;
- > Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- > Foinsí radaíochta ianúcháin;
- > Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

### Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- > Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- > Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- > Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- > Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbhig a fhorfheidhmiú
- > Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- > Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- > An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaoil.

### Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaoil

- > Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- > Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- > An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- > Reachtaíocht ar rialú ceimiceáin sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

### Bainistíocht Uisce

- > Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- > Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéal uisce agus sreabhadh abhann.

### Eolaíocht Aeráide & Athrú Aeráide

- > Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- > Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Gníomhú ar son na hAeráide;

- > Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

### Monatóireacht & Measúnú ar an gComhshaoil

- > Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- > Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- > Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- > Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- > Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaoil na hÉireann.

### Taighde agus Forbairt Comhshaoil

- > Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- > Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

### Cosaint Raideolaíoch

- > Monatóireacht a dhéanamh ar leibhéal radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- > Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as tasmí núicléacha;
- > Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- > Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

### Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- > Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- > An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- > Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- > Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

### Comhpháirtíocht agus Líonrú

- > Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíochta agus ranna rialtais chun cosaint comhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

## Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhuanaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Gníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

## EPA Research

**Webpages:** [www.epa.ie/our-services/research/](http://www.epa.ie/our-services/research/)  
**LinkedIn:** [www.linkedin.com/showcase/eparesearch/](http://www.linkedin.com/showcase/eparesearch/)  
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