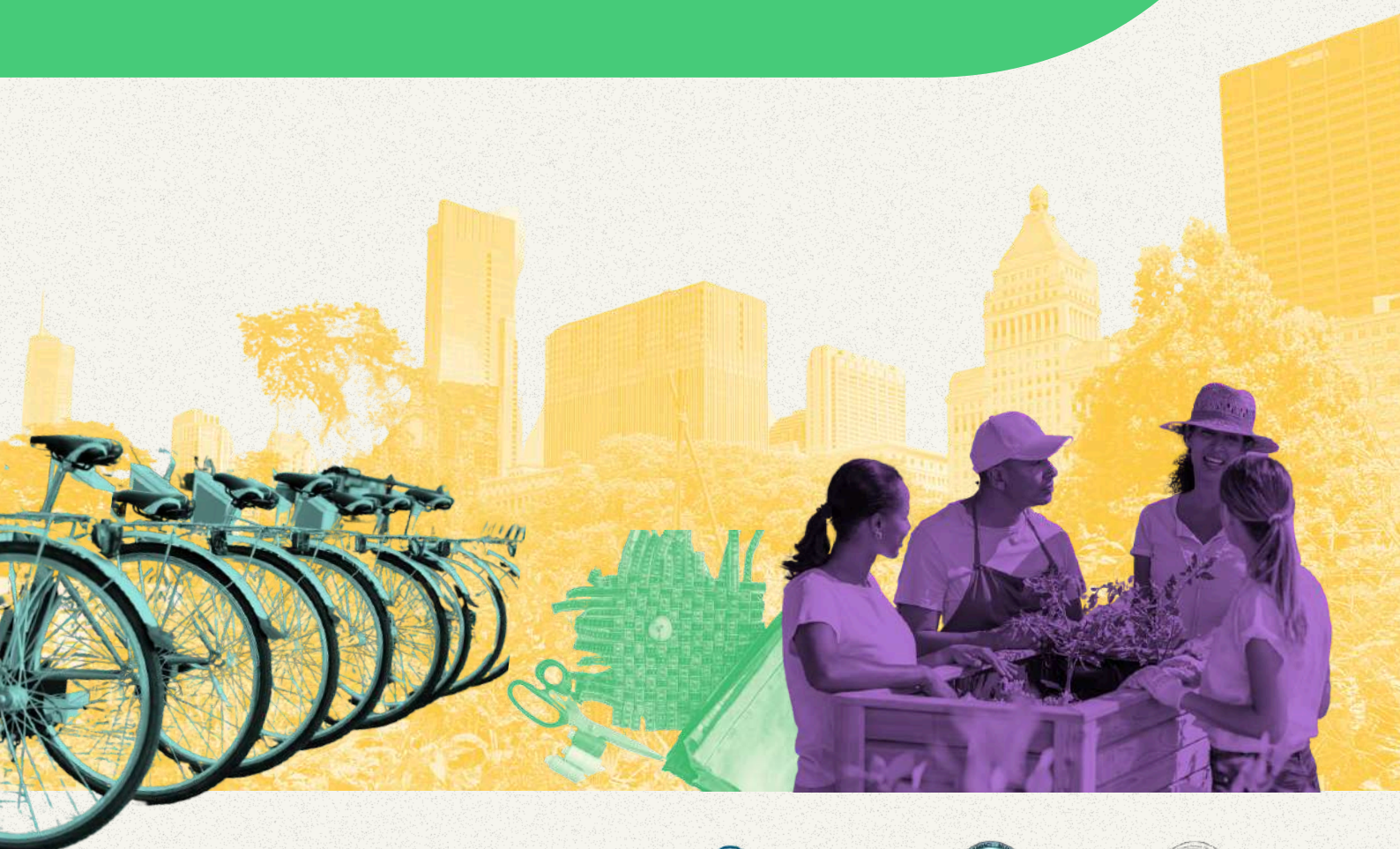


STUDY ON CIRCULAR PRACTICES FOR EDUCATION IN THE DIGITAL UNIVERSE



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SUMMARY

1	Introduction	1
2	Circular Economy and CE approaches in Education	2
3	Circular Mobility Solutions in Education	11
4	Future Perspectives of Use of AI for CE	20
5	Survey Results on Circular Approaches in Secondary Education Curricula	30
6	Survey Results on Teachers' Perspectives, Experiences and Needs Regarding CE Education in Schools	33
7	Conclusion	45

1. Introduction

In the face of escalating environmental challenges and social inequalities, traditional linear economic models characterized by a "take, make, dispose" approach are increasingly proving unsustainable. For example, planned obsolescence, where products are designed with a limited lifespan to incite consumers to purchase it again, is a strategy to generate profit in this economy. Therefore, transformations towards a Circular Economy are crucial in tackling the climate crisis and connected challenges.

This study "Circular Practices for Education in the Digital Universe" is a result of the CircEdu project (2024-1-DE03-KA220-SCH-000250897), co-funded by the European Union. In all partner countries involved in the creation of this study (Bulgaria, Germany, Greece, Portugal, Poland and Türkiye) the need for comprehensive educational practices and materials on circular education was identified. Therefore, the CircEdu project consortium, consisting of Kolleg für Management und Gestaltung Nachhaltiger Entwicklung (KMGNE, Germany), Sucessos Criativos Lda Portugal Norte (SC, Portugal), Higher School of Transport "Todor Kableshkov" (HST, Bulgaria), FIFTH GENERAL LYCEUM Larisas (FGLL, Greece), Fritz-Greve-Gymnasium (FGGM, Germany), Zespół Szkół Agrotechnicznych i Ogólnokształcących im. Józefa Piłsudskiego (ZAI, Poland) and Hadiye Kuradaci Bilim Ve Sanat Merkezi Tarsus (HKB, Türkiye) conducted an extensive desk research and created two different surveys addressed to the secondary schools in the project consortium and their teachers. With these surveys the consortium has been able to detect the reality of the project's target groups, their knowledge and needs and an insight into the state of CE practices in secondary education in European schools.

The investigation has shown that there is a great extent of research related to circular economy in general, but insufficient material in the field of secondary education both in research and in practice. Thus, the aim of this study is to bring together knowledge around this topic and which can serve as a basis for the further development of learning methodologies. The results of the questionnaires are presented in comparison of the four different countries in a summarized report.

Besides the introduction, the study is divided into five chapters:

2. Circular Economy and CE approaches in Education
3. Circular Mobility Solutions in Education
4. Future Perspectives of Use of AI for CE
5. Survey Results on Circular Approaches in Secondary Education Curricula
6. Survey Results on Teachers' Perspectives, Experiences, and Needs Regarding CE Education in Schools

2. Circular Economy and CE approaches in Education

In the following chapter the concept of Circular Economy (CE) in general and CE education in particular will be introduced.

With the Club of Rome report "Limits to Growth" (1972), the UN Brundtland Report (1987) and the UN World Conference in Rio de Janeiro (1992), the general perception of the consequences of the capitalist metabolism began to shift towards a new and necessary development paradigm. This desired change of path was called sustainable development, aiming to shift societal and individual practices to being less, more circular, more long-lasting, more regional, more cooperative. In consequence the economic system subordinates and integrates itself into the finite organism Earth (see Lovelock & Margulis 2007).

Aligning with this paradigm, the Circular Economy (CE) acknowledges that natural resources are limited and seeks to extend the lifecycle of materials by keeping them in use through practices like reuse, repair, remanufacturing, sharing, and recycling. Core principles of the CE include the 3Rs - reduce, reuse, and recycle - and an expanded version known as the 6Rs, which adds redesign, remanufacture, and recover (see Jawahir & Bradley 2016). The CE is an economic framework in which the planning, resourcing, procurement, production, and reprocessing stages are intentionally designed and managed to enhance both ecosystem health and human well-being (see Murray et al. 2017). As a generative and restorative model, the CE seeks to preserve the value of products, materials, and resources for as long as possible, thereby reducing the creation of final waste (Ranta et al. 2018).

Although much of the focus is on innovation like creating new technologies and business models to maintain material circulation it also involves eliminating waste through better design, replacing non-renewable materials with renewable alternatives, and supporting the regeneration of natural ecosystems. The European Parliament (2023) states the following key benefits of a transition to CE: limiting biodiversity loss, reducing greenhouse gas emissions, reducing waste, decreasing raw material dependence and saving consumers money through more durable products. Additionally, economic growth is mentioned, whereas this point is not reflecting many scientific findings which assume CE goes hand in hand with degrowth (see Winans et al. 2015: 825–826). However, following post-growth approaches, it does not necessarily mean a decline in well-being but can even lead to an increase.



Figure 1: The circular economy model: less raw material, less waste, fewer emissions.
Source: European Parliament Research Service (European Parliament 2023).

The concept of the CE does not have a clearly identifiable single origin or creator. However, several key figures have shaped its development, including U.S. academic John Lyle, his student William McDonough, German chemist Michael Braungart and architect and economist Walter Stahel (see Winans et al. 2015: 825–826). Influences on the CE idea may also include Rachel Carson's *Silent Spring*, the aforementioned Club of Rome's 1970s report on the "limits to growth," the "spaceship Earth" analogy introduced by Barbara Ward and Kenneth Boulding, and the work of eco-economist Herman Daly (ibid.).

The CE framework is interconnected with other ideas, some of which existed earlier, such as industrial symbiosis (see Winans et al. 2015: 825–826). Within the realms of industrial ecology and systems theory, CE is linked to diverse disciplines, including thermodynamics and ecological economics (ibid.). According to systems theory and thermodynamic laws, implementing CE strategies tends to shift economic systems toward a phase of ‘degrowth’ rather than supporting traditional growth-oriented development (ibid.), supporting post-growth and degrowth economic theories.

In some countries like Germany and Portugal the CE concept is applied for waste management and many businesses use the concept to improve their material flows (ibid.: 826). The EU implemented a CE action plan with the goal “to build a circular and climate-neutral economy by 2050” (European Parliament 2023), implementing a variety of legislations covering ecodesign, packaging, greenwashing, the right to repair and waste management (see ibid.). While the number of initiatives in this area is growing, the social component is often not considered thoroughly.

The UN 2030 Agenda highlights that environmental, social, and economic sustainability are deeply interconnected and cannot be addressed in isolation. As the connections between environmental challenges like climate change, excessive resource use, and waste and social challenges such as inequality and the changing nature of work become more evident, the need to align environmental action with social justice is becoming increasingly important. Therefore, the concept of a “just transition” combining environmental sustainability, fair employment, social inclusion, and the elimination of poverty is gaining traction in sustainability discourses.

A just transition within the circular economy framework offers a way to reduce waste, drive innovation, and promote sustainable development, while also addressing social and economic inequalities in line with the UN Sustainable Development Goals to leave no one behind (see Schröder 2020). As circular economy policies advance, especially amid digitalization and industrial shifts, it is crucial to assess their impact on jobs and livelihoods. Social protections must be integrated to prevent vulnerable groups from bearing the brunt of changes such as job loss or deteriorating work conditions (ibid.).

Low- and middle-income countries, which depend on linear economic sectors like mining, manufacturing of fast-moving consumer goods, textiles and agriculture, may face challenges by the circular transitions (ibid.). These nations will need targeted international support to adapt.

Effective global cooperation, transparent and accountable finance mechanisms, fair governance, and coordinated policies across all levels of government will be key to managing the transition (ibid.).

Furthermore, Kate Raworth's Doughnut Economics offers an additional transformative framework that envisions a safe and just space for humanity. This model balances the need to meet everyone's essential needs (the social foundation) without exceeding the planet's ecological limits (the ecological ceiling) (see Raworth 2017). The Doughnut model challenges the conventional emphasis on perpetual economic growth, advocating instead for regenerative and distributive economies. It underscores the importance of systems thinking, recognizing the interconnectedness of social and ecological systems. The CE can complement the Doughnut model by proposing a systemic shift from linear to circular systems incorporating social and economic opportunities and resilience.

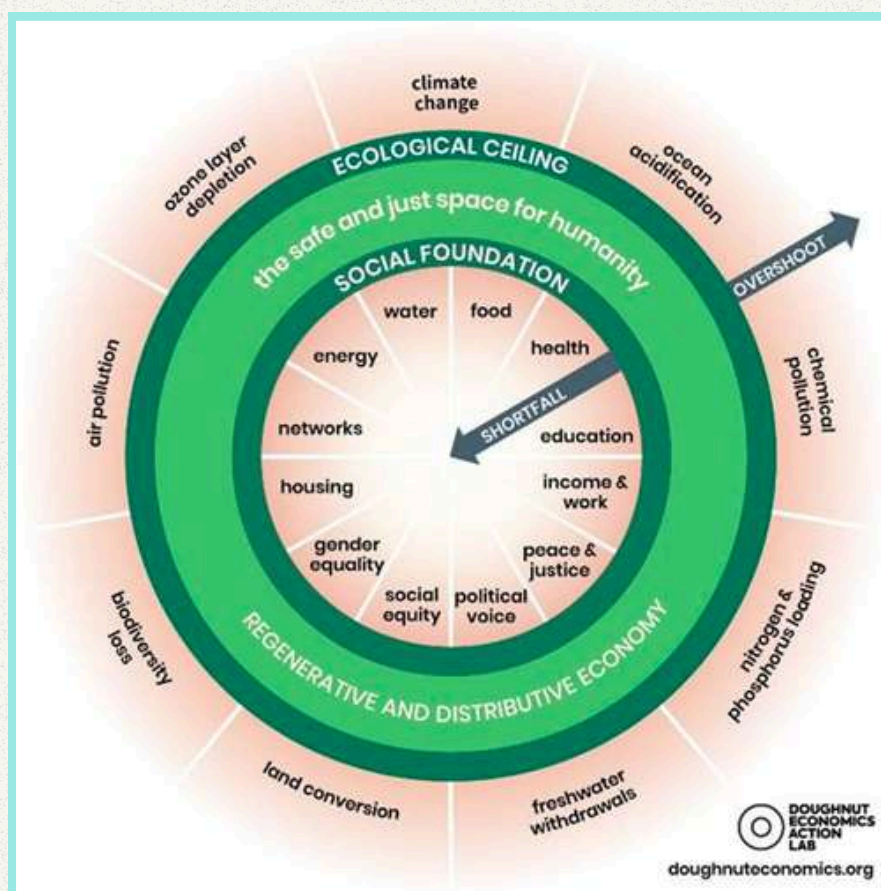


Figure 2: The Doughnut of social and planetary boundaries.

Source: Kate Raworth and Christian Guthier. CC-BY-SA 4.0 (Raworth 2017).

Implementing CE principles requires a fundamental change in how societies produce and consume goods. It involves rethinking product design, business models, infrastructures, policies and individual behaviour. Awareness rising can play a pivotal role in facilitating this transition by equipping individuals with the knowledge and skills to participate in circular practices and drive institutional and systemic change. Therefore, Education is a critical enabler of the transition to a Circular Economy. Beyond fostering awareness, it cultivates skills, and shapes values that align with sustainable practices. Integrating CE concepts into education systems prepares students to navigate and influence the evolving socio-ecological transformation.

Concepts like Education for Sustainable Development (ESD) are already highly established, while being interpreted in a lot of different ways. For example, interpretations of ESD provide a variety of definitions for CE, some mostly dealing with recycling, others, like in this study, offering more wide-ranging holistic approaches including social factors and cultural change (see Kirchherr & Piscicelli 2019). On the contrary, research on specific education for the CE is still limited. Kirchherr & Piscicelli (2019) offer an approach based on ESD literature and identify five suitable ECE (Education for Circular Economy) teaching core principles: “interactivity, non-dogmatism, and reciprocity as well as constructive alignment and problem-based learning”.

Another contributing framework in this context is GreenComp - The European sustainability competence framework, developed by the Joint Research Centre (JRC), the European Commission’s science and knowledge service (see Bianchi et al. 2022: 2). It aims to foster sustainability attitudes, skills and knowledge and proposes 12 competences in four key areas:

1. “Embodying sustainability values, including the competences: valuing sustainability, supporting fairness and promoting nature,
2. Embracing complexity in sustainability, including the competences: systems thinking, critical thinking and problem framing,
3. Envisioning sustainable futures, including the competences: futures literacy, adaptability and exploratory thinking,
4. Acting for sustainability, including the competences: political agency, collective action and individual initiative” (ibid.).

Some countries already include CE education in practices and policies. In Finland, for example, CE education is embedded across all levels, from primary schools to vocational training. Programs like Yrityskylä provide experiential learning opportunities where students engage in simulated economic activities that incorporate CE principles (see Circular Design Suomi 2023 and Tiippana et al. 2023). Tiippana et al. (2023) propose to adapt the Finnish model to different education systems.

Secondary education serves as a critical juncture for instilling CE principles. At this stage, students develop the cognitive abilities to understand complex systems and the agency to effect change. Integrating CE not only into subjects like science, technology, engineering, and mathematics (STEM), but also in subjects as humanities, languages, arts and social sciences, provides a holistic understanding of sustainability. Students can be empowered to develop their own projects including circular practices.

Beyond practical applications, CE education invites a philosophical shift in how we perceive our relationship with the environment to foster cultural change through the narratives we tell about the world. It encourages a move from linear, anthropocentric worldviews to circular, ecocentric perspectives that recognize the interdependence of all life forms. This aligns with many indigenous philosophies that emphasize relationships with the more-than-human and ecological life cycles. It can open up discourse about alternative concepts of spiraling time, linking human history with nature as well as more appropriately link human generations, including ancestors and descendants (see Fritsch 2024) and the unity of life and death. Incorporating these perspectives into education fosters a deeper ethical commitment to sustainability. It challenges students to consider not only the technical aspects of CE but also the moral imperatives of multispecies kinship (see Haraway 2016) and social equity.

Furthermore, integrating traditional knowledge and practices into CE education enriches learning by connecting students with local histories and sustainable practices. For example, exploring traditional building techniques that utilize local, renewable materials can offer insights into sustainable circular design. In this way, helpful strategies that disappeared over time can be revived and adapted to modern times or combined with new ideas (see Watson 2019). This approach not only preserves cultural heritage and strengthens the connection of students to their environment but also demonstrates the relevance of traditional practices in addressing modern sustainability challenges.

The transition to a circular economy necessitates a comprehensive educational strategy that encompasses cognitive, practical, and ethical dimensions. By embedding CE principles into secondary education, we equip students with the tools to critically engage with and shape a sustainable future. This educational transformation is essential for cultivating a society that values social and ecological sustainability, laying the foundation for a resilient and just society that thrives within the planet's ecological boundaries.

Sources

Bianchi, G., Pisiotis, U., Cabrera Giraldez, M. (2022). GreenComp – The European sustainability competence framework. Bacigalupo, M., Punie, Y. (ed.), EUR 30955 EN, Publications Office of the European Union, Luxembourg.

Circular Design Suomi (2023). Circular Design – a path towards circular economy, training programme. <https://circulardesignsuomi.fi/en/frontpage/>

European Parliament (2023). Circular economy: definition, importance and benefits. <https://www.europarl.europa.eu/topics/en/article/20151201STO05603/circular-economy-definition-importance-and-benefits>

Fritsch, M. (2024). Indigenous Accounts of Spiraling Time. Yearbook for Eastern and Western Philosophy, 7(1), 60-86.

Haraway, D. J. (2016). Staying with the trouble: Making kin in the Chthulucene. Duke University Press.

Jawahir, I. S., & Bradley, R. (2016). Technological elements of circular economy and the principles of 6R-based closed-loop material flow in sustainable manufacturing. Procedia Cirp, 40, 103-108.

Kirchherr, J., & Piscicelli, L. (2019). Towards an education for the circular economy (ECE): five teaching principles and a case study. Resources, Conservation and Recycling, 150, 104406.

Lovelock, J., & Margulis, L. (2007). The gaia hypothesis. New York.

Murray, A., Skene, K., & Haynes, K. (2017). The circular economy: an interdisciplinary exploration of the concept and application in a global context. Journal of business ethics, 140, 369-380.

Ranta, V., Aarikka-Stenroos, L., Ritala, P., & Mäkinen, S. J. (2018). Exploring institutional drivers and barriers of the circular economy: A cross-regional comparison of China, the US, and Europe. Resources, Conservation and Recycling, 135, 70-82.

Raworth, K. (2017): Doughnut Economics: Seven Ways to Think Like a 21st Century Economist. London: Penguin Random House.

Schröder, P. (2020). Promoting a just transition to an inclusive circular economy (pp. p-33). London: Royal Institute of International Affairs.

Tiippana-Usvasalo, M., Pajunen, N., & Holuszko, M. (2023). The role of education in promoting circular economy. *International Journal of Sustainable Engineering*, 16(1), 92–103.

Watson, J. (2019). *Lo-TEK: Design by radical indigenism*. Taschen.

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, 68, 825-833.

3. Circular Mobility Solutions in Education

As the world transitions toward more sustainable systems, the concept of Circular Mobility has emerged as a crucial pillar within the Circular Economy. As there is a growing global circularity gap (Rakowski et al. 2025), integrating this approach into secondary education is essential to prepare students for a future that prioritizes sustainability, innovation, and responsible resource use.

Circular mobility encompasses various sustainable transportation strategies such as electric vehicles, shared mobility services, renewable energy integration, and smart urban planning. Embedding these concepts into the school curriculum encourages students to understand the interconnectedness of technology, environment, and society. It equips them to think critically about how transportation systems can evolve from linear models of consumption to circular models of resource optimization.

Project-based learning can simulate real-world challenges that mobility managers face—balancing efficiency, infrastructure, and environmental goals—allowing students to explore strategic, technical, and logistical solutions. Through interdisciplinary projects, students can study how cities reduce emissions, how materials are reused in vehicle manufacturing, and how renewable energy can power future transport systems.

This chapter provides a comprehensive guide to Circular Mobility Solutions, exploring their implementation, benefits, challenges, and future prospects through expert insights, real-world case studies, and practical strategies (Green.org. 2024).

Key Themes for Classroom Integration

1. Sustainable Transportation

The transition to sustainable transportation includes electric vehicles (EVs), bike-sharing programs, and low-emission public transit. These initiatives reduce fossil fuel dependency and improve air quality (European Commission 2025a).

2. Resource Efficiency in Mobility

The automotive industry increasingly uses recycled materials and implements closed-loop production to minimize waste and optimize resource use (Green.org 2024).

3. Urban Planning & Green Infrastructure

Incorporating technologies in urban planning, such as smart traffic systems and Sustainable Urban Mobility Plans, improves mobility and lowers emissions (Hartley et al. 2023).

4. Renewable Energy Integration

Using solar and hydrogen technologies in transportation decreases carbon emissions and promotes energy efficiency. Expanding EV charging networks powered by renewables is key (Barman et al. 2023).

5. Waste Reduction in Mobility

Automakers are adopting strategies to recycle and reuse materials such as aluminum, plastics, and batteries. Circular supply chains and eco-friendly manufacturing reduce waste (Lean Manufacturing Junction 2022).

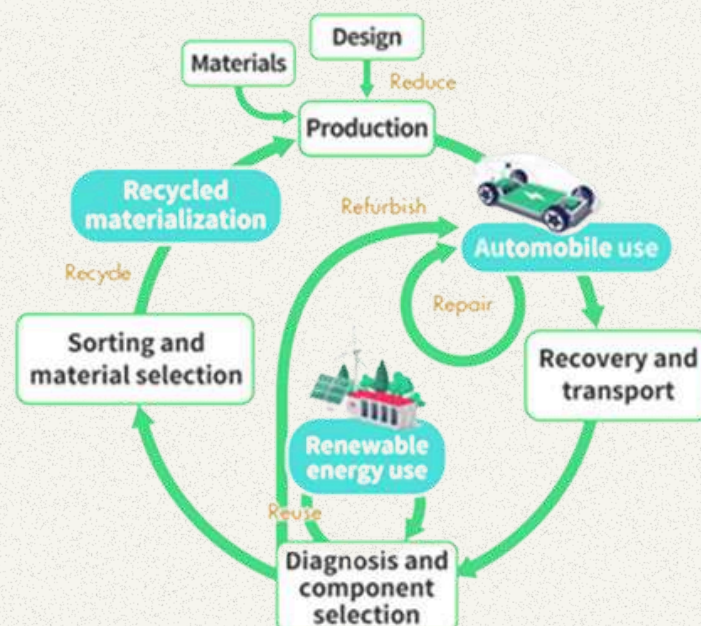


Figure 3: Implementation of CE principles in automobile production.

Source: https://www.tytlabs.co.jp/en/assets/images/technology/project/project2_image_01.png

6. Policy & Regulations

Governments and global organizations implement strategies to encourage sustainable mobility. The EU's strategy aims to reduce transport emissions by 90% by 2050 (European Commission 2025b).

7. Education & Public Awareness

Integrating circular economy principles into school curricula and community programs fosters sustainability. Workshops and digital tools promote sustainable behavior and teach students how to raise community awareness on circular mobility (World Economic Forum 2022).

8. Technology & Innovation

AI-based traffic management, smart logistics, and automation improve transport efficiency and reduce environmental impact.

9. Collaborative Models

Industry and community partnerships promote sustainable mobility. Programs like URBACT demonstrate effective local cooperation (European Commission 2025b).

10. Economic & Social Impact

Circular mobility supports job creation, economic growth, and urban sustainability by reducing emissions and encouraging innovation (World Economic Forum 2022).

11. Implementation

The circular economy requires a fundamental transformation in transportation and logistics, demanding new infrastructure, processes, and technologies to ensure sustainability and efficiency. A key strategy is to prioritize sustainability across all operations, integrating eco-friendly practices into vehicle selection, fuel choices, warehouse design, and waste management and implementing practices like Reverse Logistics (RL) and Remanufacturing (Ji-Hyland et al. 2025). Additionally, digitization plays a crucial role in enabling circular logistics. Technologies such as IoT and blockchain enhance product life cycle tracking, resource optimization, and supply chain collaboration. Advanced AI and machine learning further improve route optimization, reduce empty miles, and minimize fuel consumption (Schumann et al. 2022).

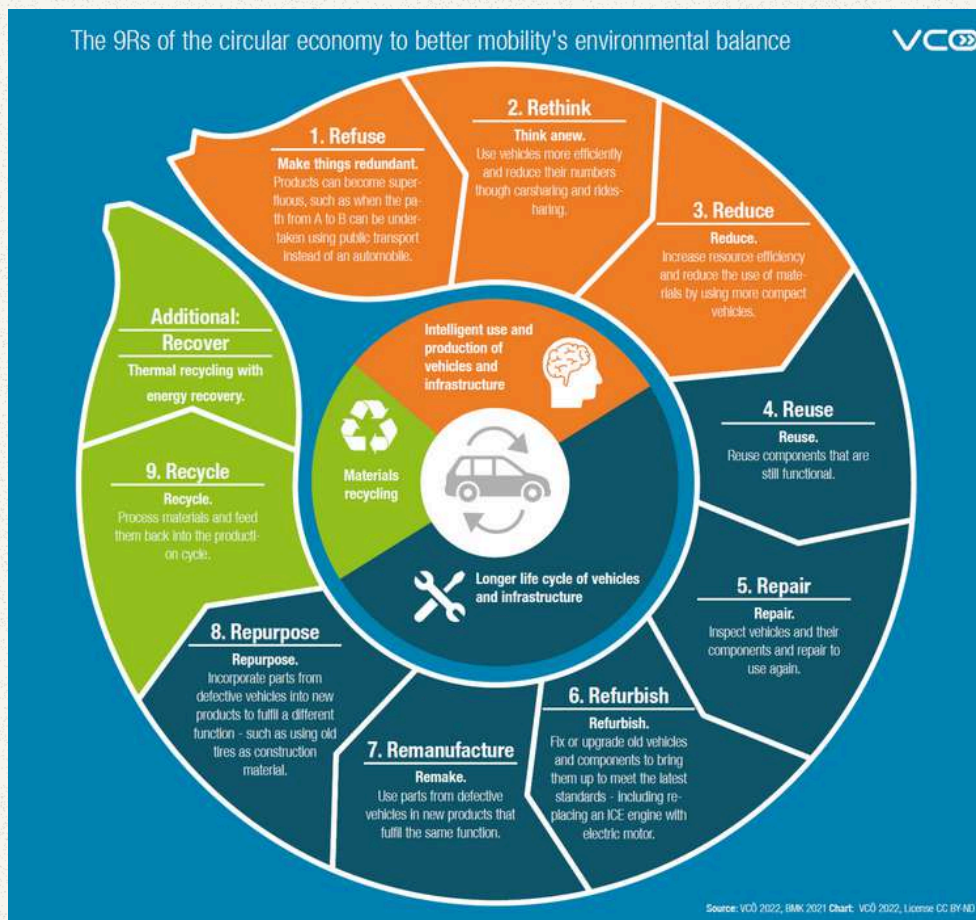


Figure 4: The 9Rs of circular economy to better mobility's environmental balance.
Source: VCÖ 2022 <https://vcoe.at/publikationen/vcoe-factsheets/detail/implementing-the-circular-economy-in-mobility>

Investing in intermodal transportation is another essential step. Encouraging the use of rail, water, and other sustainable transport modes reduces emissions while improving collection, sorting, and processing infrastructure. Successful implementation of circular economy principles requires collaboration among stakeholders, including logistics providers, manufacturers, policymakers, and partners, ensuring data sharing and open communication for efficient resource use (Crispin & Parthasarathy 2025).

The last mile of delivery presents unique challenges, requiring micro-mobility solutions, drone delivery, and local collection points to enhance efficiency. Additionally, fostering a culture of sustainability within the industry is crucial, involving employee education, training programs, and ambitious sustainability goals (Crispin & Parthasarathy 2025).

By embracing innovation, collaboration, and sustainability, logistics providers can build a more resilient and eco-friendly future. This transformation demands significant investment in technology, infrastructure, and human capital, but the long-term benefits make it a critical endeavor.

Successfully adopting Circular Mobility Solutions requires a strategic approach, careful planning, and collaboration among key stakeholders. Organizations must embrace sustainable practices while avoiding common pitfalls to maximize efficiency and long-term impact.

Strategies for Success

Embrace technology and innovation: Leverage IoT, AI, and data analytics to optimize resource management, enhance predictive maintenance, and improve shared mobility services. These technologies enable smarter, more efficient circular operations.

Collaborate with diverse partners: Engage with stakeholders across the value chain, including suppliers, policymakers, and consumers. Cross-sector collaboration fosters innovative solutions and ensures alignment with sustainability goals.

Continuously assess and adapt: Regularly evaluate key performance indicators (KPIs) and make adjustments as needed. Circular mobility requires ongoing improvements to stay ahead of industry trends and maintain operational efficiency.

Avoid These Common Pitfalls

Overlook stakeholder engagement: Lack of involvement from key partners can slow down adoption and create resistance to change. Ensure transparency and collaboration in circular initiatives.

Focus solely on short-term gains: While cost savings are beneficial, prioritizing long-term sustainability ensures lasting business success. Short-term thinking undermines circular mobility efforts and limits environmental benefits.

Ignore regulatory changes: Stay informed about emerging policies and compliance requirements related to transportation and sustainability. Failure to adapt to regulations can lead to operational risks and reputational damage.

12. Future Trends

Circular mobility solutions aim to make transportation more sustainable by reusing, recycling, and optimizing resources, rather than following the traditional take-make-dispose model. This approach extends the lifespan of vehicles, infrastructure, and transport materials through various strategies.

Optimized vehicle lifecycles through remanufacturing and refurbishing play a key role in reducing waste and maximizing efficiency. Recycled infrastructure materials for roads and transport hubs contribute to minimizing environmental impact. Renewable energy sources for public transport and logistics support climate neutrality goals. Smart logistics help reduce waste through efficient packaging and reverse supply chains. Shared mobility solutions, such as car-sharing and bike-sharing, minimize individual vehicle ownership and decrease urban congestion. AI & IoT technologies improve route optimization and predictive maintenance, making transport systems more efficient. Circular supply chains further reduce waste through closed-loop systems, ensuring maximum resource reuse. Government policies enforce eco-friendly transport regulations, driving broader adoption of circular mobility practices.

Hands-On Implementation in Schools

Educators can design activities that mimic the implementation of circular mobility systems. This includes route planning with carbon footprint calculations, designing solar-powered charging stations for model EVs, or simulating drone delivery routes for the last mile. Through STEM-integrated projects, students explore how smart logistics, reverse supply chains, and digital tracking reduce environmental impact.

Preparing Students for a Circular Future

Circular mobility represents a transformation in how society approaches transportation—shifting from ownership to access, from waste to reuse, and from carbon dependency to renewable solutions. Embedding these themes into secondary education encourages systems thinking, ecological literacy, and entrepreneurial problem-solving.

Conclusions & Recommendations

Education plays a vital role in promoting sustainable practices. Curriculum development, hands-on projects, community partnerships, and public outreach campaigns ensure secondary education supports circular mobility. This educational shift not only supports global climate goals but also empowers youth to imagine and create a circular, equitable future.

The circular economy focuses on reducing waste and extending the lifespan of products and materials through reuse, repair, and recycling. Unlike the traditional linear model of production and disposal, circularity emphasizes keeping materials in use for as long as possible, ultimately minimizing resource consumption and environmental impact.

One of the key areas where the circular economy is gaining momentum is transportation and logistics, as these industries face significant sustainability challenges. These include high fossil fuel consumption, waste from packaging and equipment, and the increasing volume of e-commerce product returns, which contribute to emissions, excess packaging, and landfill waste.

To address these challenges, the transportation sector can adopt circular strategies, such as optimizing delivery routes to reduce empty miles and fuel usage, integrating renewable energy in vehicles and operations, and encouraging reusable and recyclable packaging. Additionally, efficient return and reuse systems can help minimize waste while creating economic opportunities. Businesses can expand into repair and refurbishment services, as well as recycling initiatives for transport equipment.

A significant hurdle in implementing circular practices lies in reverse logistics management. Effective integration requires careful planning, efficient collection systems, sorting facilities, and remanufacturing centers. Moreover, handling the growing variety of materials demands flexibility, advanced technology, and robust data management systems.

By adopting circular economy principles, transportation and logistics can move toward a more sustainable and resource-efficient future, balancing economic growth with environmental responsibility.

By embracing technology, fostering collaboration, and committing to continuous improvement, organizations can effectively implement Circular Mobility Solutions while avoiding common pitfalls. A proactive approach ensures sustainability, efficiency, and long-term success in an evolving transportation landscape.

Sources

Barman, P., Dutta, L., Bordoloi, S., Kalita, A., Buragohain, P., Bharali, S., & Azzopardi, B. (2023). Renewable energy integration with electric vehicle technology: A review of the existing smart charging approaches. *Renewable and Sustainable Energy Reviews*. <https://www.sciencedirect.com/science/article/pii/S1364032123003751>

Crispin, A. & Parthasarathy, P. (2025). Geochemical characteristics and paleo weathering in sediments of Noyyal River Basin, Tamilnadu–India. *Environmental Research & Technology*, 8 (1), 163–171 (Scopus Index).

European Commission (2025a). Sustainable transport. Retrieved from https://transport.ec.europa.eu/transport-themes/sustainable-transport_en

European Commission (2025b). Sustainable urban mobility planning and monitoring. https://transport.ec.europa.eu/transport-themes/urban-transport/sustainable-urban-mobility-planning-and-monitoring_en

Green.org (2024). The circular economy in automotive: Closing the sustainability loop. <https://green.org/2024/01/30/the-circular-economy-in-automotive-closing-the-sustainability-loop/>

Hartley, K., Schülzchen, S., Bakker, C. A., & Kirchherr, J. (2023). A policy framework for the circular economy: Lessons from the EU. *Journal of Cleaner Production*, 412, Article 137176. <https://doi.org/10.1016/j.jclepro.2023.137176>

Ji-Hyland, C., White, D., & Khaydarov, R. (2025). The impact of circular economy practices on sustainable logistics performance. *International Journal of Logistics: Research and Applications*. <https://www.tandfonline.com/doi/pdf/10.1080/13675567.2025.2465579>

Lean Manufacturing Junction (2022). The best ways to reduce waste in automotive manufacturing. [Hartley, K., Schülzchen, S., Bakker, C. A., & Kirchherr, J. \(2023\). A policy framework for the circular economy: Lessons from the EU. Journal of Cleaner Production, 412, Article 137176. https://doi.org/10.1016/j.jclepro.2023.137176](https://doi.org/10.1016/j.jclepro.2023.137176)

Rakowski, D., Ewalts, D. & Dall' Acqua, C. (2025). The Global Circularity Gap Report. <https://www.deloitte.com/global/en/issues/climate/global-circularity-gap.html>

Schumann, C., Riedel, R., Franke, S., Nitsche, A., & Runte, C. (2022). Artificial intelligence support for smart logistics systems in industrial environments. SAE Technical Paper, 2022-01-0347. <https://doi.org/10.4271/2022-01-0347>

World Economic Forum (2022). Circular economy key to accelerating net-zero transportation. <https://www.weforum.org/stories/2022/05/circular-economy-net-zero-transportation/>

4. Future Perspectives of Artificial Intelligence in Circular Economy

As educators seek to equip the next generation with the knowledge and tools to lead this transition, integrating digital technologies into Circular Economy Education becomes increasingly vital. Among these technologies, Artificial Intelligence (AI) stands out for its powerful capacity to model complexity, optimize decision-making, and automate sustainability processes. Furthermore, Machine learning (ML) offers a growing set of computational techniques capable of addressing the complexity and dynamism of circular economy (CE) systems, which should be a key topic in secondary school education. In recent years, researchers and practitioners have applied various types of ML to optimize resource flows, enhance material recovery, forecast environmental outcomes, and enable smarter decision-making across sectors. The studies summarized in the accompanying table reflect diverse applications of ML aligned with CE principles, including reuse, regeneration, reduced emissions, and closed-loop processes.

Supervised learning remains one of the most widely applied ML paradigms in CE research. This approach involves training models on datasets that contain both input variables and known outcomes, allowing the algorithm to learn predictive relationships. Once trained, the model can estimate unknown outcomes for new data. Within circular systems, supervised learning is used to forecast the yield or quality of recycled materials, predict resource availability, or assess supplier performance based on sustainability criteria. Common supervised learning algorithms include Artificial Neural Networks (ANN), which are particularly effective at recognizing complex patterns in environmental or agricultural data; Support Vector Regression (SVR), used for precise numerical predictions; and Random Forest, a robust ensemble method that handles multi-variable decision environments such as PET plastic recycling.

Unsupervised learning differs by operating on data without labeled outcomes. It is commonly used to explore underlying patterns, clusters, or anomalies in complex datasets. In the context of CE, unsupervised learning supports functions such as identifying trends in consumer behavior related to sustainable products, clustering waste streams by composition, or detecting irregularities in recycling networks. Clustering techniques and topic modeling are particularly valuable when analyzing unstructured data sources, including social media, waste logs, or sensor feedback from infrastructure systems.

Reinforcement learning introduces adaptability through feedback loops. In this model, an agent learns optimal strategies through iterative interactions with a system, receiving rewards or penalties based on outcomes. This trial-and-error mechanism makes reinforcement learning particularly suited for dynamic operational contexts such as logistics, fleet management, or adaptive scheduling in bio-circular supply chains. Studies applying this technique often focus on minimizing fuel use, reducing emissions, and improving service efficiency—goals closely tied to CE's emphasis on resource conservation and system resilience.

Deep learning techniques, including convolutional neural networks (CNN), are gaining traction in applications that involve image recognition, classification, and sensory analysis. These are particularly effective in automating waste sorting, detecting contamination in recyclables, or assessing quality in refurbished goods. Deep learning enables high-speed, scalable automation of material classification processes, which is essential for increasing recovery rates and reducing labor-intensive operations in CE infrastructure.

Lastly, Explainable AI (XAI) has become a critical innovation where model transparency and accountability are required. Unlike traditional “black-box” ML models, XAI provides insights into the factors that influence predictions, supporting decision-making in environmental policy, emissions reduction planning, or sustainable urban development. Models such as XGBoost, when combined with SHAP (SHapley Additive exPlanations) values, can reveal the most influential variables driving sustainability outcomes, enabling more informed and justifiable interventions in CE governance.

Together, these ML approaches form a complementary toolkit for operationalizing circularity. Their application ranges from prediction and optimization to automation and compliance—each supporting the systemic redesign of production, consumption, and recovery systems needed for a circular economy transition.

Machine Learning Approaches in Circular Economy Contexts

Artificial Intelligence (AI) is increasingly recognized as a strategic enabler in the advancement of the circular economy (CE). Rather than serving as a background technology, AI is progressively shaping the design, control, and optimization of circular systems across diverse sectors. From agriculture to urban planning, from material recovery to product lifecycle management, AI is facilitating the transition from linear “take-make-dispose” models to regenerative, circular systems that reduce waste and maximize resource efficiency.

One of the clearest applications of AI in CE lies in predictive modeling for resource optimization. In the bio-circular agriculture sector, Pitakaso et al. (2025) applied reinforcement learning and artificial multiple intelligence to optimize the routing and scheduling of sugarcane fleet logistics. This system successfully minimized fuel consumption and emissions, contributing to circular agricultural practices that close the loop on biomass usage ([Pitakaso et al., 2025](#)). Similarly, Kravchenko et al. (2025) used support vector regression to predict the chemical properties of biochar derived from food waste. Their work supports precision engineering of waste-to-energy systems, ensuring that biochar production aligns with CE goals by maximizing reuse and reducing residual outputs ([Kravchenko et al., 2025](#)).

Another major area where AI is reshaping CE practices is in waste sorting and circular material recovery. Advances in computer vision, particularly through deep learning, are transforming the efficiency of recycling systems. Faghih et al. (2024) demonstrated how convolutional neural networks (CNNs) could classify post-consumer textiles by fabric type with high accuracy. This enhances the purity of recovered materials and supports effective reuse in the textile industry ([Faghih et al., 2024](#)). In the domain of plastic recycling, Abedsoltan et al. (2025) developed a hybrid model using Random Forest and ANN to simulate PET hydrolysis processes, helping recyclers improve both the yield and purity of recycled plastics in closed-loop systems ([Abedsoltan et al., 2025](#)).

AI is also playing a central role in circular urban systems. In smart cities, AI enables more sustainable infrastructure by dynamically managing resources like water and waste. Ojadi et al. (2024) employed AI-based time-series forecasting to optimize water usage and solid waste management in urban environments, allowing cities to adapt in real time to consumption patterns and reduce environmental stress ([Ojadi et al., 2024](#)). Beyond operational efficiency, AI is contributing to strategic urban planning. Wang et al. (2025) used Explainable AI (XAI), combining XGBoost and SHAP values, to evaluate the performance of circular carbon initiatives in China's pilot cities. Their findings offer valuable policy insights into which variables most effectively reduce emissions, thereby enhancing data transparency in CE governance ([Wang et al., 2025](#)).

Industrial systems and supply chains are also benefiting from AI integration in circular design. Ghanavati-Nejad et al. (2025) developed a stochastic artificial neural network model to support supplier selection based on resilience and circular economy metrics. The model aids manufacturers in embedding sustainability criteria into procurement, advancing goals such as remanufacturing and ethical sourcing ([Ghanavati-Nejad et al., 2025](#)).

Similarly, Meena et al. (2025) presented a decision-support framework for circular supply chains that uses AI to balance the triple bottom line: economic efficiency, environmental stewardship, and social responsibility (Meena et al., 2025).

Looking ahead, more sophisticated applications are emerging in the form of AI-coordinated industrial ecosystems. Telesca (2025) proposed the Smart Sustainable Development (SSD) model for managing Eco-Industrial Zones using AI to integrate CE performance metrics, zoning policies, and real-time energy and material flow data. The model envisions an orchestrated system where industries share resources and synchronize operations based on intelligent analytics (Telesca, 2025).

ML Applications in the Circular Economy

The table outlines key uses of machine learning (ML) within the circular economy (CE). Each entry showcases how ML techniques—including supervised, unsupervised, reinforcement, and deep learning—enable resource optimization, waste reduction, material classification, and system adaptability. The overview connects each approach with specific CE functions, offering insight into how intelligent tools support regenerative, low-impact, and data-informed solutions across industries

Title	Authors	ML Type	Algorithm	Application	Circular Economy Impact
Mapping Aquatic Weed Yields for Biochar Production	Banda et al. (2025)	Supervised Learning	Artificial Neural Networks (ANN)	Predicting biomass yield for biochar production	Converts biomass into energy, optimizing bioresource flows
Bio-Circular Green Economy in Agriculture	Pitakaso et al. (2025)	Reinforcement Learning	RL with Artificial Multiple Intelligence	Fleet routing and scheduling for biomass logistics	Optimizes transport emissions and resource recovery in agriculture
Supplier Selection in Circular Supply Chains	Ghanavati-Nejad et al. (2025)	Supervised Learning	Stochastic ANN Models	Selecting suppliers based on resilience and circularity	Enhances sustainability and agility in supply chain networks

Title	Authors	ML Type	Algorithm	Application	Circular Economy Impact
PET Hydrolysis Modeling for Circular Plastics	Abedsoltan et al. (2025)	Supervised Learning	Random Forest, ANN	Modeling efficiency of PET waste hydrolysis process	Enables closed-loop recycling of plastic through chemical process optimization
Urban Circular Carbon Economy Analysis	Wang et al. (2025)	Explainable AI (XAI)	XGBoost with SHAP analysis	Assessing sustainability performance of Chinese pilot cities	Supports urban planning aligned with CE via carbon footprint insights
AI for Biochar Property Prediction	Kravchenko et al. (2025)	Supervised Learning	Support Vector Regression (SVR)	Predicting biochar properties from food waste	Optimizes waste-to-value pathways in organic waste processing
Reimagining Compliance Through AI in Waste-to-Value Systems	Ashraf & Mustafa (2024)	Un-supervised Learning	Anomaly Detection, Pattern Mining	Monitoring compliance in digital waste valorization processes	Ensures ethical and traceable circular waste flows
AI-Driven Optimization of Water Usage and Waste in Smart Cities	Ojadi et al. (2024)	Supervised Learning	Time Series Forecasting	Optimizing urban water and waste systems	Promotes closed-loop urban resource cycles
AI-Enabled Textile Waste Sorting	Faghih et al. (2024)	Computer Vision / Deep Learning	Convolutional Neural Networks (CNN)	Classifying post-consumer textile waste for recycling	Improves recovery rates and purity in textile reuse streams
Waste Valorization Meets AI: SME Growth and Inequality	Abbas & Mustafa (2024)	Deep Learning	Multi-layer Perceptron	Predicting value extraction from recycled materials	Strengthens inclusive and scalable waste-to-resource systems

AI in the Circular Economy: Opportunities and Risks

As AI systems become increasingly embedded in circular economy (CE) infrastructures, their role is evolving from analytical support to autonomous control and predictive governance. Emerging applications include real-time lifecycle assessments (Kravchenko et al., 2025), AI-orchestrated energy microgrids, dynamic logistics for circular supply chains (Pitakaso et al., 2025), and autonomous traceability systems for monitoring material flows. These tools promise substantial gains in efficiency, transparency, and ecological sustainability. Through advanced learning, pattern recognition, and adaptive decision-making, AI supports the goals of designing out waste, regenerating ecosystems, and closing resource loops across industries.

However, these capabilities come with critical challenges. The ethical governance of AI remains underdeveloped in many CE contexts, where concerns over algorithmic bias, data opacity, and exclusion from decision-making persist (Floridi et al., 2018). Unchecked, such risks can amplify environmental injustices or undermine democratic control. For example, AI-based automation in recycling systems may marginalize informal workers or small-scale recyclers, especially in low-income economies where access to digital infrastructure remains limited (Vinuesa et al., 2020). Meanwhile, circular supply chains increasingly rely on large-scale data collection—through sensors, smart contracts, or consumer behavior tracking—raising concerns around data sovereignty and privacy.

These concerns are now receiving attention from regulators. The European Union’s Artificial Intelligence Act (EU AI Act) introduces a legal framework that categorizes AI systems based on their potential risks, with specific provisions for high-risk systems used in environmental management, urban infrastructure, and industrial control (European Commission, 2021/2024). The AI Act mandates transparency, human oversight, and algorithmic accountability for such systems—principles that are especially relevant where AI is used to monitor emissions, optimize energy usage, or enforce CE-related compliance.

The EU Artificial Intelligence Act introduces a risk-based framework that classifies AI systems into four levels, structured like a pyramid. This structure helps ensure that the regulation is proportionate: the higher the potential risk an AI system poses to people, society, or the environment, the stricter the regulatory requirements.

EU AI Act: Risk Levels

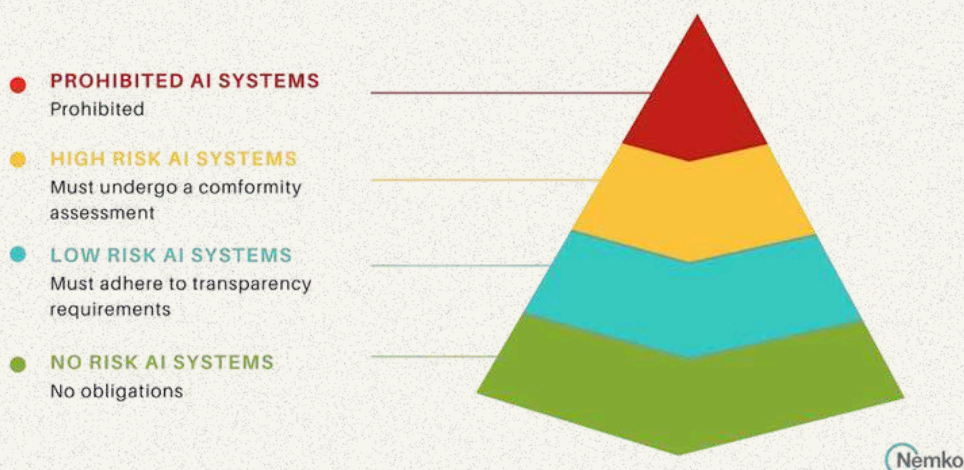


Figure 4: EU AI Act: Risk Levels.

Source: <https://www.nemko.com/blog/a-quick-dive-into-the-eu-ai-act>

At the top of the pyramid are unacceptable risk AI systems, which are considered too dangerous to be allowed in the EU market. These systems are banned outright. In the context of the circular economy, an example might be an AI system used to manipulate consumers through deceptive green marketing tactics — for instance, by using subliminal messaging to falsely portray a product as environmentally sustainable. If such a system exploits vulnerable populations (like children or elderly people), it would fall under this highest-risk category and be prohibited.

The next level down is high-risk AI systems, which are not banned but must comply with strict obligations around transparency, data quality, human oversight, and risk management. In the circular economy, this might include AI systems used in automated waste sorting facilities that classify materials for recycling. Another example would be AI that manages critical energy systems in a smart city or optimizes the distribution of reusable goods. While these systems support sustainability goals, any error or bias could have serious consequences, such as environmental damage or resource misallocation — hence they are considered high-risk.

Below that are limited-risk AI systems, which are subject mainly to transparency requirements. These systems may interact with users or influence decision-making but are less likely to cause harm. For example, a digital assistant or chatbot that guides consumers on how to reuse or recycle products falls into this category.

These AI tools must inform users that they are interacting with an AI system and may need to explain how recommendations are generated (e.g., suggesting second-hand products or repair options based on user preferences).

At the base of the pyramid are minimal or no-risk AI systems, which face no specific legal restrictions under the AI Act. These include most common applications that do not significantly affect people's rights or safety. In the circular economy, this could be AI used for internal logistics, such as optimizing routes for recycling trucks, or predictive maintenance tools for machinery in a recycling plant. These uses improve efficiency and sustainability but do not raise ethical or legal concerns, so they are freely permitted.

The AI Act pyramid ensures that AI applications in areas like the circular economy are regulated appropriately depending on their impact. Systems that are critical to public or environmental well-being are held to higher standards, while lower-risk tools are encouraged with minimal interference.

Achieving a fair and effective AI-enabled circular economy requires more than compliance. It demands responsible design, inclusive governance, and justice-centered innovation. Algorithmic decisions must be explainable, traceable, and auditable. Communities affected by automation—particularly those in vulnerable labor or ecological systems—must have a voice in how AI systems are designed and deployed. Integrating environmental justice principles into AI for CE ensures that the pursuit of sustainability does not come at the cost of equity.

In conclusion, while AI has enormous potential to scale circular models, its deployment must be guided by ethical safeguards. Frameworks like the EU AI Act provide a starting point, but ongoing dialogue among policymakers, technologists, and civil society will be essential to ensure that circular intelligence is not only smart, but also fair, inclusive, and accountable.

Sources

Abbas, S., & Mustafa, M. (2024). Waste valorization meets AI: SME growth and inequality. Working Paper, ResearchGate. <https://www.researchgate.net/publication/390629994>

Abedsoltan, R., Jafari, R., Rastegar, M., & Brar, S. K. (2025). Modeling and optimization of enzymatic hydrolysis for PET plastic using machine learning. SSRN. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5223492

Almashaleh, I., Wicaksono, H., & Valilai, O. F. (2025). A framework for social media analytics in textile business circularity for effective digital marketing. Smart Cities and Society, 1(1). <https://www.sciencedirect.com/science/article/pii/S2199853125000794>

Ashraf, M., & Mustafa, M. (2024). Reimagining compliance through AI in waste-to-value systems. Working Paper, ResearchGate. <https://www.researchgate.net/publication/390630356>

Aslam, M., & Mustafa, M. (2024). From waste to wealth: AI and FinTech strategies for equitable SME development. Working Paper, ResearchGate. <https://www.researchgate.net/publication/390630431>

Banda, M., Simukoko, M., & Kalumba, M. (2025). Utilizing machine learning to map aquatic weed yields for biochar production: A case study in the Bangweulu Wetlands, Zambia. Advances in Environmental and Energy Research, 6(2), 020. <https://www.lidsen.com/journals/aeer/aeer-06-02-020>

Faghih, M., Shokri, A., & Ramezani, M. (2024). AI-enabled textile waste classification for sustainable recycling: A deep learning approach. Sustainability, 17(10), 4264. <https://www.mdpi.com/2071-1050/17/10/4264>

Ghanavati-Nejad, M., Jolai, F., & Tavakkoli-Moghaddam, R. (2025). Supplier selection for resilient-leagile circular supply chains using stochastic ANN-based models. Soft Computing. <https://link.springer.com/article/10.1007/s00500-025-10578-z>

Kravchenko, J., Bockel, L., & Li, Y. (2025). Predicting biochar properties from food waste using support vector regression. Waste Management & Research. <https://www.sciencedirect.com/science/article/pii/S2213343725014873>

Meena, P. L., Ghadge, A., & Kumar, V. (2025). A triple bottom line approach to circular supply chain optimization using artificial intelligence. *Annals of Operations Research*. <https://link.springer.com/article/10.1007/s10479-025-06510-1>

Ojadi, F., Eze, S. C., & Adeleke, I. (2024). AI-driven optimization of water usage and waste in smart cities. Working Paper, ResearchGate. <https://www.researchgate.net/publication/390695591>

Pitakaso, R., Jittamai, W., & Chaitiamwong, N. (2025). Bio-circular green economy development in agriculture using reinforcement learning. *Computers and Electronics in Agriculture*. <https://www.sciencedirect.com/science/article/pii/S016816992500537X>

Telesca, L. (2025). A systemic sustainable development model for industrial circular economy in special economic zones. University of Basilicata Doctoral Thesis. <https://iris.unibas.it/bitstream/11563/196975/1/tesi%20dottorato%20di%20ricerca%20Lo%20VECCHIO%20con%20firme.pdf>

Wang, L., Xu, Y., & Zhang, T. (2025). Explainable machine learning to evaluate circular carbon performance in pilot cities. *Environmental Development*. <https://www.sciencedirect.com/science/article/pii/S2212095525001233>

5. Survey Results on Circular Approaches in Secondary Education Curricula

This evaluation is based on a survey that was carried out in the four public secondary schools in the project consortium with one representative of each school: FIFTH GENERAL LYCEUM Larisas (FGLL, Greece), Fritz-Greve-Gymnasium (FGGM, Germany), Zespół Szkół Agrotechnicznych i Ogólnokształcących im. Józefa Piłsudskiego (ZAI, Poland) and Hadiye Kuradaci Bilim Ve Sanat Merkezi Tarsus (HKB, Türkiye). It was conducted to gather insights into the curricula, existing practices and needs regarding CE education approaches. While all participating schools report some inclusion of CE topics within their national or regional curricula, the depth and breadth of this inclusion vary significantly across countries.

All schools stated that their national/regional curriculum has specific CE topics included in the curriculum with the restriction that in Poland only a small part of some subjects is devoted to CE.

All four schools acknowledge that CE-related topics are part of the formal curriculum, primarily embedded within science-related subjects (e.g. Biology, Chemistry, Physics) and humanities (e.g. History, Social Studies, Economics). In Türkiye and Poland, the scope is broader, extending into IT, and languages in both schools and additionally arts in Türkiye. However, Germany highlights a focus more on sustainability in general rather than CE explicitly.

There is a reliance on integrating CE topics into existing subjects, which is common across Greece, Poland, and Germany. Türkiye stands out for emphasizing project-based learning and the use of technology and digital tools. In Poland it is furthermore included into extracurricular activities and collaborations with external organizations, while the German school additionally applies project-based learning.

All schools cover core CE themes in their curriculum, with Poland addressing the most comprehensive set. Climate change gets integrated in all schools, biodiversity in Greece, Poland and Germany, renewable energy and sustainable consumption in Türkiye, Poland and Germany and waste management and recycling in Greece, Türkiye and Poland. Poland and Germany additionally include water conservation and social justice and equity. Environmental ethics are only part of the Greek curriculum.

Germany again reports a less explicit focus, noting that topics like energy production may be taught without teaching renewable energy as such. This variation suggests that while CE themes are present, the terminology and scope may differ, potentially leading to inconsistencies in student understanding.

Only Türkiye explicitly references the SDGs being part of the curriculum. Poland and Germany report partial reference, while Greece indicates none. This is significant, as SDGs provide a globally recognized framework that aligns well with CE education and could contribute to a more cohesive educational strategy.

All schools declared that no specific frameworks or guidelines for curriculum analysis (e.g., UNESCO Education for Sustainable Development, local frameworks) are used and that students, but not parents are involved in CE education at their school.

Beyond the curriculum, schools were asked about the inclusion of circular economy principles in their teaching practices. Greece involves them as part of the curriculum and in environmental programs, while Türkiye emphasizes CE project-based learning being integrated in their in-class activities. The Polish school involves students in extracurricular activities carried out by teachers and by joining activities with external organizations or local communities. In Germany, it is also implemented in regular lessons or by starting special projects.

Poland is the only school with active partnerships with external organizations to promote CE education. All others report no such collaborations, representing an important area for potential improvements in practical learning opportunities in the “real world”. On the practical side, all schools run sustainability-themed events (e.g., Earth Day, Eco Fair) and most schools additional recycling programs (Greece, Poland, Germany). Furthermore, Türkiye and Poland offer tree planting or gardening projects, while Türkiye also composting projects and Poland, moreover, clean-up drives.

The student engagement level in designing or implementing CE projects also varies: Poland reports active involvement, Türkiye and Germany partial, and Greece none. This reflects differing school cultures and available resources for student-led initiatives. Furthermore, most schools don’t monitor the impact of these practical activities, with only Poland evaluating the results of extracurricular activities.

No school offers formal teacher training in CE, and resources are generally lacking. Teachers rely on printed materials (Greece, Germany, Türkiye), workshops, digital resources and tools (Türkiye), or self-sourced content (Poland). The Turkish school is comparatively better equipped than the others, while Poland underscores the need for a centralized knowledge hub for CE materials.

The most commonly cited barriers in implementing CE education include:

- ✦ Lack of resources like teaching materials and funding (all schools)
- ✦ Limited curriculum flexibility (all schools)
- ✦ Insufficient teacher training (Greece, Poland, Germany)
- ✦ Insufficient skills from teachers (Türkiye)
- ✦ Bureaucratic overload (particularly noted in Germany)
- ✦ Lack of institutional support and educational policy frameworks (especially in Türkiye and Poland)
- ✦ Lack of student interest (Türkiye)
- ✦ Limited time teachers can devote to CE, as it has to be prepared voluntarily (especially in Germany and Poland)

These challenges reflect broader systemic issues of the respective educational policies, while still showing opportunities for change on a school-level.

Poland and Germany report the most developed CE-related projects. Poland lists initiatives like the “Green Classroom,” “Oxford Debates,” electric waste projects, “Classroom under the Cloud (Arboretum),” “Earth Day” and “Cleaning the World Day,” while Germany showcases the entrepreneurial school company “Freiday” delivering and selling food in reusable cups and a scheduled long-term student project implementing a school garden for this company. In this context students have the possibility to create and realize their own project ideas, and the winner project gets promoted. The Greek school has implemented a recent Erasmus+ program titled “Let’s Get Green - raising the awareness of ecological problems” and Türkiye has not yet realized any successful projects in this area.

Student engagement, while varied, tends to be more pronounced where extracurricular and project-based opportunities exist. The Polish students are actively involved in all the activities organized by the school and external organizations and show awareness of the threats connected with climatic change, reuse of materials, recycling and saving. In Germany, the students are engaged in the aforementioned projects. In contrast, the Greek student involvement is limited to recycling, and in the Turkish school to the described project-based learning activities.

Needs and Recommendations

To improve CE education, schools expressed clear needs for:

- ✦ More curricular flexibility and dedicated time for CE, e.g. for interdisciplinary school projects or new subjects related to CE (especially Germany and Greece)
- ✦ Practical teaching resources tailored to CE (all countries)
- ✦ Opportunities for teacher training and peer exchange (Poland)
- ✦ Stronger institutional and policy support, including less bureaucracy (Germany)
- ✦ Collaboration with external organizations and industry (Germany)

ZAI's (Poland) suggestion of a centralized knowledge hub confirms the need for this project and is particularly promising, as it could address several challenges at once -resource gaps, teacher support, and quality control.

Conclusion

The survey data reveal a shared recognition of the importance of circular economy education, but also considerable variation in implementation, depth, and support. Poland appears to be the most advanced in terms of student engagement, variety of themes, and external collaboration, while Türkiye demonstrates strong potential through digital infrastructure and project-based approaches. Germany and Greece highlight structural and systemic challenges that limit the depth of CE integration despite teacher interest.

To move forward, there is a need for:

- ✦ National policy alignment with CE and SDG principles
- ✦ Investment in teacher training and materials
- ✦ Support for interdisciplinary, project-based learning
- ✦ Enhanced collaboration with external actors

Such steps would help transition from isolated efforts to a more cohesive, impactful CE education system across Europe. The study highlights the importance of the CircEdu project as it addresses several of these points.

6. Survey Results on Teachers' Perspectives, Experiences, and Needs Regarding CE Education in Schools

The following results conclude the evaluation of a survey conducted with circa half of the teaching staff of each of the four public secondary schools in the project consortium: FIFTH GENERAL LYCEUM Larisas (FGLL, Greece), Fritz-Greve-Gymnasium (FGGM, Germany), Zespół Szkół Agrotechnicznych i Ogólnokształcących im. Józefa Piłsudskiego (ZAI, Poland) and Hadiye Kuradaci Bilim Ve Sanat Merkezi Tarsus (HKB, Türkiye). This survey aimed to assess teachers' perspectives, experiences, and needs regarding circular economy education in schools. In total, 56 teachers answered the survey, including 15 teachers from Greece, 19 from Poland, 11 from Germany and 12 from Türkiye.

Subject Areas

In Germany, the largest proportion of teachers specialize in Languages (33.3%), followed by Humanities (e.g. History, Social studies, Economics) with 26.7%, Science (e.g. Biology, Chemistry, Physics) with 20%, and Arts (13.3%). IT is the least represented, at 6.7%.

In Greece, the majority of respondents teach Science (35.7%), followed by Humanities (28.6%). Languages and Mathematics each account for 14.3%, and Ancient Greek & Latin make up 7.1%. Notably, Arts and IT are not represented.

Poland shows a more diverse distribution. Science, Humanities, and Languages are equally represented at 18.2% each. Additional areas include educational lessons, Family life education, Student support, Hospitality, IT, Mathematics, Science, Gastronomy, Vocational education, Career advising, and Physical Education, each at 4.5%.

In Türkiye, the most represented subject is IT (33.3%), followed by Science (26.7%), Languages (20%), Arts (13.3%), and Humanities (6.7%).

Years of Teaching Experience

In terms of experience, Greece, Poland, and Türkiye show a strong majority of highly experienced educators. In Greece, 92.9% of teachers have been teaching for more than 10 years, with a small minority (7.1%) having less than 2 years experience. Poland reflects a similar trend, with 84.2% having over 10 years of experience and 15.8% in the 2–5 years range.

Türkiye also aligns with this pattern, where 83.3% have more than 10 years of experience, and 16.7% fall into the 6–10 years category. Germany, on the other hand, presents a more balanced distribution. While 45.5% of respondents have over 10 years of experience, a significant portion (27.3%) has been teaching for 2–5 years, and 18.2% for 6–10 years. Additionally, 9.1% are relatively new to the profession with less than 2 years of experience.

Training in Circular Economy Education

Training on circular economy concepts remains limited across the surveyed countries. Teachers in Germany, Greece, and Türkiye report no formal training in this area, underscoring a lack of institutional emphasis on the topic. Poland stands out, with 31.6% of respondents indicating they have received some form of training. However, even in Poland, such training is not yet widespread. This points to a systemic need for professional development opportunities tailored to sustainability education.

Teachers' Understanding of Circular Economy

Teachers generally demonstrate a basic understanding of the circular economy, whereas the depth and scope varied extensively.

Polish teachers provided the most comprehensive definitions, often referencing sustainability, environmental responsibility, and product life cycles. Overall, there was a strong understanding of core circular economy principles: reuse, recycling, waste reduction, sustainability, life-cycle extension. Some emphasised the educational impact: awareness, values, and behavior change. Others recognized the role of curriculum and vocational education (e.g., food services, hospitality). Some responses connect circular economy to global environmental challenges (e.g., climate change).

German responses focused more on economic and societal dimensions: The definitions emphasize systemic thinking, involving society, economy, institutions, and resource cycles. There is a focus on closed-loop processes, with some interest in how circular economy applies within the school itself. They provide an analytical lens on resource efficiency and sustainability as a systemic issue.

Teachers in Türkiye emphasized practical applications such as reuse and sustainability in education: The definitions range from basic reuse-recycling to deep pedagogical insights. Notable contributions include one advanced response linking CE to a learning ecosystem (digital sustainability, project-based learning). Some emphasize resource consciousness, sustainability, and curricular inclusion. Other responses acknowledge limited familiarity with the concept.

In Greece, the answers showed a strong association of CE with recycling and waste management. Several responses mention practical classroom activities and training. Some emphasize behavioral change through hands-on education or mention eco-schools, teacher training, and curriculum adaptation.

Integration of CE in Teaching

The integration of circular economy topics into the curriculum varies considerably. In Germany, most teachers incorporate circular economy into existing subjects, with 36.4% of respondents indicating this approach. Project-based learning and collaboration with external organizations are each used by 18.2% of respondents, though they are not widespread. 27.3% of the teachers reported not addressing circular economy in their teaching at all, and 9% added that circular economy is barely mentioned in upper secondary grades (11th and 12th).

In the Greek school, the majority of the respondents (44.4%) integrate the circular economy into existing subjects rather than teaching it as a standalone topic. Project-based learning and extracurricular activities are each used by 16.7% of teachers, as is collaboration with external organizations. However, 26.7% of Greek teachers do not address circular economy at all, indicating noticeable gaps in coverage.

The highest engagement in the Polish school comes from dedicated lessons on circular economy, cited by 36.8% of respondents, and integration into existing subjects, mentioned by 57.9%. Collaboration with external organizations is used by 21.1% of teachers, while project-based learning and extracurricular activities are less commonly employed. Only 5.3% of Polish teachers reported not covering circular economy, suggesting a relatively structured and comprehensive approach.

In Türkiye, circular economy is primarily introduced through project-based learning, used by 75% of respondents, and extracurricular activities, cited by 33.3%. A smaller portion (8.3%) indicate integrating CE into existing subjects, and 16.7% report offering dedicated lessons. 8.3% highlighted the use of art projects with recyclable materials as a creative method for engaging with sustainability. Despite these efforts, 16.7% of Turkish teachers said circular economy is not addressed in their teaching.

Germany and Greece largely integrate circular economy into existing subjects, but it is not a primary focus. Poland shows the highest engagement with structured, dedicated lessons, while Türkiye relies heavily on project-based learning.

Extracurricular activities and external collaborations are limited across all countries, suggesting a potential area for expansion.

Coverage of CE Topics in Class

Circular economy teaching content centers mostly on waste reduction, recycling, and sustainable consumption:

In the German school, the most frequently addressed aspects of the circular economy in education are sustainable consumption and production, covered by 72.7% of respondents, and waste reduction and recycling, mentioned by 63.6%. Repair and reuse strategies were referenced in 36.4% of the answers, while product lifecycle and resource efficiency appeared in just 9.1%. Notably, 18.2% of the teachers did not cover circular economy topics at all.

In Greece, the school has the highest proportion of teachers not addressing circular economy concepts, with 33.3% indicating no coverage. Waste reduction and recycling were the most commonly discussed elements, present in 40% of the responses, followed by sustainable consumption and production, mentioned by 20%. Product lifecycle and resource efficiency were identified in 13.3% of the responses.

The Polish teachers demonstrate broad engagement with circular economy themes. Waste reduction and recycling were addressed by 73.7% of teachers, and sustainable consumption and production appeared in 52.6% of the responses. Product lifecycle and resource efficiency were mentioned in 47.4%, and repair and reuse strategies were noted by 42.1% of participants. Additionally, the sharing economy and related concepts were highlighted in 26.3% of the responses. 15.8% of respondents indicated that they do not cover circular economy in their teaching.

In Türkiye, all respondents addressed at least one aspect of the circular economy. Waste reduction and recycling were integrated by all participants, while 66.7% included sustainable consumption and production. Product lifecycle and resource efficiency were noted by 50% of respondents, and repair and reuse strategies by 41.7%. The sharing economy was mentioned by 8.3%, and uniquely among the four countries, Türkiye included circular economy in the context of urban planning and communities, cited by 8.3% of teachers.

This analysis shows varying levels of integration of circular economy topics in education across the four countries, with Poland and Türkiye demonstrating the most comprehensive and consistent engagement.

CE Teaching Methods

The teaching methods used to explain circular economy concepts vary significantly across the four countries. Traditional lectures remain the dominant method, though hands-on activities and experiments are gaining traction in all countries with Greece coming last. Türkiye stands out for its higher use of digital tools and student-led projects. However, the use of gamified learning and digital simulations is generally low across the board.

Traditional methods, such as lectures and theoretical lessons, are the most common approach overall. They are most heavily used in Poland, where 73.7% of respondents reported relying on this method. This is followed by Greece with 60%, Türkiye with 50%, and Germany with 54.5%. While this indicates a solid foundation in theory, it also suggests a need for more diverse instructional approaches.

Hands-on activities and experiments show strong usage in Türkiye (58.3%), Germany (54.5%), and Poland (31.6%). Interestingly, Greece does not report using this method explicitly, highlighting a potential gap in experiential learning.

Field trips and site visits are used most frequently in Poland, with 42.1% of respondents incorporating them into their teaching. In contrast, these methods are far less common in Greece (20%), Türkiye (8.3%), and Germany (9.1%), indicating that real-world engagement is still limited in many contexts.

Digital and gamified learning approaches remain underutilized in general. Serious games are used by 15.8% of Polish teachers and 18.2% of German teachers, while no responses from Türkiye or Greece mentioned this method. The use of digital tools and interactive simulations is highest in Türkiye at 41.7%, followed by Poland at 31.6%, and very limited in Germany (9.1%) and Greece (6.7%). Türkiye demonstrates the strongest integration of digital educational technologies among the four countries.

Collaborative and student-led learning is also unevenly applied. Guest speakers and collaborations are relatively rare, with only 9.1% of German, 15.8% of Polish, and 8.3% of Turkish respondents mentioning them. Greece did not report any use of guest speakers. However, Türkiye stands out in its use of student-led projects, with 50% of respondents indicating they employ this approach. In comparison, Poland and Greece each reported 10.5% and 13.3%, respectively, and Germany reported no use of student-led projects.

Overall, Poland demonstrates the widest variety of teaching approaches, combining traditional instruction with field trips, hands-on activities, and some use of digital and gamified methods. Türkiye and Germany also show a diversified approach, with notable use of interactive tools. In contrast, Greece appears to have the most limited set of teaching strategies, with 26.7% of respondents indicating they do not use circular economy teaching methods at all. Poland also reported 15.8% not using any specific methods, while Germany had 18.2% of teachers in the same category. These differences underscore the varying degrees of engagement and innovation in circular economy education across the participating countries.

Access to Circular Economy Teaching Materials

Access to specific educational materials varies significantly across countries. In Germany, only 18.2% of teachers reported having any form of such materials, with 9.1% of those limited to basic content in school textbooks. A striking 81.8% indicated no access at all. Greece presents the most critical gap, as no teachers reported access to circular economy materials, underscoring an urgent need for resource development. Poland leads in access, with 36.9% of teachers having materials, and 5.3% specifically citing ekopotencjal.pl as a resource. Nevertheless, 63.2% of Polish teachers still lack access. In Türkiye, access is moderate at 23.1%, but the majority—76.9%—do not have materials available. These disparities highlight the need for targeted efforts to improve the availability and distribution of CE educational resources across Europe.

Key Challenges in Integrating CE into Teaching

Common barriers to integrating circular economy education include:

- + **Lack of training** was most frequently cited across all countries: Germany (25%), Greece (23.1%), Poland (20.9%), and Türkiye (23.1%). This highlights a widespread need for more teacher development programs on circular economy topics.
- + **Insufficient teaching materials** are particularly pronounced in Germany, where 37.5% report difficulty in accessing teaching materials. Greece (25.6%), Poland (27.9%), and Türkiye (20.5%) also struggle, showing a consistent gap in educational resources.

- + **Limited curriculum flexibility** is a major challenge in all countries, with Germany showing the highest rate (33.3%) followed by Greece (25.6%), Poland (20.9%), and Türkiye (17.9%).
- + **Lack of Student Interest & Engagement** was particularly reported by the Turkish school (15.4%). Greece (7.7%) and Poland (4.7%) also mention it, while Germany does not report this issue at all.
- + Poland (7%) and Türkiye (10.3%) indicate some lack of **parental support**, while Greece (2.6%) reports minimal concern. No country reports lack of **school administration support**, meaning the implementation of further CE education shouldn't be impacted by missing institutional backing.
- + Greece (15.4%), Poland (11.6%), and Türkiye (12.8%) highlight **insufficient inclusion in educational policies**. Germany does not report this as a challenge, possibly indicating better policy alignment.
- + Germany (4.2%), Poland (7%) indicate a small percentage of teachers that do not face any issues with circular economy education. Greece and Türkiye report no teachers who are free of challenges.

Germany struggles most with resource availability and curriculum flexibility. Greece shows the highest concern for policy gaps, parental support, and lack of student interest. Poland and Türkiye experience more varied challenges. The biggest universal problem across all countries is lack of training and insufficient teaching materials.

Desired Support to Teach CE more Effectively

Many teachers requested access to better teaching materials, making it the top priority across all countries. In Germany, this was highlighted by 90.9% of respondents, the highest demand overall. Poland followed with 89.5%, while 60% of teachers in Greece and 75% of teachers in Türkiye identified this as a key need.

Training programs and workshops were also highly requested, particularly emphasized in Greece with 93.3% and in Poland with 78.9%. Germany (36.4%) and Türkiye (50%) showed demand for these opportunities as well.

Interdisciplinary collaboration is especially valued by teachers in Germany (63.6%), followed by Poland (47.4%) and Türkiye (41.7%). Greek teachers (20%) also expressed interest in interdisciplinary approaches, although to a lesser extent.

Project-based learning and practical opportunities were heavily requested by Polish (68.4%) and Turkish (66.7%) respondents. Germany (54.5%) and Greece (26.7%) also showed interest in more hands-on and applied learning formats.

Support from external organizations and experts was appreciated across all countries: Poland (36.8%), Germany (45.5%), Türkiye (50%), and Greece (33.3%) indicated the value of such collaborations. This suggests an opportunity for partnerships with nonprofits, industry, and political organisations to enhance circular economy education.

Teachers in Poland showed the greatest need for stronger educational policies and institutional support (42.1%), followed by Greece (33.3%). Germany did not report this need at all, and only 8.3% of teachers in Türkiye mentioned it.

Finally, Poland also expressed the highest need for parental support (26.3%). This was a lower priority in Türkiye (16.7%), Germany (9.1%), and Greece (6.7%). Curriculum flexibility was mentioned exclusively in Germany (9.1%).

School-Level CE Initiatives

All schools implement some sort of CE initiatives. Recycling Programs were mentioned by all schools, while repair and reuse workshops only exist in Poland and Türkiye. Sustainable school infrastructure (e.g. water-saving systems, solar panels) is implemented in the German and the Polish school, highlighting opportunities for investment in eco-friendly school designs in the other countries. CE themed competitions & events are hosted by the schools in Germany, Poland and Türkiye, while Greece does not report any events. The Turkish, Polish and German school actively collaborate with local businesses & organizations. Furthermore, Greece mentioned the yearly participation in the national environmental program on forest ecosystems, sustainability and sustainable management, including activities related to CE.

In Türkiye (57,1%) and Greece (13,3%), a number of teachers indicated that there are no initiatives currently in place at their school, despite the mentions of projects by their colleagues. Furthermore, in all countries teachers gave highly varying answers regarding the initiatives they know about at their school. This indicates problems of communication and coherence and missing interdisciplinarity.

Student Involvement

In all schools, the active participation of students in designing or implementing CE projects was reported. Germany mentioned the student company, where the youth evolves their own sustainable business project, the implementation of own projects connected to SDGs and the “Freiday” project, where students create their own sustainable project. In Greece, mostly recycling and the above mentioned environmental project are implemented. The Turkish school carries out TÜBITAK and Teknofest projects and partly involves the students in project based studies, while initiatives based on product creation are the most popular. In Poland, most teachers indicate the involvement of students, but without further explanations.

The evaluation of this questions affirms the forementioned assumption of lacking consistency and exchange between teachers and communicative measures regarding the implemented projects as the answers contradicted each other highly in all schools.

Overall, the consistent implementation of student-led practical and diverse or even interdisciplinary projects could highly benefit the schools, ensuring active youth leadership in CE solutions.

Assessment Practices

Evaluation of circular economy efforts is primarily done through student projects and presentations in all countries. Türkiye (66.7%), Greece (64.3%), and Poland (58.3%) report the highest reliance on this method. Germany (38.5%) also utilizes this approach, but less frequently, while relying more on student/staff feedback compared to other countries (30.8%). Greece (14.3%), Poland (20.8%), and Türkiye (6.7%) use surveys to a lesser extent. Data collection (waste reduction & energy savings) is incorporated by the schools in Greece (21.4%), Poland (12.5%), and Türkiye (20%). Germany on the other hand does not use data collection.

Poland (4.2%) and Türkiye (6.7%) produce reports and publications, though at lower levels, while Germany and Greece do not publish formal reports at all. In the German school a high number of teachers is indicating no assessment of CE initiatives, while in all other schools all participants reported some kind of assessment despite a small percentage of Polish teachers not knowing about the measures.

Overall, the assessment is not very comprehensive in all countries. Structured surveys, reports and data collection remain underused in most countries.

Successful CE Projects with Students

Across the four countries, various circular economy and sustainability projects have been implemented in schools, each reflecting different levels of student involvement, innovation, and institutional support.

Germany

- + Focus on upcycling (furniture, art projects) and waste separation, but the latter efforts were not always successful.
- + The student company created their own recycling model for a sustainable breakfast.
- + Workshops with external experts (Spirit of Football project) connecting sustainability with sports
- + Students taught younger children about waste reduction, fostering peer-led education.
- + Concerns about the lack of sustainable principles implemented in the school itself

Greece

- + Existing projects focus on battery recycling, old material reuse, tree planting, and environmental visits
- + One Erasmus+ project
- + No mention of student-driven innovation, mostly pre-structured sustainability efforts.

Poland

- + External cooperations with Arka Environmental Education Centre
- + Recycling projects: "Cleaning the World Day" and an electronic waste collection.
- + Campaigns like "Clean Mountains" promoting environmental protection and promoting biodiversity
- + Fashion-related circular economy projects (Eco-Wave: Fast Fashion awareness).
- + Projects involve alternative energy models and sustainable gardening and humus harvesting.
- + Gastronomy-focused closed-loop economy projects, showing industry-specific sustainability integration.

Türkiye

- ✦ Hands-on creative projects using waste materials, including rocket and car-building
- ✦ City planning projects integrating sustainability concepts.
- ✦ TÜBİTAK award-winning mobile application for water conservation.
- ✦ Gamified learning techniques increase student interest.
- ✦ Research projects with students

The Polish school shows the broadest range of projects, while the Turkish school stands out for its creative and technology-driven approaches. The Greek school has a primary focus on traditional recycling and environmental activities. and the German school emphasizes peer learning, where students teach others about sustainability.

Advice for Educators on Teaching Circular Economy Concepts

Integrate Circular Economy into Everyday Teaching

- ✦ Include circular economy topics in daily lessons and real-life examples (Germany).
- ✦ Use project-based learning and extracurricular activities (Greece, Türkiye).
- ✦ Encourage students to start initiatives like clothing swaps or zero-waste projects (Poland).

Seek External Support & Collaborations

- ✦ Invite experts and collaborate with local businesses and environmental organizations (Germany, Greece, Türkiye).
- ✦ Form peer learning networks to share best practices (Greece).
- ✦ Encourage partnerships with sustainability-focused institutions (Poland, Türkiye).

Use Practical & Hands-on Learning Approaches

- ✦ Organize workshops, field trips, and interactive student activities (Greece, Türkiye).
- ✦ Implement small-step sustainability projects, such as battery recycling or school solar panels (Türkiye).
- ✦ Teach through gamified learning, including eco-competitions and circular economy games (Poland).

Advocate for Curriculum & Policy Integration

- + Encourage curriculum updates to formally include circular economy concepts (Türkiye).
- + Push for institutional support and funding to strengthen sustainability education (Greece, Poland).
- + Launch pilot programs before wider implementation (Greece).

Access & Develop Teaching Resources

- + Search for appropriate educational materials and case studies (Germany, Greece).
- + Create resource libraries with lesson plans, videos, and case studies (Greece).
- + Promote online courses and teacher workshops on circular economy (Poland, Türkiye).

Conclusion and Recommendations

The survey findings reveal a fragmented yet evolving landscape of circular economy education. While Poland demonstrates the most comprehensive and structured approach, other countries show isolated efforts with significant gaps in training, materials, and student involvement.

Recommendations include:

1. Develop national training programs for educators in circular economy concepts.
2. Create and distribute standardized teaching materials, accessible in all languages and adaptable to various education levels.
3. Promote interdisciplinary and project-based learning, encouraging real-world application.
4. Foster collaborations with businesses, NGOs, and local communities to enhance practical exposure.
5. Support student-led initiatives, ensuring youth are not just passive learners but active contributors to sustainability efforts.
6. Implement clear assessment frameworks that track both learning outcomes and environmental impact.

Therefore, the survey also highlights the importance of the CircEdu project implementing a European learning landscape including a capacity building program and a knowledge hub.

7. Conclusion

This study highlights the urgent need to integrate Circular Economy principles into secondary education as a transformative response to the environmental and social crises driven by linear economic models. Through a comprehensive desk review and survey-based research across Germany, Greece, Poland, and Türkiye, the CircEdu project has revealed both the widespread recognition of CE's importance and the significant gaps in curricular integration, teacher training, and resource availability.

While there is a growing body of research and innovative practice in the broader field of circular economy, its incorporation into educational systems, particularly at the secondary level, remains fragmented and underdeveloped. The study underscores the value of education not only in raising awareness but in equipping future generations with the skills, values, and systems thinking necessary to lead a sustainable transformation. It also demonstrates the potential of interdisciplinary, project-based, and digitally supported learning models to foster meaningful engagement with CE concepts.

The insights gathered from educators and institutions across the partner countries form a strong foundation for the next phases of the CircEdu project. To move forward, sustained efforts are needed to build capacity, create adaptable teaching resources, and raise awareness regarding policy framework changes that embed circular thinking into school cultures and curricula. By empowering both teachers and students, education can become a catalyst for a just and regenerative circular economy in the digital age.